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Carbon emissions in UK fisheries: recent trends, current levels, and pathways to Net Zero

Final report for Defra project C8118 *Towards Net Zero Carbon Fisheries*

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High-level policy summary

- In order to mitigate human-induced climate change, UK Government has **committed to reaching 'Net Zero' carbon emissions by 2050**, and to have reduced emissions by 78% by 2035 compared to 1990 levels (timelines for emission targets differ in detail between Devolved Administrations).
- Fisheries, however, typically use fossil fuels for propulsion, and for many other activities, so the question may be asked: **How could UK fisheries move towards Net Zero by 2050?**
- Here we show that currently, total emissions by the UK fishing fleet are **still substantial**, estimated as 802 and 702 kt CO_2e in 2019 and 2020, respectively (in 2019, equivalent to 0.18% of UK total territorial emissions, or 0.66% of UK domestic transport emissions).
- However, there have also been **significant reductions in total emission levels**: by –32% over a period of 15 years (from 1150 and 1065 kt CO_2e in 2004 and 2005, respectively). Over the same period, total fisheries landings showed some fluctuations but generally remained stable.
- While recent trends in emission reductions do indicate that significant progression can be achieved, **major change will still be needed** to fully reach Net Zero.
- A 'roadmap' of pathways for reducing emissions in fisheries, should incorporate:
  (1) **technological changes** (e.g. in propulsion methods, fuel types, electrification, hybridisation, port facilities);
  (2) **operational changes** (e.g. fishing methods, gear design, trip planning); and
  (3) **policy changes** (e.g. management of fisheries, ports and the maritime sector generally, consideration of an 'ecolabel', participatory approach).
- **Only in combination, and through partnership** between industry, science and policy, could these ultimately lead to carbon neutrality, while maintaining both sustainable living resources and prosperity in the fishing fleet and its dependent communities.

Executive summary

- This report describes the main outcomes from Defra project, *Towards Net Zero Carbon Fisheries*, and addresses the question:

  How could UK fisheries move towards Net Zero Carbon by 2050?

- Given the close connection between the different parts of the UK fishing fleet, this report considers all UK fisheries in its scope. However, given that fisheries management is devolved within the UK, it will be for individual fisheries administrations to consider the outputs of the report as part of their overall evidence base used to inform individual plans to tackle climate change and Net Zero.
- The question 'how could UK fisheries move towards Net Zero Carbon by 2050' is directly relevant to the UK Government's target to reach 'Net Zero Carbon Emissions' by 2050, and to have reduced emissions by 78% by 2035 compared to 1990 levels. Different targets for achieving Net Zero are in place in different parts of the UK. It is also relevant to the 'Climate Change' objective of the Fisheries Act 2020, specifically that *"the adverse effect of fish and aquaculture activities on Climate Change is minimised."* Moreover, it aligns with the Clean Maritime Plan (Maritime 2050): the Government's route map for the transition to a future of zero emissions shipping.
- This final report examines:
  (1) 'at-sea' carbon emissions by the UK fishing fleet, compared to other European countries;
  (2) recent trends and current levels of total carbon emissions for the UK fishing fleet, over the period 2004–2020;
  (3) 'at-sea' emissions (assessed through different emission 'metrics'), compared between 9 main gear types and 31 fine-scale segments of the UK fishing fleet – including how these have changed between the first and second decade of the 21st century;
  (4) a review of pre-harvest, at-sea and post-harvest emissions, as well as a review of indirect carbon emissions associated with bait sourcing required for some fisheries;
  (5) a roadmap of potential pathways that could help reduce emissions and move towards Net Zero carbon, with feedback from industry stakeholders on actions already taking place, and on potential challenges and opportunities.
- The main 'metric' used to quantify carbon emissions is that of carbon dioxide equivalent (CO_2e). Analyses are primarily based on fisheries data collated by Seafish (Seafish Authority) and STECF (Scientific, Technical and Economic Committee for Fisheries, EU), with greenhouse gas emission conversion factors sourced from the Department for Business, Energy & Industrial Strategy (BEIS).
- Our evidence (based on data for 2015–2019, focusing on 'at-sea' emissions) indicates that **the UK fishing fleet, compared to 22 other European countries, is not leading (but neither trailing) in terms of reducing its carbon emissions.** Its emission levels are in the mid-range compared to those from other European fishing fleets – the precise ranking depending on which metric is being used (total emissions, emissions per-vessel, emissions per-quantity of fish landed, or per-value of fish landed).
- Total carbon emissions by the UK fishing fleet are **still substantial – estimated at 802 and 702 kt CO_2e during 2019 and 2020** respectively. We do note that in 2020, due to the Covid pandemic, fisheries were substantially limited. Nevertheless, there is evidence of a **significant decrease in emissions:** in 2004 and 2005 respectively, emissions amounted to 1150 and 1065 kt CO_2e. If averages for 2004–2005 and 2019–2020 are compared, then this represents a **reduction of –32%**

over a 15-year period. It is important to appreciate that **total landings fluctuated but remained fairly stable** over the same period.

- For 2019, the last 'typical' year in the series, estimated emissions by the UK fishing fleet would have represented **0.18% of the UK's total territorial emissions** (455 Mt CO_2e), or **0.66% of UK domestic transport emissions** (122 Mt CO_2e). Estimated emissions by the UK fishing fleet would have been equivalent to **1.7% of total agricultural emissions** in 2019 (46.3 Mt CO_2e), noting that the total value of UK fisheries landings (£953 million) was equivalent to 3.5% of total agricultural gross output (£27.3 billion).
- Wide differences in carbon emission levels exist between nine main fleet segments within the UK fishing fleet, defined based on the major gear type used. Generally, as may be expected, **passive gear types tend to have lower emissions than active gears**, but this is not always consistently the case. The precise rankings again depend on the metrics used to quantify emissions (total, per-vessel, per-quantity of fish landed, or per-value landed).
- **Per-vessel**, 26 large (40m+) **pelagic trawlers were estimated to have the highest emissions**; however, these vessels had the **lowest emissions per-quantity** of fish landed. Vessels using drift or fixed nets had the lowest emission levels **per-value** of fish landed. Both **per-quantity** and **per-value of fish, beam trawlers were found to have highest emission levels** (ranking second highest in terms of emissions per vessel). Demersal trawlers and seiners, nephrops trawlers, and dredgers had **intermediate** levels of emissions (rankings depending on the metrics being used). As passive gears are often applied from small vessels where fuel efficiency may be less efficient, associated emission levels were sometimes not as low as may have been expected.
- An in-depth analysis of carbon emissions for 31 fine-scale segments within the UK fishing fleet (following the same definitions as applied by Seafish) allowed an assessment of **'progression' in emission reductions** across the fleet, by comparing two time-slices on average 10 years apart: 2005–2009 and 2015–2019. **Many, although not all** fleet segments (25 of 31) showed reductions in total emissions over the decade examined (on average by –17%). These reductions did coincide with a major reduction in total vessel numbers, so fewer emissions might have been expected; but importantly, total landings did *not* decrease, and there was also a reduction in average per-vessel emissions (–20%), emissions per-quantity of landings (–25%), and per-value of landings (–36%). So overall there is evidence of **real progression in emission reductions** at least since the early 2000s.
- We reviewed **life cycle** assessment studies where carbon emissions were compared between the 'pre-harvest phase' of fishing (e.g. vessel construction, bait preparation), the 'at-sea phase' (e.g. harvest, fishing itself, steaming, onboard refrigeration), and 'post-harvest phase' (e.g. processing, transportation). In each study, the majority of carbon emissions (60% or above) were found to be during the 'at-sea phase', especially from fuel use. In some passive fishing methods, sourcing of bait is required with an associated emission cost (up to 31%), though overall these gears are less carbon-intensive than active gears. Generally speaking, **pathways for emission reductions in UK fisheries could initially focus on 'at-sea' emission reductions**.
- We recommend a number of actions that could help reduce emissions in UK fisheries, recognising that this is for individual fisheries administrations to determine in partnership with their stakeholders. These potential pathways could be organised and considered along three major lines: technological; operational/behavioural; and managerial/policy pathways.

- **Technological pathways** could include: in the short term, a switch to biofuels compatible with current engine types; hybrid diesel-electric propulsion; and fully electric propulsion for inshore vessels. In the mid-term, these could include: liquefied natural gas (LNG), and battery or solar powered vessels. In the longer term, full carbon neutrality may be achieved through: ammonia powered, or hydrogen powered fuel cell vessels (but these technologies currently have some way to go).
- **Operational pathways** could include: regular maintenance of the vessel's hull to reduce drag, and regular engine maintenance; reducing steaming and/or trawling speeds if this does not significantly hamper fishing success; removing excess weight on the vessel; modifying fishing gear to make it more fuel-economic (e.g. lighter twine, wider mesh); fully switching to alternative, lower-emission gear; redirecting fishing towards grounds closer to port; or alternatively, changing the landing port to one closer to the fishing grounds.
- **Managerial pathways** could include a focus on enabling adaptation and removing barriers for implementing low- or zero-carbon solutions. This could be through policy schemes that encourage low-emission gears, or stimulate low-emission propulsion types (e.g. buying schemes, innovation funding). Fuel policies may include subsidies to low-emission fuels, and/or taxation of (or subsidies removed from) high-emission fuels. Policy schemes could also be developed that benefit a fishery that can demonstrate being low-emission: either through a 'government route' (e.g. access to quota or specific areas if vessels have the right credentials) or through a 'consumer route' (e.g. an 'eco-label' offering a better price or market access). By and large, a participatory approach is recommended where dialogue between governance, industry and science, and co-design of solutions are encouraged.
- Through ten online **stakeholder workshops** with industry representatives, from fisheries and producer organisations in different devolved administrations representing a broad range of fleet segments, we sought realistic feedback on the various potential pathways towards reduced emissions highlighted above. Regarding technological and operational pathways, this report collates experiences on **what initiatives are already taking place** within UK fisheries**,** and what are industry's views on **potential barriers and/or enablers** for emission reductions. With regard to potential policy pathways, this report describes industry perspectives on what policy or managerial options they would either be **supportive of,** or would see as creating major **challenges or barriers** with potentially adverse or unexpected consequences.
- This study has shown that carbon emissions in UK fisheries are still substantial but also that significant emission reduction has taken place at least since the turn of the millennium, demonstrating that progression can be achieved. As a next step, it would be valuable to **reconstruct past emission levels back to 1990, the 'benchmark year'** against which progress towards future emission targets will be assessed.
- In order to further reduce emissions towards Net Zero, the theoretical 'roadmap' provided consisting of potential technological, operational and policy changes, may serve to inform government, industry, and research. Through the inclusion of extensive feedback and experiences from industry, it is hoped this work will **stimulate workable solutions and collaborative partnerships** that help achieve these aims, and may inform policy choices that minimise disruption and optimise the long-term environmental, industry and societal benefits.

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1 Background and policy question

This report describes the main outcomes from Defra project, *Towards Net Zero Carbon Fisheries*, which addresses the policy question:

How could fisheries in the United Kingdom move towards Net Zero carbon emissions by 2050?

This question is closely aligned with new, ambitious climate change targets that the UK has set, specifically in June 2019 when the country became the world's first major economy to commit to reaching Net Zero carbon emissions by 2050[1]. The commitment was applauded widely but will also imply major changes to how UK citizens live their daily lives, and to the way that all industries work. In April 2021, a new challenging target was announced: to reduce carbon emissions by 78% by 2035 compared to 1990 levels[2] (Figure 1; timelines for emission reduction targets differ in detail between the Devolved Administrations[3]).

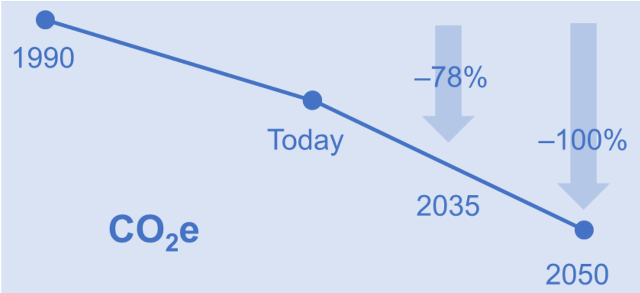

Figure 1. UK carbon emission (CO_2e) reduction targets.

The question is also directly relevant to the Fisheries Act 2020, which sets out a commitment for UK fisheries administrations to develop policy to deliver the 'Climate Change' objective (8), to mitigate (a) and adapt (b) to climate change:

(a) *the adverse effect of fish and aquaculture activities on Climate Change is minimised, and*
(b) *fish and aquaculture activities adapt to Climate Change.*

Moreover, the question aligns with the Clean Maritime Plan (Maritime 2050: Navigating the Future): the government's route map for the transition to a future of zero emissions shipping (DfT, 2019).

At present however, carbon emissions by UK fishing vessels are still substantial – although with variable estimates, e.g. estimated as 914.4 kt (kilotonne) of carbon dioxide (CO_2) emitted between May 2012 and May 2013 (Coello et al., 2015), as 570 kt of carbon dioxide equivalent (CO_2e) in 2012 (NAEI BEIS, 2021), and as 561 kt CO_2e for 2018 (NAEI BEIS, 2021). Achieving the aim of reducing emissions to Net Zero carbon is likely to require major changes to the way that UK fisheries will work. Important operational and technological changes will be needed; some of these will be achievable in the short term but others will require mid to long term action.

In line with meeting these policy objectives and addressing implementation challenges, the project *Towards Net Zero Carbon Fisheries* aims at determining what zero-carbon fisheries might look like in

[1] https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law
[2] https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035
[3] Scotland: https://www.gov.scot/policies/climate-change/; Wales: https://gov.wales/climate-change-targets-and-carbon-budgets; Northern Ireland: https://www.economy-ni.gov.uk/publications/energy-strategy-path-net-zero-energy

the UK and, following an assessment of current carbon emissions in the sector, what pathways and interventions might help to achieve this.

This report describes recent trends and current levels of carbon emissions by the UK fishing fleet. In doing so it is aimed at setting a stage or 'benchmark' against which any future developments may be compared. The overall focus is on at-sea emissions linked with fuel use – generally accepted to be the primary source of emissions. This is confirmed in a section that reviews life cycle studies on emissions in fisheries, and which compares pre-harvest, at-sea and post-harvest emissions, as well as indirect carbon emissions associated with bait sourcing required for some fisheries. The report closes off with a section that looks ahead into the future and identifies potential pathways that may lead to a reduction of emissions to Net Zero levels by 2050 – distinguishing between technological, operational, and managerial pathways. Through a series of stakeholder interviews, industry feedback, experience and expertise was sought on any actions towards reducing emissions that are already taking place, and on industry's perspectives on barriers and/or enablers of emission reduction.

The present report examines:

(1) 'at-sea' carbon emissions by the UK fishing fleet, compared to other European countries (section 3.1);
(2) recent trends and current levels of total carbon emissions for the UK fishing fleet, over the period 2004–2020 (section 3.2);
(3) 'at-sea' emissions (assessed through different emission 'metrics'), compared between 9 main gear types (section 3.3) and 31 fine-scale segments of the UK fishing fleet (section 3.4) – including how these have changed between the first and second decade of the 21st century;
(4) a review of pre-harvest, at-sea and post-harvest emissions, as well as a review of indirect carbon emissions associated with bait sourcing required for some fisheries (section 4);
(5) a roadmap of potential pathways that could help reduce emissions and move towards Net Zero carbon, with feedback from industry stakeholders on actions already taking place, and on potential challenges and opportunities (section 5).

2 Approach

This section includes the general approach to the study including those elements required to understand the results and main conclusions. For a full description of the methodology to estimate carbon emissions, we refer to the Technical Annex. Two primary data sources have supported the studies on recent and current carbon emissions:

(1) Data on production and economic performance of the UK fishing fleet for 2004–2020, collected by Seafish during the annual 'Seafish Surveys' (Quintana et al., 2020; and see https://www.seafish.org/insight-and-research/fishing-data-and-insight/uk-fishing-fleet-survey/). These include data for 31 fleet segments, which include vessels of different lengths and engine sizes that use one of eight main fishing gear types. These can either be 'active gears' such as pelagic trawls, beam trawls, demersal trawls and seines, nephrops trawls, and dredges; or they can be 'passive gears' that include pots and traps, drift or fixed nets, and gears using hooks (lines). In addition, fairly substantial numbers of registered fishing vessels are inactive either most or all of the year; while 'low activity' vessels (defined as grossing <£10,000 per year) were included in the present analysis as a ninth main fleet segment, fully 'inactive' vessels were excluded. Specifically, for each of the different fleet segments, information was collated on total numbers of vessels, total fisheries landings, economic value of landings, and fuel use.

(2) To allow comparisons of emission levels between the fishing fleets of the UK and other European countries, data were sourced from the EU Scientific, Technical and Economic Committee for Fisheries (STECF, Joint Research Centre, Ispra, Italy: see STECF, 2021). Data for the years 2015–2020 were collated, describing production and economic performance of the fishing fleets of all EU countries (then including the UK). Specifically, information was selected on the total numbers of vessels, total fisheries landings, economic value of landings, and fuel use for each country. It is of note that the 'raw' data are collected by each individual country separately, adhering to Data Collection Framework (DCF) protocols but with slight differences between countries which relate to the diversity of the fisheries in each country. These data are compiled annually by STECF, to which the UK provided data up to 2019.

The fuel use data for UK and wider EU fisheries, sourced from STECF and Seafish, were then combined with (fuel type-specific) conversion factors provided by the Department for Business, Energy & Industrial Strategy (BEIS, 2021a), to convert figures on fuel use (by country or fleet segment) into estimates of greenhouse gas emissions. The three main greenhouse gases, resulting from marine fuel oil combustion onboard fishing vessels are CO_2, methane (CH_4) and nitrous oxide (N_2O), representing approximately 98.56%, 0.04% and 1.40%, respectively, of greenhouse gas emissions from marine fuel oil (BEIS, 2021; but values differing slightly between years). As a means to quantify overall greenhouse gas emissions, the amount of 'carbon dioxide equivalent' (CO_2e) is then calculated as the total amount of greenhouse gas emissions.

For each of the different European countries, as well as within the UK for each of the main fleet segments, different 'metrics' were then calculated from the available data sources, each describing the levels of carbon emissions by country or fleet segment in different ways. These included: the total levels of carbon emissions in any given year (unit: kt or Mt CO_2e); the average emissions per vessels in any given year (unit: t or kt CO_2e / vessel); the average emissions per quantity of fish or shellfish landed (unit: kg CO_2e / kg fish); and the average emissions per value of fish or shellfish landed (unit: for comparisons between European countries, kg CO_2e / € fish, and for comparisons within the UK, kg CO_2e / £ fish).

The review of studies on emissions during the pre-harvest, at-sea and post-harvest phases, as well as on emissions associated with bait required for some fisheries, is based on a study of both primary, peer-reviewed scientific papers, and reports and papers that form part of the 'grey literature'.

The section on 'Pathways towards emission reductions' is based on literature searches, on initial consultation with stakeholders within parts of science, policy and industry, and on our own experiences with regards fisheries vulnerability and risk assessments, and fisheries adaptation to climate change. Specifically, this section has built upon the 'Pathways' section within the scoping report for this study (Engelhard et al., 2021), but has been expanded to incorporate the feedback obtained from a set of 10 online workshops with stakeholders from the fishing industry of the UK.

During the industry stakeholder workshops, information was collated through asking feedback on a standardised set of questions around potential technological, operational and/or optional policy 'pathways' towards emission reductions. Regarding technological and operational changes, we asked for feedback and expertise on (1) what initiatives are already taking place within UK fisheries with regard to reducing emissions; (2) what are the perspectives about the future, including on what is being seen as real barriers, and/or as enablers for reducing emissions, with considerations of what type of support may be needed. With regard to various, potential policy options (at present all theoretical) around emission reductions, we asked for feedback on (3) what policy or managerial options they would either be supportive of, or would see as creating major barriers or challenges.

All workshops were held online between 17th December 2021 and 10th February 2022. Twenty stakeholders were interviewed, representing 7 fisheries producer organisations (both in England and Scotland), the vessel building sector, and Inshore Fisheries and Conservation Authorities; feedback was also sought from Department for Transport (DfT) and BEIS. Combined, industry stakeholders interviewed covered many sectors of the UK fishing fleet, ranging from small inshore vessels to large pelagic, beam and demersal trawlers, seiners and scallop dredgers, among other fleet segments. The interviews were recorded and transcribed to facilitate note taking (recordings and transcripts not retained long-term) and thematic analyses carried out based on these, according to the three main pathway themes laid out in this study. Discussions adhered to a confidentiality agreement which had been provided to all stakeholders consulted, prior to each of the interviews taking place; in all cases, informed consent was obtained. The confidentiality agreements put in place were in accordance with Government Social Research Professional Guidance on Ethical Assurance for Social and Behavioural Research in Government (GSR, 2021).

It is of note that the actions and possible pathways proposed here should be seen as initial concepts that aim to stimulate discussion between different stakeholder groups linked with the marine environment and sustainable use of marine living resources. The pathways presented are intended to provide additional information to inform the wider evidence base – they are formulated as they are to stimulate inclusive and participatory debate and the development of informed decisions later on.

3 Results

3.1 At-sea emissions: comparison of the UK fleet and other European countries

To allow an informed comparison of carbon emission levels between the fishing fleets of the UK and other European countries, the total size of the fishing sector for each country needs to be considered. Averaged over the period 2015–2019, the UK was the third-largest contributor to fisheries production among EU countries, if expressed as total quantities of landings (Figure 2, Table 1; UK annual landings averaging 691 kt). UK fisheries production ranked below that of Spain (910 kt) and Denmark (772 kt) and was followed by France (543 kt), the Netherlands (359 kt) and other countries. The UK contributed on average 13.7% of the total landings by the EU fleet (5.046 million t annually, averaged over 2015–2019; Table 1).

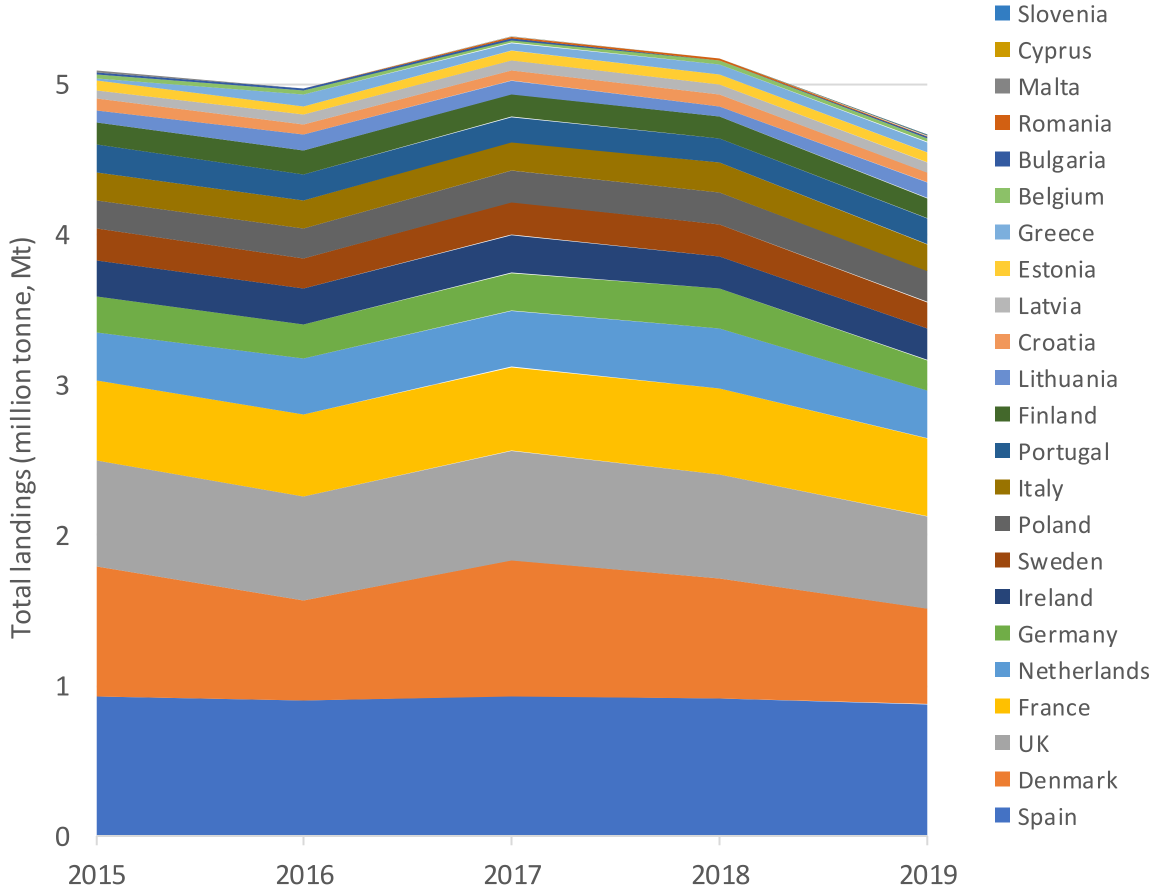

Figure 2. Total landings by the fishing fleets of the UK and 22 other fishing nations part of the European Union during 2015–2019.

While the UK ranked third highest among EU countries in terms of total fisheries production during 2015–2019, it ranked fourth in terms of total carbon emissions by its fishing fleet (Figure 3; Table 1). While the UK fleet contributed 13.7% of total landings, it emitted 11.7% of all carbon by all EU countries' fishing fleets (EU fleet: annual emissions 7.299 Mt CO_2e; UK fleet: 857 kt CO_2e, averaged over 2015–2019; Table 1). Total annual carbon emissions were higher for the fishing fleets of Spain (1893 kt CO_2e), Italy (1107 kt CO_2e) and France (983 kt CO_2e), which each have larger total numbers of vessels than the UK. Nineteen EU fishing nations had lower total carbon emissions for their fleets; it should be noted these also had lower total fisheries production, with the exception of Denmark (mean annual emissions 303 kt CO_2e).

Between 2015 and 2019, there has been very little change in the UK's contribution to total EU fisheries landings (13.9% versus 13.2%) and neither in the UK's contribution to total EU emission levels (11.52% versus 11.57%).

As we shall see later in the report, the total carbon emissions by countries' fishing fleets are not only associated with total fisheries production but also by factors including total number and sizes of fishing vessels, and different types of fishing. The direct interpretation of total emission levels as symbolising degree of progression in emission reduction requires some caution.

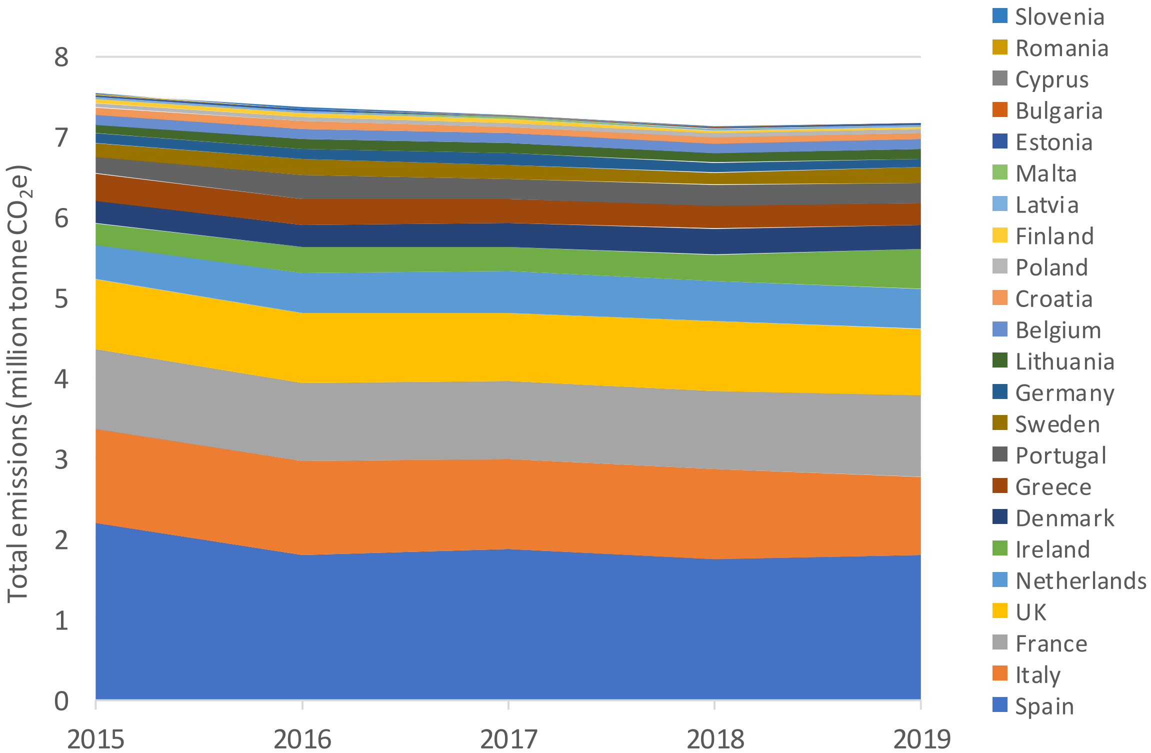

Figure 3. Estimates of total carbon emissions by the fishing fleets of the UK and 22 other fishing nations, part of the European Union during 2015–2019, based on economic data sourced from STECF.

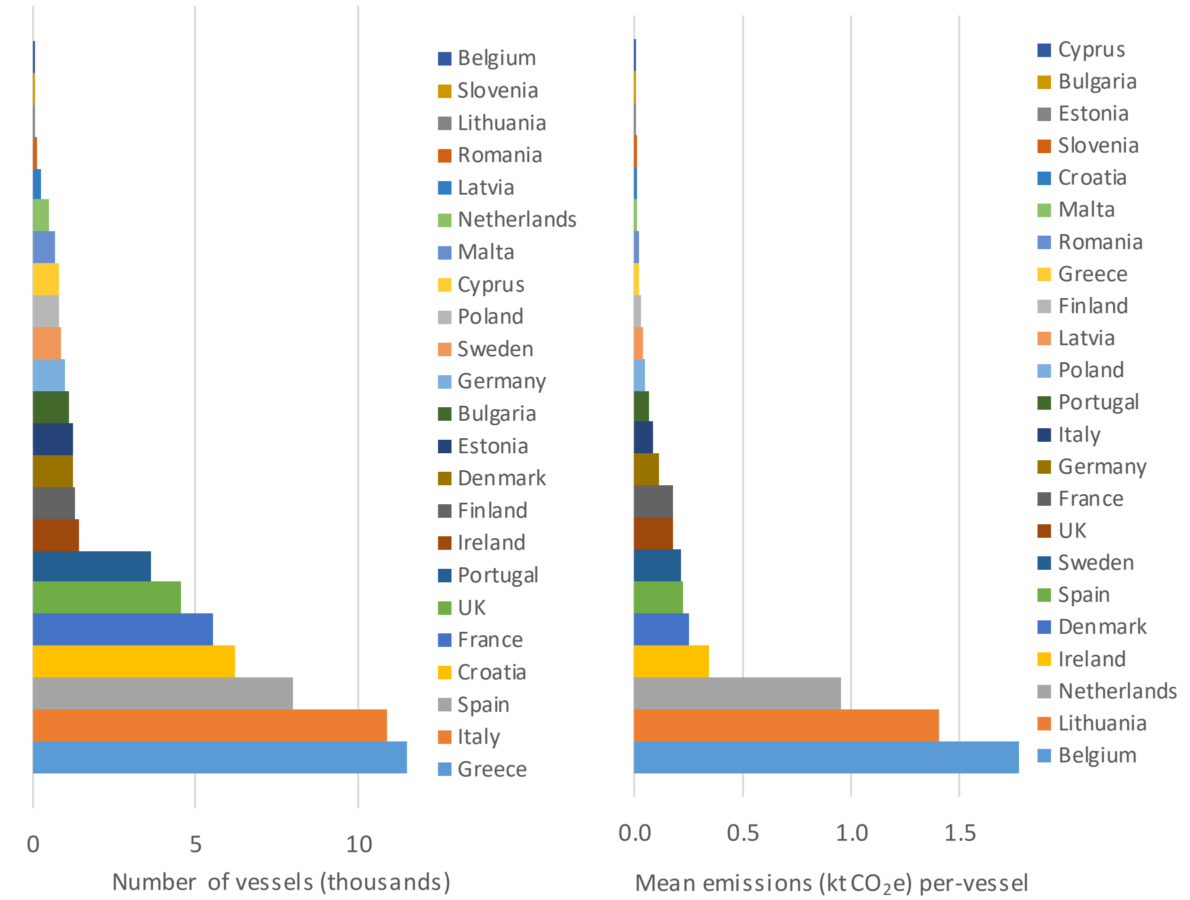

Figure 4. *Left:* the total number of registered fishing vessels for each of 23 EU countries with fishing fleets in 2019 (excluding inactive vessels, including 'low activity' vessels). *Right:* the average carbon emissions per fishing vessel in 2019 (excluding inactive vessels).

A very different picture emerges if the carbon emissions are assessed on a per-vessel basis (Figure 4). In 2019 (the most recent year where Europe-wide data were available), the UK's fleet numbered 4548 registered vessels (excluding inactive vessels but including low-activity vessels). Several Southern European countries have fleets comprising more, but often smaller vessels (including Greece, Italy, and Spain); some countries have few, but generally large vessels, including Belgium and the Netherlands (Figure 4, left).

In 2019, UK fishing vessels (excluding inactive vessels) on average emitted 183 t CO_2e per vessel over the course of year (Figure 4, right; 189 t in 2015). This is much less than the average emissions per vessel for Belgium (which has few vessels, mainly beam trawlers: 1780 t CO_2e/vessel), Lithuania and the Netherlands (which also have fewer vessels, many of these are large: 1404 and 957 t CO_2e/vessel, respectively).

The UK, in terms of carbon emissions per vessel, ranked 8th-highest out of 23 countries in 2019 (and 6th-highest in 2015). Per-vessel, the UK emitted more than the EU average for 2019, estimated at 114 t CO_2e/vessel.

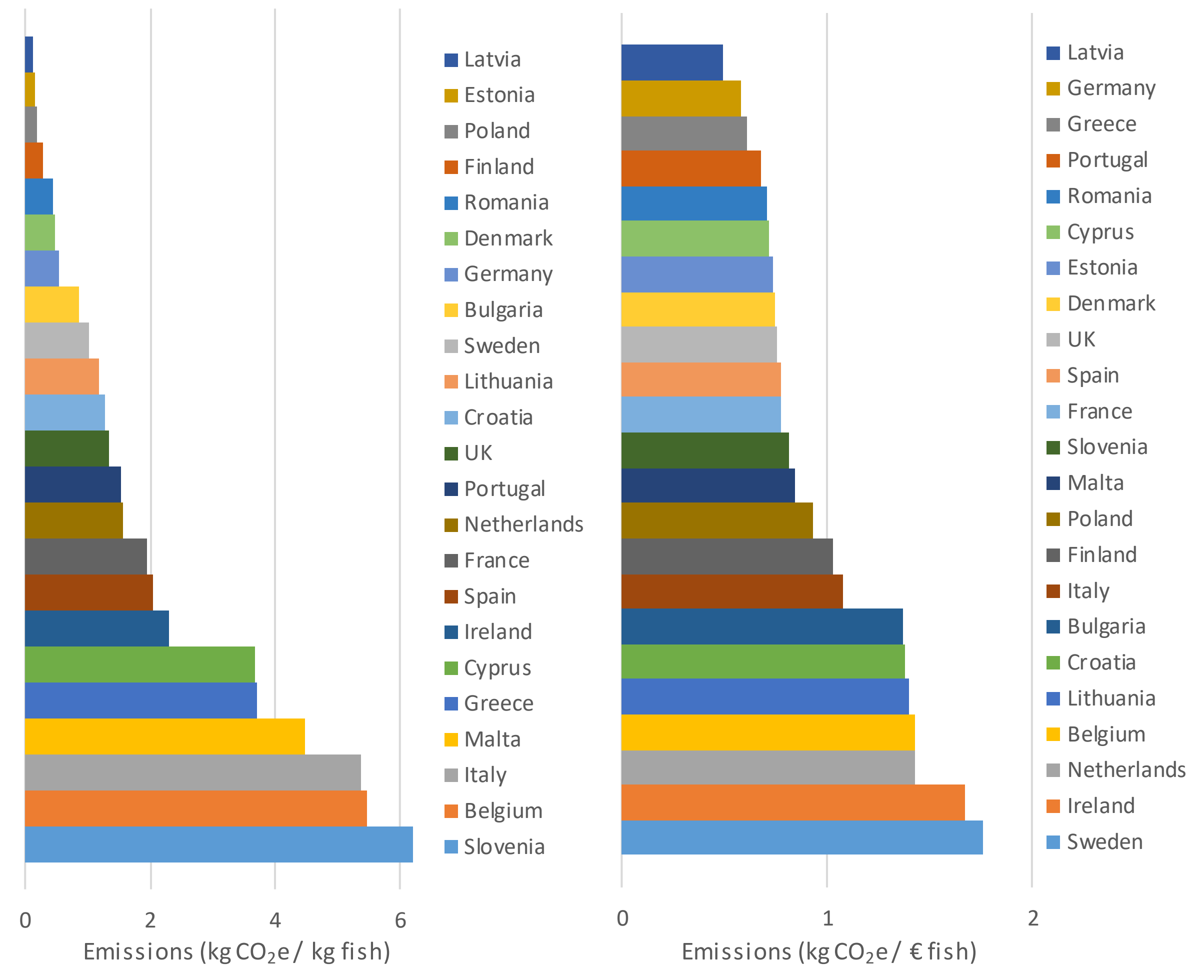

Figure 5. *Left:* average carbon emissions per-quantity of landed fish (including shellfish; in kg CO_2e / kg fish), for each of 23 EU countries with fishing fleets in 2019. *Right:* average carbon emissions per-value of landed fish (kg CO_2e / € fish), in 2019.

Of particular interest is a consideration of the carbon emission levels by fishing fleets in the context of total fisheries production (in terms of quantities of fish and shellfish landed), and of the total economic value of fisheries landings per country (Figure 5).

In 2019, the UK ranked 12th lowest in terms of carbon emissions per kg of landed fish (Figure 5, left), on average emitting 1.24 kg CO_2e per kg fish. This was less than the EU average, which was 1.55 kg CO_2e per kg fish. In 2019, highest emissions per kg fish were recorded for Slovenia, Belgium and Italy (respectively, 6.22, 5.47 and 5.38 kg CO_2e / kg fish), followed by Malta, Greece and Cyprus (respectively, 4.49, 3.71 and 3.68 kg CO_2e / kg fish). By contrast, these values were much lower for Latvia, Estonia, Poland and Finland (respectively, 0.13, 0.16, 0.20 and 0.28 kg CO_2e / kg fish).

The ranking of emissions per landed value is very different from the ranking of emissions per landed weight of fish. In 2019, the UK fishing fleet was estimated to have emitted on average 0.753 kg CO_2e per € landed fish, ranking it 9th lowest among 23 EU countries with fishing fleets. For the EU overall, this was on average 0.878 kg CO_2e per € landed fish.

Differences in rankings, depending on whether emissions are assessed based on either the quantity or value of landings, are exemplified by several Mediterranean countries including Italy, Slovenia and

Malta. Here, the emissions per kg landed are high (which may relate to generally small and/or less efficient engines vessels); however as the average price per kg is also high, the emissions per landed value are modest (compare Figure 5a with 5b; see also Table 1 for average values over 2015–2019).

Table 1. Comparison between 23 European countries in terms of numbers of active vessels, fisheries production (expressed as total weight and total value of landings), and metrics related to carbon emissions by fisheries: total emissions, average emissions per vessel, emissions per-quantity (kg) of landed fish, and emissions per-value (€) of landed fish. All values represent averages over 2015–2019. Overall values for the EU are indicated in italics and colour-shading is indicative of a country's fleet size, quantity or value of landings (green-shaded) and emissions (red-shaded).

Country	Vessels	Landings		Emissions			
	(Active only) (n)	Total annual quantity (t)	Total annual value (000 €)	Total annual ($t\ CO_2e$)	Per vessel, per year ($t\ CO_2e$)	Per quantity landed ($kg\ CO_2e$ / kg fish)	Per value landed (kg CO2e / € fish)
Belgium	68	23,847	85,816	118,848	1,754	5.01	1.39
Bulgaria	1,207	8,925	7,099	8,106	7	0.91	1.17
Croatia	5,296	69,354	58,868	82,043	17	1.19	1.40
Cyprus	783	1,524	8,030	6,689	9	4.40	0.84
Denmark	1,310	771,542	446,763	303,235	233	0.40	0.68
Estonia	1,424	63,482	14,961	10,062	7	0.16	0.67
Finland	1,448	148,547	36,343	46,473	32	0.31	1.28
France	5,673	542,723	1,302,803	983,075	173	1.81	0.76
Germany	1,017	236,184	226,120	124,760	123	0.53	0.55
Greece	13,173	56,920	335,986	297,953	23	6.73	1.17
Ireland	1,381	232,369	268,474	335,137	242	1.47	1.24
Italy	11,175	191,282	920,721	1,106,896	99	5.78	1.20
Latvia	255	65,795	19,039	14,003	55	0.21	0.73
Lithuania	93	90,042	67,738	122,997	1,321	1.38	1.85
Malta	721	2,408	11,780	11,793	16	4.93	1.02
Netherlands	524	358,640	411,862	490,512	937	1.37	1.20
Poland	796	200,815	48,100	50,692	64	0.25	1.05
Portugal	3,762	170,850	383,221	260,992	69	1.53	0.68
Romania	131	7,226	4,232	2,522	19	0.36	0.60
Slovenia	80	145	983	717	9	5.11	0.74
Spain	8,241	909,786	2,034,123	1,892,796	229	2.08	0.94
Sweden	926	202,996	119,157	171,961	186	0.86	1.45
UK	4,618	690,539	1,115,254	856,840	186	1.24	0.77
All included	***64,102***	***5,045,943***	***7,927,473***	***7,299,100***	***114***	***1.45***	***0.92***

3.2 Trends in total at-sea emissions for the UK fishing fleet

Over the years 2004–2020, total annual production by the UK fishing fleet in terms of fisheries landings averaged 623,000 tonnes (623 kt; Figure 6, left), and in spite of fluctuations, was fairly stable overall during this 17-year time span. Over the same period, we estimated total carbon emissions for the UK fishing fleet, based on economic data sourced from Seafish (Figure 6, right). These do indicate that emission levels have declined: from 1150 and 1065 kt CO_2e in 2004 and 2005 respectively, to 802 and 702 kt CO_2e in 2019 and 2020. This represents a decrease by –32% over a 15-year period.

It should be noted that for the first year included here (2004), fleet economic data were less complete (with under-10 m vessels not being well sampled), and also that the last year in the series, 2020, coincided with the Covid pandemic outbreak when UK fishing activities were substantially limited.

For 2019, the last 'typical' year in the series, estimated emissions by the UK fishing fleet (802 kt CO_2e) would have represented 0.18% of the UK's total territorial emissions (455 Mt CO_2e: BEIS, 2021), or 0.66% of the UK's domestic transport emissions (122 Mt CO_2e; DfT, 2021). Estimated emissions by the UK fishing fleet would have been equivalent to 1.7% of total agricultural emissions in 2019 (46.3 Mt CO_2e: BEIS, 2021). By comparison, the total value of UK fisheries landings (£953 million) was equivalent to 3.5% of total agricultural gross output (£27.3 billion; National Statistics, 2020).

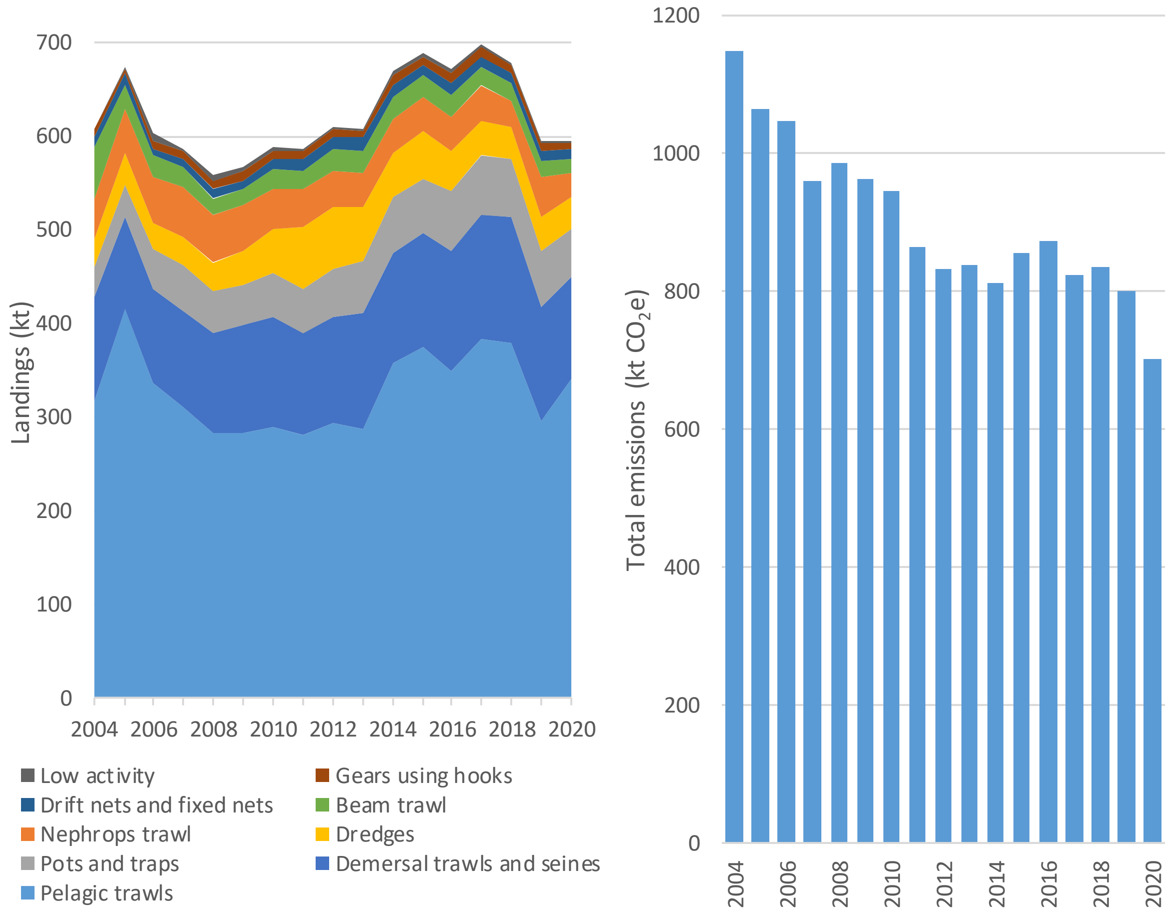

Figure 6. *Left:* Total production by the UK fishing fleet, shown as annual landings for each of 9 major fleet segments during 2004–2020. *Right:* Estimates of total carbon emissions by the UK fishing fleet during the same years, based on economic data sourced from Seafish.

Nine major gear categories used by vessels of very different sizes, ranging from under-10m to well over 40 m in total length (see Tables 3 to 5 for an overview of fleet segments by size) contributed highly unequally to the total quantities of fish landed in the UK (Figure 6, left). Half of the landings comprised of pelagic species, caught by a small number of large (40 m+) pelagic trawlers: in 2019, only 26 vessels landed 49.7% of the UK's total catch. In the same year, 20.5% of total UK landings were demersal fish caught by 369 demersal trawlers and seiners; and 10.2% were caught by a large number (1542) of vessels using pots and traps – generally of small size (mostly <10 m; Table 5). In decreasing order of importance regarding total quantities, the other gear types were: nephrops trawls (288 vessels, 7.1%); dredges (264 vessels, 6.3% of landings in 2019); beam trawls (69 vessels, 2.8%); drift and fixed nets (230 vessels, 1.9%); and gears using hooks (229 vessels, 1.3%). This high diversity of the UK fishing fleet needs to be considered when assessing carbon emissions by different fleet segments.

3.3 At-sea emissions: comparison of major segments of the UK fishing fleet

Different types of fishing result in widely different levels of carbon emissions. However as will be shown in this section, the outcomes depend on which metrics are used to compare carbon emissions – total emissions, or emissions per vessel, per quantity of fish landed, or per value of fish landed (see Table 2 for an overview of average values over 2015–2019).

Table 2. Comparison between 9 main segments within the UK fishing fleet, in terms of numbers of vessels, fisheries production (expressed as total weight and total value of landings), and metrics related to carbon emissions: total emissions, average emissions per vessel, emissions per quantity (kg) of landed fish, and emissions per value (£) of landed fish. All values represent averages over 2015–2019. Colour-shading is indicative of the quantity or value of landings (green-shaded) and emissions (red-shaded).

Gear Type	Vessels	Landings		Emissions			
	(Active only) (n)	Total annual quantity (t)	Total annual value (000 £)	Total annual ($t\ CO_2e$)	Per vessel, per year ($t\ CO_2e$)	Per quantity landed ($kg\ CO_2e$ / kg fish)	Per value landed (kg CO2e / £ fish)
Beam trawl	73	19,915	58,941	106,954	1,461	5.37	1.81
Demersal trawls and seines	402	128,031	270,410	249,302	620	1.95	0.92
Nephrops trawl	296	36,135	93,106	119,548	404	3.31	1.28
Dredges	289	40,933	79,907	85,413	296	2.09	1.07
Pelagic trawls	26	356,190	303,198	131,771	4,991	0.37	0.43
Drift nets and fixed nets	237	11,512	28,320	13,481	57	1.17	0.48
Gears using hooks	216	9,632	29,626	23,141	107	2.40	0.78
Pots and traps	1411	61,003	161,492	100,784	71	1.65	0.62
Low activity vessels	1646	2,287	6,057	7,556	5	3.30	1.25
All included	**4596**	**665,638**	**1,031,057**	**837,950**	**182**	**1.26**	**0.81**

In terms of total carbon emissions (Table 2; see also Figure 7), the fleet segment contributing most to the UK's total (annual average 249 kt CO_2e, or 29.8% of UK total over 2015–2019) comprised demersal trawlers and seiners (369 vessels in 2019), which ranked second in terms of total fisheries landings (compare with Figure 6). Twenty-six pelagic trawlers contributed 15.7% (132 kt CO_2e) to the carbon emissions by the UK fishing fleet in 2015–19; this is less than expected considering these contributed 50% to the total landings. The nephrops trawl fleet, comprising 288 vessels in 2019, contributed 14.3% (120 kt; averaged over 2015–2019) to the UK fleet's total carbon emissions. The total carbon emissions by three fleet segments were of comparable magnitude despite very different numbers of vessels: the beam trawl fleet (69 vessels, 107 kt CO_2e, 12.8% of total UK fishing fleet emissions); potters and trappers (1542 vessels, 101 kt CO_2e, 12.5%); and dredgers (264 vessels, 85 kt CO_2e, 10.2%). Vessels using gears with hooks (23 kt CO_2e), netters (13 kt CO_2e) and 'low activity vessels' (7.6 kt CO2e) contributed far less to the total emissions (2.8%, 1.6% and 0.1% respectively).

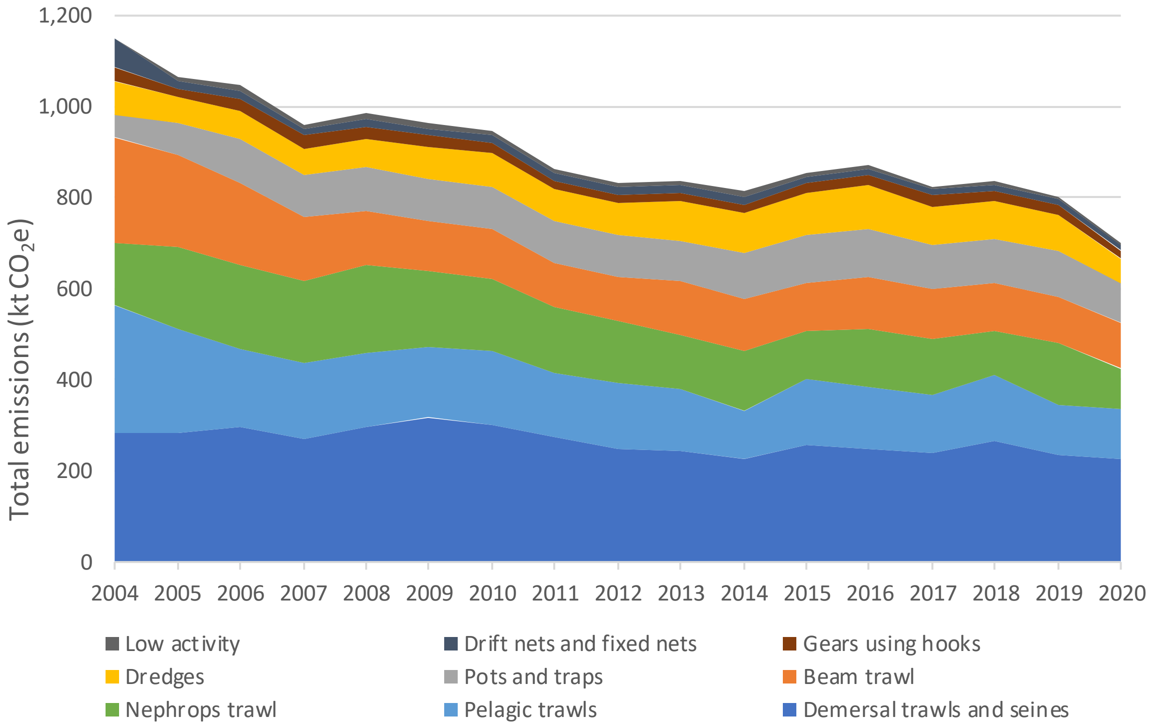

Figure 7. Total carbon emissions (CO_2e) of 9 main segments within the UK fishing fleet, based on major gear type, during 2004–2020. Note that total numbers of vessels and productivity levels do not only vary between the various fleet segments, but have also changed over time.

Over the years 2004–2020, the total emissions of many, but not all of the nine main segments of the UK fishing fleet have declined (Figure 7). More specifically, if average emissions are compared between 2005–2009 and 2015–2019, then these are found to have declined for 7 of the 9 main fleet segments (by –29% for beam trawlers; by –15% for demersal trawlers and seiners; by –34% for nephrops trawlers; by –26% for pelagic trawlers; by –15% for netters; by 11% for liners; by –25% for low activity vessels). However they have increased for dredgers (+37%) and potters and trappers (+13%). As we shall see in the next section of the report, these decreases in emissions (and in some cases increases) are due to a combination of reductions (or increases) in vessel numbers (but not necessarily in total landings), changes in the composition of fleets (smaller and larger vessels, different engine sizes, etc.), as well as real improvements in fuel or catching efficiency.

On an emissions per-vessel basis, the large pelagic trawlers (all >40m total length) ranked by far the highest (e.g. in 2019, estimated at 4301 t CO_2e/vessel (Figure 8, right) – although this has reduced since 2005 (7207 t CO_2e/vessel: Figure 8, left). Next-highest were beam trawlers (1470 t CO_2e/vessel in 2019) followed by demersal trawlers and seiners (632 t CO_2e/vessel), nephrops trawlers (478 t CO_2e/vessel) and dredgers (289 t CO_2e/vessel). It is of note that each of these vessel types use 'active gears', that are dragged through the water column (as in pelagic trawlers) or over the seafloor (as in the other fleet segments; with some of these to some extent penetrating the seabed, and others barely touching). On a per-vessel basis, those vessel types using 'inactive gears' tend to have much lower emission levels: these include liners using hooked gears (102 t CO_2e/vessel in 2019), potters and trappers (66 t CO_2e/vessel) and netters (52 t CO_2e/vessel), the latter being characterised by the lowest average emissions per vessel.

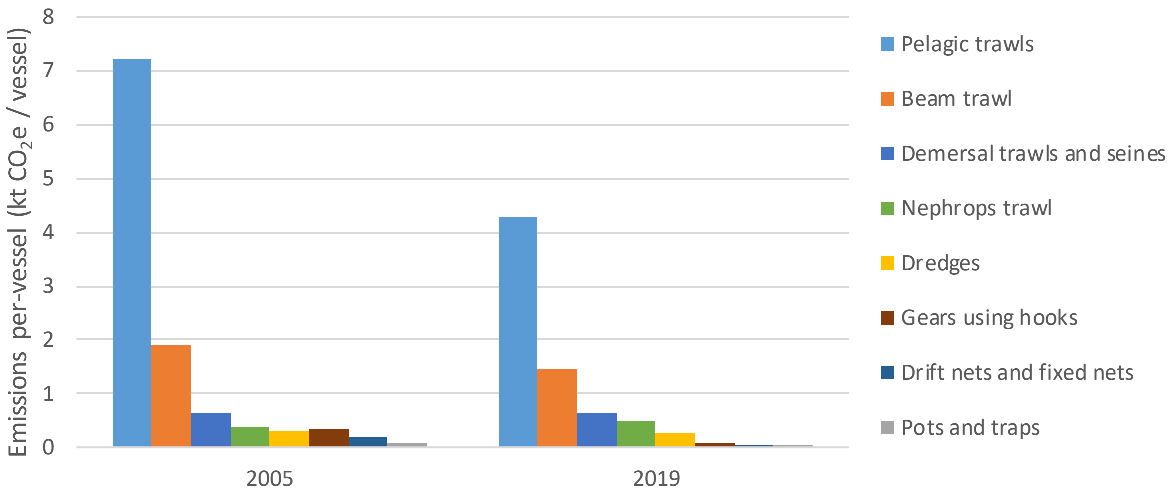

Figure 8. Average emissions per-vessel for 8 main gear types within the UK fishing fleet, estimated for the years 2005 (left) and 2019 (right; excluding low activity vessels, where comprehensive data were lacking). Note that some gear types are typically used on either smaller or larger fishing vessels.

There is evidence that on average, per-vessel emissions have decreased over the time-period considered (e.g. Figure 8, compare left and right panels). Between 2005 and 2019, emissions per-vessel decreased not only for pelagic trawlers but also for dredgers, liners using hooked gears, netters, and potters and trappers; they stayed approximately the same, or increased marginally (on average), for demersal trawlers and seiners, and nephrops trawlers. For the entire UK fishing fleet, annual per-vessel emissions averaged 228 t CO_2e/vessel d 2005–2009 and 182 t CO_2e/vessel over 2015–2019; thus overall, per-vessel emissions decreased by –20% over this 10-year period.

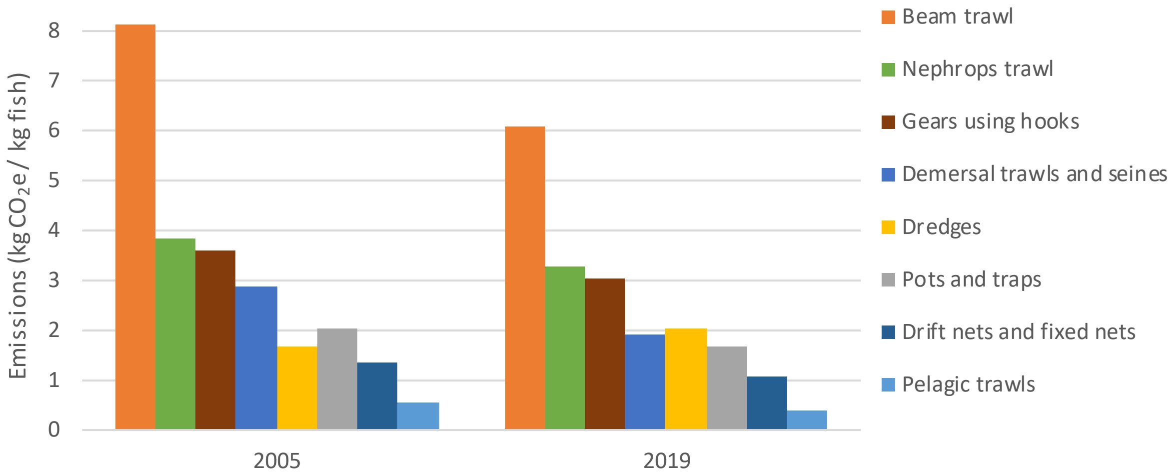

Figure 9. Average carbon emissions per-quantity of fish landed in 2005 and 2019 (kg CO_2e / kg fish, including shellfish) for 8 main gear types within the UK fishing fleet (excluding low activity vessels, where comprehensive data were lacking).

If the carbon emissions per-quantity (weight) of landed fish are compared between fleet segments (Figure 9), then the pelagic trawlers stand out as having the lowest emissions per kg of fish landed (0.38 kg CO_2e / kg fish in 2019). This relates to the large quantities of pelagic fish caught and landed, and hence economics of scale. Next lowest ranks another (much smaller-scale) fishery that mainly targets pelagic fish, but using inactive gears – drift and fixed netters. If carbon emissions are assessed per economic value (£) of the total quantities of landed fish (rather than per total weight of landings), then the pelagic trawlers and netters likewise stand out as having lowest emissions (Figure 10), albeit their ranking reversed (related with higher average price per kg in the case of netters). Vessels using pots and traps also rank relatively low in terms of emissions per-quantity (kg) or per-value (£) landed.

At the other end of the spectrum, beam trawlers had the highest emissions among the main gear types, both in terms of emissions per-quantity (kg) and per-value (£) of landings (Figures 8 and 9). This is reflective of this fishing method typically being more fuel intensive. Typically, beam trawlers target high-value species such as sole, so a drop in emissions per £ compared to emissions per kg might have been expected – this appeared not to be the case in UK beam trawlers, likely reflecting that these currently land a variety of high- and low-value species.

The other three active gear types ranked intermediate with regard to emissions per-quantity or per-value of landings. In the case of dredgers, more modest emissions per-quantity of landings than per-value, might relate to the shells of scallops, which add to the weights of landings but little to their value (compare rankings in Figure 9 with Figure 10).

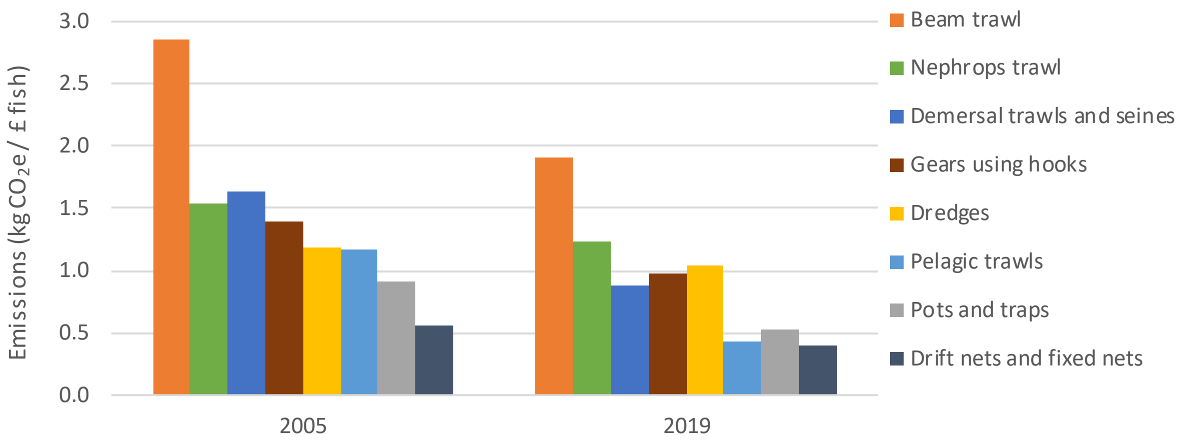

Figure 10. Average emissions per unit of economic value of seafood landed in 2005 and 2019 (kg CO_2e / £ fish or shellfish landed) for 8 main gear types within the UK fishing fleet (excluding low activity vessels, where comprehensive data were lacking). Values of £ adjusted to 2020 inflation.

Carbon emissions per-quantity (kg) of fish landed have reduced between 2005 and 2019, for 7 of the main segments of the UK fishing fleet (Figure 9, compare left and right panels). The exception to this are the scallop dredgers – where total landings have increased, but emissions have increased to a greater extent, and hence emissions per-quantity landed increased (from 1.66 to 2.03 kg CO_2e / kg fish). If expressed as emissions per-value of landings, then these have reduced for all of the main gear segments between 2005 and 2019 (Figure 10, compare left and right panels).

For the UK fleet overall, emissions per-quantity (kg) of fish landed averaged 1.68 kg CO_2e / kg fish in 2005–2009, and 1.26 kg CO_2e / kg fish in 2015–2019, which implies a reduction of –25% over this ten-year period. For the entire UK fleet, the emissions per-value (£) of fish landed decreased still more: from 1.26 kg / £ fish in 2005–2009 to 0.81 kg CO_2e / £ fish in 2015–2019 (£ value adjusted to 2020 inflation); this represents a reduction of –36%. It should be noted that the £ value has been adjusted here for inflation up to the year 2020; the reduction would have been higher, if £ values not adjusted for inflation would have been used (from 1.61 to 0.89 kg CO_2e / £ fish, i.e. by –45%) – but the comparison would be less appropriate.

3.4 At-sea emissions: detailed analysis of 31 UK fleet segments

This section provides an in-depth analysis of carbon emissions for 31 finer-scale segments within the UK fishing fleet, following the same definitions as those applied by Seafish in their annual fleet surveys. Again, the 'metrics' used to assess emission levels are: total annual emissions of the full fleet segment; average, annual per-vessel emissions; and emissions per-quantity (kg) and per-value (£) of landings. In all cases, £ values have been adjusted for inflation up to the year 2020. Specifically, this section compares emission levels between two time-slices, on average 10 years apart: 2005–2009 and 2015–2019. this allows an assessment of the extent to which there may have been progression in emission reductions, or possibly a lack thereof.

We note that from the year 2019 to 2020, there was a significant drop in total emission levels (from 802 to 702 kt CO_2e), by –12.5%. However as fishing activities were severely disrupted in 2020 due to the Covid pandemic, and hence emissions reduced, we have not included this year in the present analysis, as this would have potentially not provided a fully 'representative' picture of progression in emission reductions.

Beam trawlers. Between 2005–2009 and 2015–2019, total annual emissions by the UK beam trawl fleet (which as noted above, is characterised by fairly high emissions per-vessel, per-quantity, and per-value) decreased by –29% (from 150 to 107 kt CO_2e; Table 3). This was, however, largely due to a reduction in fleet numbers, particularly for large-engine beam trawlers (defined as >300 kW in the North Sea, and as >250 kW in the South West). Per-vessel, emissions have increased within each of the 4 segments within the beam trawl fleet. However because of the reorganisation of engine sizes within the beam trawl fleet (now relatively more small-engine, fewer large-engine vessels), per-vessel emissions for the beam trawl fleet overall have decreased (by –5%; Table 3).

For North Sea beam trawlers <300 kW (which typically catch shrimp), total landings decreased between 2005–2009 and 2015–2019, and accordingly emissions per-quantity increased (by +12%) as did emissions per-value landed (by +7%; Tables 4, 5). Per-quantity and per-value emissions decreased, however, for the other three segments of the beam trawl fleet: North Sea beam trawlers >300 kW (which typically catch sole and plaice) and South West beam trawlers <250 and >250 kW (both typically catching sole and other flatfish, cuttlefish, and monkfish). For the UK beam trawl fleet overall, reductions in per-quantity and per-value emissions amounted to –25% and –29% respectively over the decade examined.

Demersal trawlers and seiners. Total emissions decreased between 2005–2009 and 2015–2019 (by –15%) but mainly due to a reduction in fleet numbers from 499 to 402; per-vessel emissions increased (by +6%; Table 3). In spite of fewer vessels, total landings have increased (by +23%) as did total value of landings (by +34%) so that there has been a substantial improvement in emissions per quantity of fish landed (–31%) and per value landed (–37%).

UK demersal trawlers and seiners consist of 9 smaller-scale fleet segments; between 2005–2009 and 2015–2019, all of these have shown reductions in emissions per value (£) of fish landed, and 8 of 9 in emissions per quantity (kg) landed (Tables 4, 5). Per-quantity emissions increased marginally (+2%) in NSWOS (North Sea and West of Scotland) demersal trawlers of 10–24m and <300 kW, a small fleet segment targeting a range of demersal species that has shrunk in vessel numbers (from 28 to 18), but improved in per-vessel emissions (reduced by –11%).

Per-vessel, emissions increased for NSWOS demersal pair trawlers/seiners, and NSWOS demersal seiners (by +29% and +25% respectively) however these segments have increased their total landings, and landings value, in spite of reductions in the numbers of vessels. For both these segments the emissions per quantity landed have actually reduced (–39% and –29%), as did the per-value emissions (–47% and –39%).

Nephrops trawlers. Between 2005–2009 and 2015–2019 the number of vessels declined by –34%, and total emissions likewise declined by –34%; this implied no change overall in per-vessel emissions (+1%). Nephrops landings decreased to a lesser extent (–26%), so that per-quantity emissions reduced (–10%), as did per-value emissions (–6%).

Progress in emission reductions, per-quantity and per-value of nephrops landed, was greater in fleet segments West of Scotland and in the Irish Sea (VIIa) than in the North Sea (where nephrops landings declined substantially). Per-vessel, emissions reduced most in North Sea nephrops trawlers <300kW (–12%), but they increased in those >300 kW (+7%).

Scallop dredgers. This fleet expanded substantially between 2005–2009 and 2015–2019, but especially the number of smaller scallop dredgers (under 15m length) increased (from 120 to 203 vessels), less so the over 15m dredgers (from 74 to 86). Perhaps unsurprisingly with the growth in this fleet, total carbon emissions also increased (by +37%). Per-vessel emissions increased within the <15m segment (by +7%) and marginally so within the >15m segment (by +2%), but as especially the smaller dredgers increased in number, overall per-vessel emissions decreased for the dredging fleet (by –8%). Emissions per-quantity of scallop landings increased (+9%), although the emissions per-value of landings declined moderately (–5%).

Considered overall, it appears that while the scallop dredging fleet in the last decade expanded substantially in fleet size and quantity and value of total landings, it achieved less progression in emission reductions than most other fleet segments.

Pelagic trawlers. While both the quantity and especially the value of landings increased between 2005–2009 and 2015–2019 (by +9% and +58% respectively), all metrics related with emission levels decreased for the UK pelagic trawler fleet: total emissions (–26%), per-vessel emissions (–13%), per-quantity emissions (–32%) and per-value emissions (–53%).

As highlighted above, the pelagic trawlers have the highest emissions levels per-vessel of all vessels in the UK fleet although the lowest emissions per-quantity landed. Per-quantity and per-value, this fleet has made the greatest reductions among all 9 main fleet segments over the decade examined here.

Drift and fixed netters. In this fleet, numbers of large vessels (gill netters >10m) have decreased (from 46 to 29) between 2005–2009 and 2015–2019, whereas numbers of small, <10m netters have increased (from 165 to 209).

For the >10m netters, per-vessel emissions have increased (+23%) but total emissions, per-quantity and per-value emissions have decreased (by –23%, –25% and –24% respectively). For the smaller (<10m) netters, per-vessel emissions decreased (by –20%) resulting in virtually no change in total emissions (+1%) in spite of the marked increase in number of <10m netters. Landings, and emissions per-quantity of landings, have both also stayed about the same for <10m netters, but the total value of landings has increased so that there was a –14% reduction in emissions per-value of catch landed.

As outlined above, total emissions, and emissions per-vessel, per-quantity and per-value landed are relatively low for both segments (under and over 10m) of the UK netting fleet.

Vessels using hooked gears (liners). In this fleet, the total number of vessels has markedly increased, from 89 to 216, between 2005–2009 and 2015–2019. This was mainly driven by growth in the <10m sector using hooks, from 63 to 188 vessels; longliners (>10m length) only increased in number from 26 to 28 vessels. It is of note that the latter are far larger than the former, reflected in far higher emissions per-vessel (e.g. 722 t annually, compared to 17t in the former, in 2015–2019).

The near-trebling in numbers of <10m liners was reflected in a large increase in total emissions (by +129%). Nevertheless, their magnitude of total emissions has remained modest (e.g. 3.2 kt annually averaged over 2015–2019, compared to 20 kt for all >10m longliners, in spite of the latter's far smaller number). Per-vessel emissions decreased, for both <10m liners (by –24%) and >10m liners (also by –24%). Averaged over all liners, per-vessel emissions have, because there are now so many more small liners, reduced even more, by –63%.

With strong increases in landings (+30%) and especially in landings value (+83%), the emissions per-quantity have dropped (–31%) as did those per-value of landings (–51%). These reductions were not only evident for all liners combined, but also if the <10m and >10 segments were assessed separately.

Overall, this indicates significant emission reductions for this fleet (acknowledging that the overall vessel size composition has changed towards many more of the smaller vessels), against a background of an increase in both quantity and value of the landings.

Potters and trappers. Total numbers of all 3 vessel sizes in this fleet increased (<10m, 10–12m, >12m length), with numbers increasing most for the smaller category. This is one of two main gear categories (along with dredgers) where total emissions increased from 2005–2009 to 2015–2019 (by +13%). Emissions per-vessel decreased (by –5%), partly reflecting the changing size composition of the fleet.

There were increases in total landings (+43%) and total value of landings (+54%) for all 3 size categories of potters and trappers, by considerable margins. Accordingly, emissions per-quantity (–21%) and per-value of landings (–26%) decreased, albeit to slightly different degrees for each of the 3 size groups of vessels.

Low activity vessels. This fleet segment is defined as those vessels that, per year, gross less than £10,000 in catches, and is divided in <10m and >10m vessels – the former much greater in numbers than the latter (e.g. 1646 in 2015–2019, compared to 46). Typically only active during some 15–30 days per year, low activity vessels represented 0.3% of total landings quantity for the UK fleet in 2015–2019, 0.5% of the total value, and 0.9% of the total emissions. Between 2005–2009 and 2015–2019, total emissions for all low activity vessels have decreased (–25%) as did emissions per-vessel (–25%). However as landings quantity decreased more (–54%), the emissions per-quantity landed increased (+63%). Nevertheless, emissions per-value landed did decrease (–13%).

Table 3. Numbers of vessels, total annual emissions, and emissions per vessel for 9 main gear types and 31 finer-scale segments of the UK fishing fleet, showing the mean values for two periods on average 10 years apart (2005–2009 and 2015–2019), as well as the percentage change over the 10 intervening years (red-shaded: increased emissions; blue-shaded: decreased emissions).

Fleet segment	Vessels		Annual emissions (t CO_2e)			Annual emissions per vessel (t CO_2e)		
	2005-2009	2015-2019	2005-2009	2015-2019	Change (%)	2005-2009	2015-2019	Change (%)
North Sea beam trawl <300kW	23	17	6158	5468	-11%	263	318	21%
North Sea beam trawl >300kW	20	8	72760	39891	-45%	3712	4749	28%
South West beamers <250kW	19	23	14233	18648	31%	749	811	8%
South West beamers >250kW	35	25	56790	42947	-24%	1623	1746	8%
All beam trawlers	***97***	***73***	***149940***	***106954***	***-29%***	***1546***	***1461***	***-5%***
NSWOS demersal under 24m <300kW	28	18	7617	4428	-42%	276	246	-11%
NSWOS demersal under 24m >300kW	38	37	41471	44596	8%	1103	1192	8%
NSWOS demersal over 24m	44	43	129035	110489	-14%	2906	2546	-12%
NSWOS demersal pair trawl seine	39	25	30473	25311	-17%	781	1004	29%
NSWOS demersal seiners	25	16	15215	11745	-23%	604	753	25%
Area VIIA demersal trawl	17	12	5618	3621	-36%	323	292	-10%
Area VIIBCDEFGHK trawlers 10-24m	64	61	14629	13574	-7%	227	223	-2%
Area VIIBCDEFGHK 24-40m	16	13	34892	24589	-30%	2237	1891	-15%
Under 10m demersal trawl/seine	228	176	14264	10947	-23%	63	62	-1%
All demersal trawlers and seiners	***499***	***402***	***293213***	***249302***	***-15%***	***587***	***620***	***6%***
North Sea nephrops <300kW	93	64	31436	18938	-40%	337	296	-12%
North Sea nephrops >300kW	92	51	86900	52017	-40%	945	1012	7%
WOS nephrops <250kW	134	73	25651	14580	-43%	191	200	4%
WOS nephrops >250kW	31	38	13497	16767	24%	430	441	3%
Area VIIA nephrops <250kW	62	38	9127	5455	-40%	147	145	-1%
Area VIIA nephrops >250kW	35	32	13430	11791	-12%	382	373	-2%
All nephrops trawlers	***448***	***296***	***180040***	***119548***	***-34%***	***402***	***404***	***1%***
UK scallop dredge under 15m	120	203	18791	34023	81%	157	167	7%
UK scallop dredge over 15m	74	86	43493	51390	18%	588	600	2%
All dredgers	***194***	***289***	***62284***	***85413***	***37%***	***321***	***296***	***-8%***
UK pelagic trawlers over 40m	***31***	***26***	***177445***	***131771***	***-26%***	***5724***	***4991***	***-13%***
Under 10m drift and/or fixed nets	165	209	5359	5400	1%	32	26	-20%
Gill netters	46	29	10511	8081	-23%	228	281	23%
All drift and fixed netters	***211***	***237***	***15870***	***13481***	***-15%***	***75***	***57***	***-24%***
Under 10m using hooks	63	188	1409	3221	129%	22	17	-24%
Longliners	26	28	24551	19920	-19%	944	722	-24%
All gears using hooks	***89***	***216***	***25960***	***23141***	***-11%***	***292***	***107***	***-63%***
Under 10m pots and traps	923	1139	47400	51735	9%	51	45	-12%
Pots and traps 10-12m	173	176	12279	13135	7%	71	75	5%
Pots and traps over 12m	85	96	29450	35913	22%	346	373	8%
All potters and trappers	***1181***	***1411***	***89129***	***100784***	***13%***	***75***	***71***	***-5%***
Low activity vessels under 10m	1578	1600	8302	6494	-22%	5	4	-23%
Low activity vessels over 10m	69	46	1790	1062	-41%	26	23	-10%
All low activity vessels	***1647***	***1646***	***10091***	***7556***	***-25%***	***6***	***5***	***-25%***
UK fishing fleet	***4398***	***4597***	***1003974***	***837950***	***-17%***	***228***	***182***	***-20%***

Table 4. Total annual landings and average emissions per quantity landed for 9 main gear types and 31 finer-scale segments of the UK fishing fleet, showing the mean values for two periods on average 10 years apart (2005–2009 and 2015–2019), as well as the percentage change over the 10 intervening years (red-shaded: increase; blue-shaded: decrease).

Fleet segment	Total annual landings (t)			Average emissions per quantity landed (kg CO_2e / kg fish)		
	2005-2009	2015-2019	Change (%)	2005-2009	2015-2019	Change (%)
North Sea beam trawl <300kW	831	659	-21%	7.41	8.30	12%
North Sea beam trawl >300kW	10558	7622	-28%	6.89	5.23	-24%
South West beamers <250kW	2459	4718	92%	5.79	3.95	-32%
South West beamers >250kW	7123	6916	-3%	7.97	6.21	-22%
All beam trawlers	***20972***	***19915***	***-5%***	***7.15***	***5.37***	***-25%***
NSWOS demersal under 24m <300kW	3523	2000	-43%	2.16	2.21	2%
NSWOS demersal under 24m >300kW	13714	17204	25%	3.02	2.59	-14%
NSWOS demersal over 24m	37009	47693	29%	3.49	2.32	-34%
NSWOS demersal pair trawl seine	19776	27082	37%	1.54	0.93	-39%
NSWOS demersal seiners	11568	12532	8%	1.32	0.94	-29%
Area VIIA demersal trawl	1598	1694	6%	3.52	2.14	-39%
Area VIIBCDEFGHK trawlers 10-24m	6669	7880	18%	2.19	1.72	-21%
Area VIIBCDEFGHK 24-40m	4647	6813	47%	7.51	3.61	-52%
Under 10m demersal trawl/seine	5930	5134	-13%	2.41	2.13	-11%
All demersal trawlers and seiners	***104433***	***128031***	***23%***	***2.81***	***1.95***	***-31%***
North Sea nephrops <300kW	8283	4324	-48%	3.80	4.38	15%
North Sea nephrops >300kW	20876	14301	-31%	4.16	3.64	-13%
WOS nephrops <250kW	7901	4765	-40%	3.25	3.06	-6%
WOS nephrops >250kW	3716	5439	46%	3.63	3.08	-15%
Area VIIA nephrops <250kW	4026	2919	-27%	2.27	1.87	-18%
Area VIIA nephrops >250kW	4230	4387	4%	3.17	2.69	-15%
All nephrops trawlers	***49032***	***36135***	***-26%***	***3.67***	***3.31***	***-10%***
UK scallop dredge under 15m	11943	18723	57%	1.57	1.82	15%
UK scallop dredge over 15m	20569	22209	8%	2.11	2.31	9%
All dredgers	***32512***	***40933***	***26%***	***1.92***	***2.09***	***9%***
UK pelagic trawlers over 40m	***325587***	***356190***	***9%***	***0.55***	***0.37***	***-32%***
Under 10m drift and/or fixed nets	3415	3410	0%	1.57	1.58	1%
Gill netters	6786	8101	19%	1.55	1.00	-36%
All drift and fixed netters	***10201***	***11512***	***13%***	***1.56***	***1.17***	***-25%***
Under 10m using hooks	879	2255	157%	1.60	1.43	-11%
Longliners	6532	7377	13%	3.76	2.70	-28%
All gears using hooks	***7411***	***9632***	***30%***	***3.50***	***2.40***	***-31%***
Under 10m pots and traps	17795	25657	44%	2.66	2.02	-24%
Pots and traps 10-12m	8347	10667	28%	1.47	1.23	-16%
Pots and traps over 12m	16467	24679	50%	1.79	1.46	-19%
All potters and trappers	***42609***	***61003***	***43%***	***2.09***	***1.65***	***-21%***
Low activity vessels under 10m	2404	1920	-20%	3.45	3.38	-2%
Low activity vessels over 10m	2560	367	-86%	0.70	2.89	314%
All low activity vessels	***4965***	***2287***	***-54%***	***2.03***	***3.30***	***63%***
UK fishing fleet	***597723***	***665638***	***11%***	***1.68***	***1.26***	***-25%***

Table 5. Total value of landings and average emissions per value landed for 9 main gear types and 31 finer-scale segments of the UK fishing fleet, showing the mean values for two periods on average 10 years apart (2005–2009 and 2015–2019), as well as the percentage change over the 10 intervening years (red-shaded: increase; blue-shaded: decrease; £ value adjusted to 2020 inflation).

Fleet segment	Total value of landings (000 £)			Average emissions per value landed (kg CO_2e / £ fish)		
	2005-2009	2015-2019	Change (%)	2005-2009	2015-2019	Change (%)
North Sea beam trawl <300kW	2129	1758	-17%	2.89	3.11	8%
North Sea beam trawl >300kW	24451	16386	-33%	2.98	2.43	-18%
South West beamers <250kW	9038	16777	86%	1.57	1.11	-29%
South West beamers >250kW	23179	24020	4%	2.45	1.79	-27%
All beam trawlers	***58797***	***58941***	***0%***	***2.55***	***1.81***	***-29%***
NSWOS demersal under 24m <300kW	6649	5415	-19%	1.15	0.82	-29%
NSWOS demersal under 24m >300kW	29744	40942	38%	1.39	1.09	-22%
NSWOS demersal over 24m	68316	95930	40%	1.89	1.15	-39%
NSWOS demersal pair trawl seine	31806	50147	58%	0.96	0.50	-47%
NSWOS demersal seiners	17820	22560	27%	0.85	0.52	-39%
Area VIIA demersal trawl	3135	3528	13%	1.79	1.03	-43%
Area VIIBCDEFGHK trawlers 10-24m	12781	15425	21%	1.14	0.88	-23%
Area VIIBCDEFGHK 24-40m	14101	22202	57%	2.47	1.11	-55%
Under 10m demersal trawl/seine	17112	14259	-17%	0.83	0.77	-8%
All demersal trawlers and seiners	***201463***	***270410***	***34%***	***1.46***	***0.92***	***-37%***
North Sea nephrops <300kW	21111	12342	-42%	1.49	1.53	3%
North Sea nephrops >300kW	59014	35293	-40%	1.47	1.47	0%
WOS nephrops <250kW	23247	14198	-39%	1.10	1.03	-7%
WOS nephrops >250kW	10073	14217	41%	1.34	1.18	-12%
Area VIIA nephrops <250kW	8696	6715	-23%	1.05	0.81	-23%
Area VIIA nephrops >250kW	9648	10342	7%	1.39	1.14	-18%
All nephrops trawlers	***131789***	***93106***	***-29%***	***1.37***	***1.28***	***-6%***
UK scallop dredge under 15m	16954	33129	95%	1.11	1.03	-7%
UK scallop dredge over 15m	38671	46778	21%	1.12	1.10	-2%
All dredgers	***55625***	***79907***	***44%***	***1.12***	***1.07***	***-5%***
UK pelagic trawlers over 40m	***191598***	***303198***	***58%***	***0.93***	***0.43***	***-53%***
Under 10m drift and/or fixed nets	8367	9802	17%	0.64	0.55	-14%
Gill netters	18272	18518	1%	0.58	0.44	-24%
All drift and fixed netters	***26640***	***28320***	***6%***	***0.60***	***0.48***	***-20%***
Under 10m using hooks	2686	8488	216%	0.52	0.38	-28%
Longliners	13526	21137	56%	1.82	0.94	-48%
All gears using hooks	***16212***	***29626***	***83%***	***1.60***	***0.78***	***-51%***
Under 10m pots and traps	54986	79883	45%	0.86	0.65	-25%
Pots and traps 10-12m	21910	29957	37%	0.56	0.44	-22%
Pots and traps over 12m	28214	51652	83%	1.04	0.70	-33%
All potters and trappers	***105110***	***161492***	***54%***	***0.85***	***0.62***	***-26%***
Low activity vessels under 10m	6643	5831	-12%	1.25	1.11	-11%
Low activity vessels over 10m	386	226	-41%	4.64	4.69	1%
All low activity vessels	***7029***	***6057***	***-14%***	***1.44***	***1.25***	***-13%***
UK fishing fleet	***794263***	***1031057***	***30%***	***1.26***	***0.81***	***-36%***

4 At-sea versus pre-harvest and post-harvest emissions

4.1 Life cycle assessment of carbon emissions

If considered holistically, then carbon emissions associated with the fisheries sector are associated with a broad range of sources and activities (Figure 13). In broad terms, these may be categorised into: (1) *pre-harvest* sources and activities, (2) *harvest* or *at-sea*, and (3) *post-harvest* sources and activities. A full life cycle assessment (LCA) of carbon emissions (e.g. Avadi & Fréon, 2013; Ruiz-Salmón et al., 2020) would take account of each of these three stages in the seafood sector, although this would also depend on the system boundaries being assessed. In its most complete form, this is done "cradle to grave", involving all stages of the life cycle; alternatively, it is assessed "cradle to gate", "gate to grave", or "gate to gate" where "gate" stands for a particular point in the life cycle e.g. the point of landing or processing (review: Ruiz-Salmón et al., 2020).

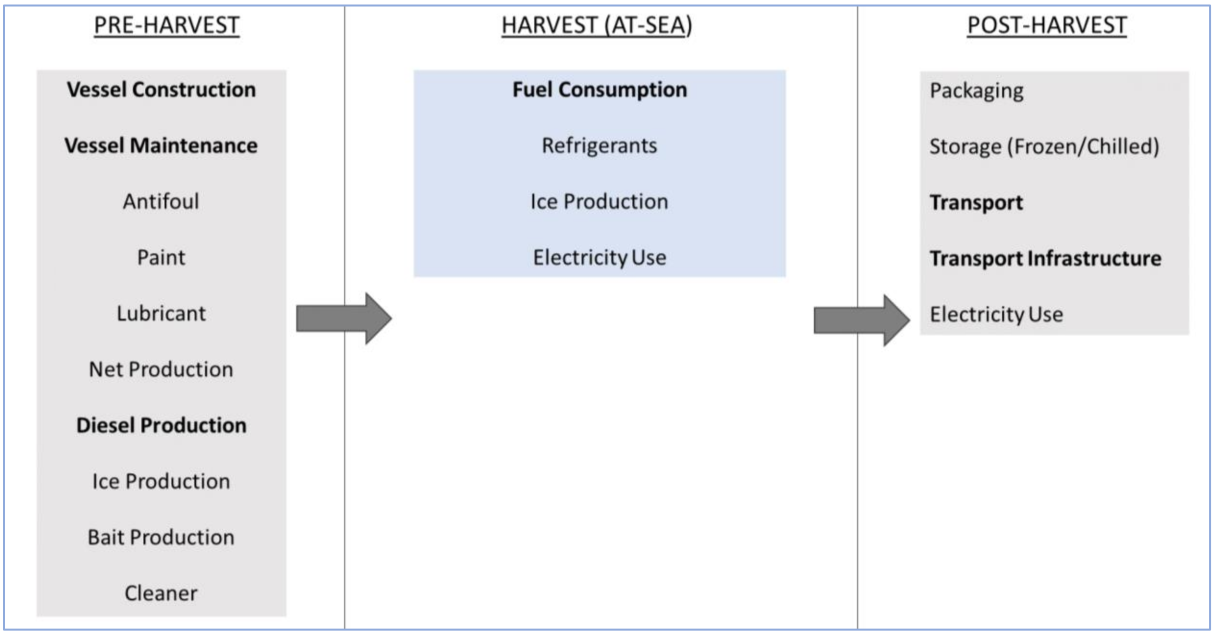

Figure 11. Three major life cycle stages in fisheries, with sources and activities that contribute to carbon emissions highlighted. Components that generally speaking, contribute most to emissions are shown in bold.

Pre-harvest carbon emissions include those associated with vessel construction (which includes not only the building materials but also, e.g. antifoul paint, cleaners, lubricant oil, and maintenance), as well as emissions associated with net or other fishing gear manufacturing, fuel production, ice production, etc. Bait is needed for some fisheries, with added associated carbon emissions. The carbon emissions associated with the *at-sea* or *harvest* phase are typically primarily from fuel consumption required for the operation of fishing itself, as well as for steaming to and from port and between fishing grounds. They also include emissions associated with refrigerants (and possible leakage of these). The *post-harvest* phase is associated with carbon emissions from the point of landing. These are, by and large, associated with packaging and (chilled or frozen) storage, with transport, and with associated infrastructure (construction and maintenance). Figure 11 has aimed at capturing these sources of emissions, with very approximate indications of their relative magnitudes (which vary considerably between studies), acknowledging that the picture will necessarily be incomplete.

Table 6 shows studies that compared greenhouse gas emissions in fisheries along the supply chain, distinguishing between the three phases of pre-harvest, at-sea (harvest), and post-harvest. These studies, sourced from a range of fisheries from widely different parts of the globe, may arguably be regarded as going some way towards covering emissions "from cradle to grave".

Table 6. Studies that compared greenhouse gas emissions in fisheries along three phases of the supply chain: pre-harvest (e.g. vessel construction and maintenance, bait preparation), at-sea or harvest (fishing and onboard refrigeration), and post-harvest (e.g. transportation, processing). Note that while studies may have used different 'units' of greenhouse gas emissions (e.g. kg CO_2/kg fish, or g CO_2e/500g fish), the relative percentages (shown in bold) of emissions during each phase are more directly comparable.

Fishery	Pre-harvest	At-sea (harvest)	Post-harvest	Reference
Mechanised and motorised fisheries, Visakhapatnam, India	Vessel construction and maintenance, and provision of fishing gear (0.006 kg CO_2/kg fish landed: **0.4%** of all emissions)	Fuel use, electricity consumption for ice production (1.267 kg CO_2/kg fish landed: **90.2%** of all emissions)	Transportation and processing (0.131 kg CO_2/kg fish landed: **9.3%** of all emissions)	Ghosh et al., 2014
Long lining fleet targeting hake, Galicia, Spain	Bait fishing, processing, and distribution (global warming potential [GWP] 0.329g CO_2/500g raw hake: **8.4%** of all emissions)	Diesel fuel, ice, net, paints, etc consumption (GWP 3.180g CO_2/500g raw hake: **81.0%** of all emissions)	Transport, electricity, material, e.g. boxes and pallets, etc. (GWP 0.416g CO_2/500g raw hake: **10.6%** of all emissions)	Vázquez-Rowe et al., 2011
Demersal trawlers, Gulf of Gabes, Tunisia	Trawler and net construction (GWP 433kg CO_2e/t seafood landed); paint, anti-foulant production (61kg CO_2e/t); lubricant production (18.9kg CO_2e/t); fuel production (2098 kg CO_2e/t). Combined: **19.0%** of all emissions, of which 15.2% for fuel production	Fuel consumption by fishing vessels (GWP 11,154kg CO_2e/t seafood landed); other inputs to fishing (2.45 kg/t). Combined: **81.0%** of all emissions	Transport of materials upstream (GWP 5.1kg CO_2e/t seafood landed). Combined: **0.04%** of all emissions.	Abdou et al., 2020
Indonesian capture fisheries, vessels of size 20–30 GT	Procurement and transport of materials needed for fishing. Gasoline and diesel fuel. 0.00454g CO_2/kg fresh fish (**0.3%** of all emissions)	Fishing operation. Ice, diesel, oil, gasoline. 1.424g CO2/kg fresh fish (**98.7%** of all emissions)	Transport to local market or processing unit. Fuel energy. 0.014g CO_2/kg fresh fish (**1.0%** of all emissions)	Fatehah et al., 2016
Spanish purse seiners targeting skipjack and yellowfin tuna in Atlantic, Pacific and Indian Ocean	Vessel construction, diesel production and anti-fouling paint production **~10%** emissions (~GWP 180kg CO_2/t frozen unprocessed tuna):	Operational inputs, mainly fuel consumption **~64%** emissions (~GWP 1152kg/t frozen unprocessed tuna)	Shipping from fishing area to Galician ports **~26%** emissions (~GWP 468kg/t frozen unprocessed tuna)	Hospido & Tyedmers, 2005

In each of these fisheries case studies, the majority of greenhouse gas emissions were found to be during the harvest (at-sea) stage: approximately 81% in longlining and trawl fisheries off Galicia and Tunisia, respectively (Vázquez-Rowe et al., 2011; Abdou et al., 2020), and over 90% in various fisheries in India and Indonesia (Ghosh et al., 2014; Fatehah et al., 2016). Distant-water Spanish purse seiners targeting tuna in the Atlantic, Indian and Pacific Oceans, in spite of having to cover very long distances between fishing grounds and ports, still spend at least 64% of total emissions during fishing operations (note that emissions from travelling from fishing grounds to the Galician ports, accounting for 26% of total emissions as reported by Hospido and Tyedmers (2005), could have alternatively also been included under 'at-sea' emissions).

It could be argued to what extent these case studies, taken from different parts of the world, can be generalised to apply to the UK fishing fleet (for which similar, "cradle to grave" studies on emissions appear to be lacking), but we have no reason to assume a very different situation. Given that at-sea carbon emissions have generally been reported to form such a large proportion of total carbon emissions associated with the fisheries seafood chain, and given the overall scope of the present project, we will primarily focus on the 'at-sea' (harvest) phase of fisheries when introducing potential pathways for emission reductions in the next section of this report.

4.2 Carbon emissions associated with obtaining bait

Generally, fleet segments using 'passive' gears (pots, traps, gill nets, set lines etc) are considered as low-carbon methods of fishing when compared to vessels involving towed gear. However, certain passive gear types (notably pots, traps and set lines) require the use of bait in order to function (typically small pelagic fish or processing wastes). The procurement of these baits may significantly add to the carbon footprint of the particular fleet segment, but this is often poorly appreciated.

Static-gear fisheries using baited pots are an increasingly valuable component of the fishing industry in the United Kingdom. Target species include common whelk (*Buccinum undatum*), edible crab (*Cancer pagurus*), European lobster (*Homarus gammarus*), nephrops (*Nephrops norvegicus*) and common prawn (*Palaemon serratus*). Pot or creel fisheries in the UK tend to rely on pelagic fish (e.g. mackerel and herring), ray or dogfish carcasses which are obtained from the inshore fishery, or offal left over after filleting fish.

In the nephrops creel fishery, the most commonly used bait is herring (*Clupea harengus*) or mackerel (*Scomber scombrus*) which can cost 5–10% of the landed first sale value for nephrops. In some instances creelers can catch the bait themselves but require quota to do so, as both herring and mackerel are TAC species (Williams and Carpenter, 2016).

Boyd (2008) provided a detailed life cycle assessment for the Southwest Nova Scotia live lobster industry, which included an analysis of procurement, storage, and transport. In terms of fishing operations, total emissions were estimated at 4168 kg CO_2e to deliver 1 tonne of live lobster, of which diesel fuel contributed 3,342 kg CO_2e (80%) and bait associated emissions amounted to 725 kg CO_2e (17%). This study also considered indirect environmental emissions associated with long-term storage (freezing) of bait and noted that "Nova Scotia electricity is generated predominantly from burning coal and consequently, the impacts associated with the electricity needed to freeze and store large quantities of bait are not trivial".

Driscoll et al. (2015) showed that the US fishery for American lobster (*Homarus americanus*) from Rockland, Maine to Boston, had a slightly lower fuel use, but three times higher use of bait per tonne landed than the Canadian fishery on the same stock. In terms of fishing operations, total emissions were estimated at 4,913 kg CO_2e to deliver 1 tonne of live lobster, of which diesel fuel contributed 66% (3,230 kg) and bait associated emissions contributed 31% (1,523 kg CO_2e).

In Australia, van Putten et al. (2015) studied environmental impacts from the fisheries for tropical rock lobster (*Panulirus ornatus*) and southern rock lobster fishery (*Jasus edwardsii*) in Australia. These two fisheries exhibited very similar greenhouse gas emissions expressed as fuel per kg of lobster landed (~10 kg CO_2e / kg); however the southern rock lobster fishery also involves the use of bait, usually sourced from Pacific jack mackerel (*Trachurus symmetricus*), Australian salmon (*Arripis trutta*), and barracuda (*Sphyraena novaehollandiae*). This raised the per-capita carbon emissions of the landed lobster by a further 0.06 kg CO_2e / kg. Bait fishing, in this context involves the use of a spotter plane and accounted for 6% of the southern rock lobster fishery's greenhouse gas emissions.

Ziegler and Valentinsson (2008) examined emissions from trawl and creel (pot) fisheries for nephrops in Sweden. In order to catch 1 kg of nephrops by means of conventional trawling, 325 MJ are used in the form of diesel. For the creel fishery this figure is 80 MJ, of which approximately 10% comes from the bait herring fishery.

Winther et al. (2020) provided an account of greenhouse gas emissions of Norwegian seafood products, including those associated with bait provisioning which is particularly relevant for the longline fishery. These authors note that amounts of bait used can, in extreme cases, exceed the volume of target fish landed. Bait can be sourced from numerous different sources, even produced artificially. In this work it was assumed that bait (for the longline fishery) is sourced primarily from Norwegian pelagic fisheries, with emissions estimated at 0.09 litres of fuel/kg live weight equivalent landed.

Overall, these sources indicate that bait use can be an important parameter regarding greenhouse gas emissions when considering passive fishing methods, especially liners, trappers, and potters. Emissions associated with bait collection or preparation will mostly be associated with the pre-harvest phase (rather than with the 'at-sea' phase), although in some cases may also occur during lining, trapping or potting operations. While passive fishing methods are generally less emission-intensive than active gears, an assessment of bait-associated emissions in addition to 'at-sea,' fuel-associated emissions (as analyses for the UK fleet above were restricted to) is well worth being considered.

5 Pathways to emission reductions

We have seen that the UK fishing fleet is generally speaking, in the mid-range compared to other European countries with regard to carbon emissions, with total emissions estimated at 802 kt CO_2e in 2019 and 702 kt CO_2e in 2020. We have also seen that important emission reductions took place between 2004–2005 and 2019–2020, by approximately –32% over the 15-year interval; although we do note that the last year in the time-series, due to the Covid pandemic, was atypical. Nevertheless, if averages between 2 time-slices ten years apart are compared (2005–2009 versus 2015–2019), a reduction in total emissions of –17% over a decade is evident. These reductions did coincide with a major reduction in the total numbers of fishing vessels, so fewer emissions might have been expected; but importantly, total landings did *not* decrease, and there was also a decline in average per-vessel emissions (–20%), emissions per-quantity of landings (–25%), and per-value of landings (–36%). So overall there is evidence of progression in emission reductions at least since the early 2000s.

These figures and trends are encouraging in that they suggest real progression in emission reductions so far (also accounting for the reduced fleet size) and that further reductions in the near future might well be realistic and achievable. It is also encouraging that total UK fishing fleet emissions in 2019 were equivalent to 1.7% of those in all UK agriculture, whereas the total value of fisheries landings equated to 3.5% of total agricultural gross output. Awareness of these more positive messages is important given that many sectors within the UK fishing fleet struggle economically, with the UK's departure from the EU affecting some fleets more than others and with the coronavirus pandemic having an impact on fishing opportunities in general.

Nevertheless, in spite of recent emission reductions the total levels for UK fisheries are still substantial and considerable further reductions are required in order to reach full carbon neutrality by 2050, as has been committed to by UK Government, or by 2045 as committed to by Scottish Government. The intermediate UK target calls for a –78% reduction in emissions by 2035, compared to 1990; intermediate targets set by Scottish Government call for reductions of –75% and –90%, respectively, by 2030 and 2040, compared to 1990. While 1990 is an important 'benchmark' year to assess emission reductions against, we have struggled to source the essential, earlier economics data for the UK fishing fleet (possibly only available through archives); we see this as an important priority for follow-up research. Having estimates of UK fishing fleet emissions back to 1990, would allow more comprehensive benchmarking of the level of progress towards the intermediate emission targets.

Fuel is not only the most important carbon emission source in fisheries (see previous section) but is also arguably the highest cost to the sector; in recent decades, fuel prices have regularly increased and in years to come, are set to rise further. So, there are many incentives to improve the efficiency of fuel use, so contributing to reducing emissions. At the same time, incentives are taking place to reduce emissions in fisheries through trials on different fuel and power systems, both in the UK and elsewhere in the world. Projects are also underway on introducing electricity as a power source, beginning with inshore vessels. However, there are various challenges and constraints regarding the uptake and successful implementation of these novel technologies, often with unknown socio-economic costs and risks. A more comprehensive framework on emission reductions might provide real benefits towards achieving targets while reducing negative impacts.

In order to help UK fisheries administrations to develop actions to support UK fisheries to reduce emissions and achieve Net Zero targets, whilst taking account of the socio-economic impacts of such actions, this section will introduce and discuss a set of possible pathways for action to mitigate and reduce emissions. These pathways will be grouped according to (a) *technological changes*, (b) *operational* or *behavioural changes* and (c) *policy* or *managerial changes* and are intended to add to the evidence base to help inform wider policy development.

Based on the ten stakeholder workshops during which UK fishing industry representatives were interviewed, we have moreover collated information on (1) what **initiatives** are already taking place within UK fisheries with regards reducing emissions; (2) what are the perspectives about the future, including on what is being seen as real **barriers**, and/or as **enablers** for reducing emissions, with considerations on what type of **support** is seen as being needed or beneficial. The interviews were structured using a standardised set of questions. Discussions adhered to a confidentiality agreement which had been provided to all stakeholders consulted, prior to each of the interviews taking place, and in all cases, informed consent was sought. The confidentiality agreements put in place were in accordance with Government Social Research Professional Guidance on Ethical Assurance for Social and Behavioural Research in Government (GSR, 2021).

5.1 Pathways to emission reductions: technological changes

When policy-makers and researchers try to map out pathways towards zero-carbon fisheries, there is a tendency to primarily think about propulsion technology and the type of fuel used (e.g. diesel versus biofuel or hydrogen etc). At-sea fuel use does indeed constitute the greatest proportion of carbon emissions in the fisheries sector, but fuel also represents the largest day-to-day economic cost to fisheries operations, and thus some efforts aimed at reducing carbon emissions might well have very real (‘win-win’) economic benefits for fishers if it also reduces the amount of fuel (usually diesel) needed, i.e. improves fuel efficiency. Poos et al. (2013) demonstrated that North Sea beam trawl fisheries are incredibly responsive to fuel price. In recent years, increased fuel prices have resulted in the widespread adoption of energy saving technologies including switching to less energy-demanding fishing gears and vessels. There have been technological advances in hull design for fishing vessels, that have greatly improved fuel-efficiency (Gulbrandsen, 2012) and hence have reduced relative carbon emissions, however it is in the area of propulsion technologies that the greatest gains are anticipated (Gabrielii and Jafarzadeh, 2020).

In this section we review emerging technologies with regard to propulsion and fuel use, in particular we pay attention to (Figure 12):

(1) Technologies that are already relatively ‘mature’ and can be retro-fitted to existing fishing vessels (and that may be available in the **short term**, i.e. next 1–5 years);
(2) Emerging technologies that might act as a medium-term ‘stop gap’ in helping to significantly reduce carbon emissions (and that may be available in the **mid-term**, i.e. 5–10 years from now); and
(3) Revolutionary or ‘disruptive’ technologies that are at an early stage of development but could lead to completely zero-carbon fisheries in the **long term** (about 10–30 years from now).
(4) Moreover we include industry’s experiences on initiatives, barriers and enablers, as well as feedback on technological changes that may be applicable to fishing ports, in the short term (next 1–5 years), mid-term (about 5–10 years from now) and long term (about 10–30 years from now).

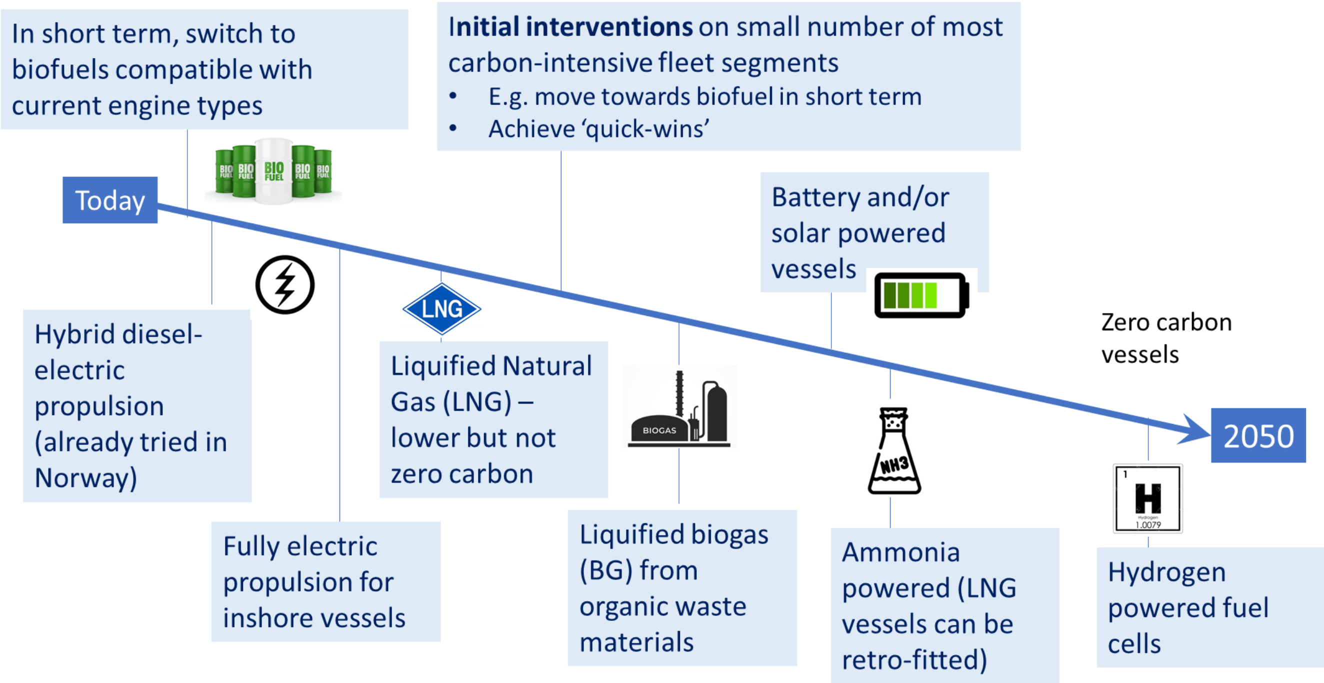

Figure 12. Pathways towards zero-carbon fisheries through changes in propulsion technology and/or the fuel.

Short term – existing technologies (next 1–5 years)

Small improvements can be made by paying attention to hull appendages including rudder, skeg, keel, sonar transducer enclosures and bilge keels. The key is to reduce the size and area of these appendages, and to streamline the shape to allow smoother water flow. Poor vessel balance can increase resistance and fuel consumption, and should be corrected by shifting weight and equipment, or in high-speed vessels by transom modifications. Fuel savings from such corrections are small but important when combined with other measures.

Retro-fitting a bulbous bow may be applicable for some fishing vessel designs and has the potential to reduce fuel consumption. Generally, such a bow is fitted only on larger vessels because of the cost of installation; but may technically be applied to vessels of any size. Potential fuel savings of 5 percent to 15 percent can be achieved (Notti and Sala, 2012).

Another short-term measure to reduce carbon emissions from the fishing sector could be to increase the uptake of biofuels from plants as a partial replacement for marine diesel, without requiring significant modification to existing vessels or engines. There are various biodiesel fuels available. One that can be applied for ships, with only minor modifications is HVO (hydrogenated vegetable oil). However, the availability (and demand) is still low. CO_2 emissions from producing and then burning/re-using HVO, amount to around 50% compared to diesel oil (Gabrielii and Jafarzadeh, 2020). In 2006, the Grimsby-based trawler *Jubilee Quest* was adapted for a trial comparing diesel with vegetable oil. The result was 80% carbon mitigation reportedly without compromising pulling power.

'Drop-in biofuels' are defined as liquid bio-hydrocarbons that are functionally equivalent to petroleum-derived fuels and fully compatible with existing petroleum structure. Drop-in biofuels chemically consist of a mixture of many different hydrocarbons and share similar combustion properties as conventional fuels. The most common biofuel, bioethanol, is usually blended with gasoline for use in petrol engines and cannot be used as a drop-in fuel for marine diesel engines (although it could be used in outboard motors). To produce a biomass-derived diesel, animal fats (tallow) and/or vegetable oils need to undergo a hydroprocessing step. Hydrotreated vegetable oils (HVO) or green diesel, or hydrotreated renewable oils (HRO) have undergone hydrotreatment and refining, usually in the presence of a catalyst. HVO production is already at a full commercial scale, with Neste being the market leader. HVO has been described as an easily accessible fuel that can reduce GHG emissions and is low in sulphur (Hsieh & Felby, 2017).

A hybrid propulsion system enables the vessel to be propelled in two ways, namely electrical (diesel-electric and/or battery) and mechanical (direct diesel-drive). Examples of hybrid fishing vessels are already operating in various EU waters (Gabrielii and Jafarzadeh, 2020), for example the 21 m netter *Angelsen Senior,* mainly fishing cod, haddock and saithe in the North Sea. This vessel relies solely on batteries when there is a low power requirement, such as when setting the gear or hauling. A switch to diesel-electric mode is made when shooting gear or when steaming up to ten knots, which also provides an opportunity to charge the battery packs. The battery solution, implying more efficient operation of the diesel generators, enables a reduction in fuel consumption by 25% and in generator running time by 75%, cutting annual CO_2 emissions by 200 tonnes (Gabrielii and Jafarzadeh, 2020).

For small, inshore vessels that operate out of ports for a single day, fully electric (battery powered) propulsion might be a viable solution. A recent project funded under the UK Seafood Innovation Fund (SIF) assessed the feasibility of moving to electric power for small-scale fisheries in southwest England, testing how possible it is to reach fishing grounds and work those grounds with a small solar powered electric outboard, with a spare battery. Elsewhere, experience with “the world’s first electric fishing vessel” the *Karoline*, proved that pure battery operation is possible during 2–3 hours per day, providing there is a recharge overnight by plugging into the shore electrical grid (Gabrielii and Jafarzadeh, 2020).

Mid-term – an important stop-gap (about 5–10 years from now)

The global use of Liquefied Natural Gas (LNG) is expected to increase significantly (Gabrielii and Jafarzadeh, 2020), especially in coastal shipping. Main drivers include regulations (e.g. MARPOL, Annex VI), potentially lower gas prices compared to oil and diesel, as well as lower carbon emissions. Indeed, Marine Scotland is currently designing its next fisheries research vessel with the assumption that this will be powered by LNG (Parker, 2021). The reduction in CO_2 emissions compared to diesel/gas oil is typically 20%, but can be somewhat counteracted by methane slip from certain engines (methane is a much more powerful greenhouse gas compared to CO_2, if released into the atmosphere).

Despite having many advantages, LNG is scarcely used in the fishing sector. There is scepticism relating to bunkering opportunities, safety issues, investment costs as well as space required for installation. According to a study by SINTEF Energy Research (Gabrielii and Jafarzadeh, 2020) only three LNG-fuelled fishing vessels are currently on order, and they are all Norwegian. Norway has been a pioneer, especially for passenger ferries – although most LNG-fuelled ships (almost 80%) are equipped with a dual-fuel (DF) engine, enabling operation on both LNG and diesel.

Liquefied Biogas (LBG) can be used as marine fuel after up-grading it (drying, purification, liquefaction). It can be produced from various types of organic waste, such as waste from fish and forest industry, food waste, and wastewater. For shipping companies that are already using LNG as fuel the transition to LBG does not require any extra investment in new vessels/equipment. Moreover, the same pipeline infrastructure can be used, meaning the same trucks, ships, tanks and filling stations can be used for supply of LNG and LBG. In 2018, the world's first LBG bunkering took place in Sweden;

an LNG-fuelled tanker ship received 40 m^3 of LBG directly from a road tanker. In 2021, Hurtigruten (Norway) will be the world's first cruise shipping company using biogas on a larger scale, when several of their ships will be fuelled by a mixture of LBG and LNG. In the United Kingdom, supplies of LBG from anaerobic digesters are very limited, and there is considerable demand for this renewable product (among citizens and in industry), and thus large-scale uptake in the UK fishing industry seems a more distant prospect.

Long-term – zero-carbon fisheries (beyond 10 years from now)

In the longer-term, great hope is being placed on the arrival of truly zero-carbon fuels such as ammonia and hydrogen. In both cases, no carbon is generated when the fuels are burnt, however it will be necessary to ensure that no carbon is also generated in the production process, given that much of the hydrogen produced today ('brown hydrogen' as opposed to 'blue hydrogen') is derived from splitting methane.

Ammonia can be used as fuel in both combustion engines and fuel cells. Compared to hydrogen, ammonia has a higher energy density and is easier to store, thus enables operating on longer distances. Since ammonia is widely used in the fertiliser industry, it is globally accessible. The main challenges with ammonia are toxicity and corrosiveness. The only emissions from an ammonia-driven fuel cell are water and pure nitrogen. Thus, if ammonia is renewably produced, it can be considered a carbon-neutral fuel. There are feasibility studies building up an ammonia producing infrastructure at sea, using ocean wind (Gabrielii and Jafarzadeh, 2020). The offshore supply ship *Viking Energy*, which today is operated on LNG, is planned to be retrofitted with a large ammonia fuel cell in the near future.

Hydrogen can be used as marine fuel, either transformed to electricity in fuel cells or in combustion engines. Fuel cells enable transformation of energy carriers (e.g. hydrogen, methanol, ammonia, natural gas, biogas) with a higher efficiency than traditional combustion engines. Water is the only emission generated from a hydrogen-driven fuel cell, which therefore is considered as a zero-emission technology (Gabrielii and Jafarzadeh, 2020). The main challenges experienced include cost, space requirements and approval of the installation by authorities (hydrogen can be explosive if not properly stored). Hydrogen can be locally produced, by water electrolysis, nearby the bunkering facility or it can be delivered by transport. Small passenger ferries are considered as the most suitable pioneers for fuel cell applications, although there are some projects related to Norwegian fishing vessels. For example, it is planned that the electric fishing boat *Karoline* (see above) will be retro-fitted with a hydrogen fuel cell, including a storage tank of 20 kg hydrogen which is estimated to be enough for one day's consumption. In Japan, the Japan Fisheries and Education Agency (FRA) has collaborated with Toyota Motor to build a tuna fishing boat powered by hydrogen fuel cells, and sea tests are planned for 2022 (Gabrielii and Jafarzadeh, 2020).

For centuries, up to the introduction of steam engines in the 1880s, all UK fishing vessels were pretty much 'zero-carbon'. Thousands of sail-powered trawlers and herring drifters operated from UK ports, and together, the quantities of fish landed were broadly comparable (or even exceeded) those today (Engelhard, 2008; Pinnegar & Engelhard, 2008). Several authors have argued there might be a place for a new generation of sail-powered fishing vessels, at least in combination with other propulsion systems. A Spanish registered fishing boat, *Balueiro Segundo*, has become the first to be fitted with a new generation of auxiliary wind-assisted propulsion technology. The project, which was funded by the EU, is seen as a demonstration of the technology and the first step toward the installation of rigid sail technology on larger commercial ships (*The Maritime Executive*, 2021). Apart from sail, also kite technology is now beginning to be tested experimentally as wind-driven aid to support conventional propulsion methods, although so far not yet applied to fishing vessels (Verdon, 2020).

5.2 Technological changes: initiatives already taking place

Vessel replacement. Clearly, one of the most important influences on uptake of new technologies and therefore the ability to achieve carbon emission reductions, will be the average age of vessels in the UK fishing fleet and the rate of replacement. Statistics on vessel turnover are available through the "UK fishing vessel lists" (https://www.gov.uk/government/collections/uk-vessel-lists) published by the Marine Management Organisation, but also in the economic survey of the UK fleet carried out by Seafish each year. As part of the current project, stakeholders were asked to comment on: (1) Which fleet segments do you represent most? and (2) How old are vessels typically and how often are they replaced? Some important insights that emerged from these questions include:

1. The newest, and most high-tech vessels in the UK fleet are associated with the Scottish pelagic sector. Most vessels were renewed relatively recently (<5-6 years old). Many new builds are regularly coming into this fleet, with a 10-year holding cycle before vessels are sold on. The smallest vessel is ~50 m long, the largest 80 m (*Ocean Star*), and the average ~70 m. This highly profitable fleet segment is characterised by rapid uptake of new technologies, including vessel and engine designs.
2. There have been pockets of renewal elsewhere in the UK fleet (e.g. in the Scottish nephrops sector), but generally, the demersal fleet segments located in southwest England and on the east coast are characterised by aging, often second-hand vessels, and slow turnover/replacement. Many beam trawlers, for example, are 40 or even 50 years old, and there remains a strong second-hand market even for 30-year-old vessels. Smaller companies cannot afford to buy new vessels; there are tax incentives against this and so they typically buy second-hand (often from sellers in the Netherlands or elsewhere in the UK).
3. The thousands of under 10m inshore fishing vessels can be very variable in age and characteristics. There remain some very old (>40 year) wooden boats in the fleet, although most are newer and made of fibreglass. Vessels are renewed infrequently and most often with second-hand replacements.

Electric vessels. Battery-powered, fully electric vessels were generally viewed as only being feasible for the inshore, non-nomadic fleet segment, where fishers return to port each day. Two Brothers Fishing Ltd, based in Brixham and operating off the South Devon coast, was awarded funding through the Seafood Innovation Fund (SIF) programme to begin trials of a battery-powered inshore fishing vessel (see Box 1) and has demonstrated that it is possible to reach fishing grounds and work those grounds with a small solar-powered electric outboard and a spare battery.

BOX 1. Electric propulsion for small-scale inshore fishing vessels

Two Brothers Fishing Ltd, a company based in Brixham, South Devon, was awarded funding through the Seafood Innovation Fund programme to begin trials of a battery-powered inshore fishing vessel. The initial feasibility study explored the practicality of being able to transit to fishing/potting grounds in a small day-boat with an electric outboard motor. The primary motivations behind the research came from the rising costs of engine fuel, alongside a developing market for sustainably caught fish. The initial study successfully demonstrated that electric- powered vessels are a viable option for small-scale fishers, establishing that it is possible to reach fishing grounds and work those grounds with a small solar-powered electric outboard and a spare battery. A second phase of the study is now underway with a scaled-up project to obtain Maritime and Coastguard Agency (MCA) approval for an electric fishing boat build. The designs include a twin-battery system that will enable sufficient battery for a full day of static-gear fishing off the South Devon coast.

Stakeholders, however, were more sceptical about the use of electric engines on larger fishing vessels that operate further offshore and overnight. Some fishing vessels have tried low power electric outboard motors, primarily for use in port. Electric outboard motors are measured by W (Watts) instead of hp (horsepower), so buyers looking for a 3 hp electric outboard motor would need a 1000 W outboard that has an equivalent power, and these usually cost in the region of £1500–3000. The NFFO mentioned that they had agreed at their last executive committee meeting to commission a study into 'electrification of inshore fleet' with the University of Hull. A major barrier to the wide-scale adoption of electrically-powered inshore fishing vessels is poor charging infrastructure in ports (see barriers and enablers – below).

Hybrid vessels. In general, fisheries in the UK have not yet moved towards hybrid propulsion technologies, unlike counterparts in Norway or the Netherlands where a wide variety of diesel-electric designs are starting to emerge. In the Scottish pelagic sector the vast majority of new builds are now running electric cranes, one running electric winches, but so far none employ hybrid-electric propulsion. Stakeholders mentioned a new (Danish) pelagic fishing vessel being constructed in the Spanish shipyard Zamakona in Bilbao (who have recently built seven pelagic fishing vessels for shipowners in Scotland). The *Gitte Henning* is a hybrid diesel-electric vessel, where the focus has been on reducing emissions through reduced energy consumption and efficient power production.

Several stakeholders mentioned that hybrid ferries are now operating in Scotland, using a system that combines traditional diesel power with electric battery energy. The ferries, MV *Hallaig*, MV *Lochinvar* and MV *Catriona*, are operated by CalMac Ferries Ltd, and were designed for use on the short crossing routes around the Clyde and Hebrides. Ferguson Shipbuilders (in Glasgow) worked alongside design specialists Seatec and electrical specialists Tec-Source to fit out the ferries.

A highly innovative hydrogen-injection hybrid system has been developed by a company based in Devon in a bid to reduce emissions, fuel costs, and wear on engines (see Box 2). The Ecomotus Eco-Pro system doses pure hydrogen into diesel engines allowing for a more efficient burn cycle, while increasing available power. It reduces CO_2 and lowers NO_x emissions by approximately 60%.

BOX 2. Hybrid hydrogen-diesel propulsion

In a bid to reduce emissions, fuel costs, wear and maintenance on engines, Devon company Ecomotus, have designed the EcoPro Electrolyser – a standalone, catalytic hydrogen injection system designed to work in harmony with existing internal combustion engines. This innovation is being advocated as a transitional (drop-in) technology, aimed at bridging the gap between fossil fuels and the longer-term future of fully hydrogen-based or electric propulsion. The EcoPro doses pure hydrogen into diesel engines allowing for a more efficient burn cycle, while increasing available power. This reduces CO_2 and lowers NO_x emissions by approximately 60%, and moreover reduces diesel consumption by around 15%. The EcoPro system can be retro-fitted to any diesel engine, including those typically used on fishing vessels.

Another hybrid technology that was mentioned by one of the respondents, involves injection of ammonia into the engine exhaust, through a process known as Selective Catalytic Reduction (SCR). The more common SCR systems used onboard ships use liquid urea, however this system carries a penalty in that a large urea storage tank is required. Injecting ammonia directly does not have such a space and weight impact and so can be used on much smaller vessels, as exemplified by the Mecmar system developed in Norway. In southwest England, the owner of a large beam trawler, has expressed an interest in trialling this technology. This interest is primarily for economic reasons, but also as a demonstration project for the wider beam trawl sector, helping to reduce their carbon footprint.

Alternative fuels. A number of stakeholders mentioned specific examples where alternative fuels are starting to become available or are being trialled in the UK fishing industry. Seafish collaborated with Regenatec on a technology which retro-fits to diesel engines and allows them to be fuelled by diesel or used cooking oil. The technology was installed on a trawler, the *Jubilee Quest*, based in Grimsby, during autumn 2006. The engine is started on conventional marine diesel (or biodiesel) and then automatically switches over to the lower cost, more environmentally friendly cooking oil. The automation greatly improves the ease of use for unskilled operators and removes the potential for engine damage when compared to manual control. However, the interviewed stakeholder reported that trials were subsequently halted as there was a concern about wear and tear to the engine.

Since 1999 the Thanet Fishermen's Association have operated a subsidiary fuel company (TFA Fuel Services Ltd.) out of Ramsgate in Kent. In 2021 a strategic decision was taken for TFA fuels to make available Hydrogenated Vegetable Oil (HVO) in addition to traditional diesel, starting from April this year (2022). HVO can be used as a 'drop-in fuel' in many existing engines, although it will be the vessel owner's responsibility to check compatibility (see Box 3).

It was reported that one vessel owner based in Lowestoft – where diesel price is very high – has now bought their own onshore storage tank and is using HVO. This vessel has an old (25-year-old) Ford engine, where the drop-in fuel works well. The vessel now does seem slower, but achieves more miles to the gallon. Reports suggest that the engine is actually running much cleaner now.

BOX 3. Uptake of Hydrogenated Vegetable Oil (HVO) among Thanet fishers

Since 1999 the Thanet Fishermen's Association have operated a subsidiary fuel company (TFA Fuel Services Ltd.) out of Ramsgate in Kent, providing marine diesel to their members (mostly small inshore fishing vessels), but also to service vessels in the offshore wind energy sector and to Thames pilot vessels. In 2021 a strategic decision was taken (in response to urging from the windfarm sector) for TFA fuels to make available Hydrogenated Vegetable Oil (HVO) in addition to traditional diesel, starting from April this year (2022). HVO can be used as a 'drop-in fuel' in many existing engines, although it is more expensive in comparison with traditional red diesel. It will be the vessel owner's responsibility to check compatibility with the existing engine, although it is thought that older engines might be better able to accommodate this novel fuel than more highly-tuned newer engines.

In supplying this new fuel, a number of challenges became apparent. Firstly, continuity of supply can be a problem as there are many competing demands for HVO elsewhere in the economy (e.g. aviation, road transport etc.). Secondly, the original source of the vegetable oils can be important, as it would be unethical if this is derived from unsustainable production, e.g. palm oil. At the moment the vast majority of HVO comes from recycled cooking oil; in the case of TFA, HVO fuels are mostly sourced from recycled oil in the Netherlands, as there is insufficient supply in the United Kingdom. Thirdly, it is necessary to combine large quantities of hydrogen gas together with the vegetable oils to produce HVO, and most hydrogen is currently produced by 'cracking' methane which itself releases CO_2 (i.e. 'grey hydrogen'). Clearly this fuel is not a perfect solution, but even so – including the CO_2 emissions from producing HVO, the reduction in CO_2 emissions is about 50% compared to diesel oil.

Several interviewees voiced their scepticism with regard to the use of Liquified Natural Gas (LNG) as a viable fuel in fisheries. They described an existing Norwegian vessel (the MV *Libas*, an 86 m pelagic purse-seiner), that uses LNG, but is in fact also equipped with a diesel engine and a massive marine diesel tank. It was suggested that most of the time, this vessel actually runs on marine diesel, rather than on LNG and that the technology has proven somewhat problematic. One correspondent suggested that every time an LNG ship changes modes, it releases a puff of methane (a very powerful greenhouse gas), so for any vessel with a variable workload (for example a fishing vessel, that changes speeds very frequently) this is likely to prove very problematic.

The reputation of LNG powered vessels has been damaged somewhat, by a long-running saga involving the substantially delayed construction of two LNG powered ferries in Scotland. Ferguson Shipbuilders have a major contract for LNG ferries (the *Glen Sannox* and the, not yet named, "Hull 802") – but LNG has proved particularly hard (and expensive) to engineer, involving the need for huge evaporators and to resolve major safety issues. A large cryogenic storage tank – like a giant chilled thermos flask – is required on the ship along with special refrigerated refuelling pipes. While the technology has been around for some time, CalMac's new ferries are the first to be built in the UK. Design decisions have to be approved by insurers and regulators at each step. These ships are currently £100 million over budget. On 30 March 2020, Scottish ferry owner CalMac started construction of LNG bunkering facilities at the Port of Uig on the Isle of Skye and the Port of Ardrossan on the Firth of Clyde.

The Port of London Authority (PLA) is leading a consortium of eight organisations to establish a national hydrogen highway network, integrating land, sea and port. The project will cover energy diversity research, trialling hydrogen power generation for vessels based at the PLA's Denton Wharf, establishing the business case for back hauling hydrogen into central London, ship design and health and safety requirements. A similar initiative is the recently announced Tees Valley Hydrogen Transport Hub, announced by the Department of Transport in March 2021 and aimed at bringing together leading figures from government, industry and academia to focus research, testing and trials across all transport modes.

Other technologies. In an effort to reduce operating costs and to improve fuel efficiency, many vessel owners have been keen to adopt new technologies over recent decades, and indeed this is apparent in a significant reduction in fuel usage per vessel over the past 30 years. Further improvements could be achieved through a more widespread installation of fuel-economy sensors on fishing vessels. Having instruments on board (equivalent to a 'smart meter') could provide enough incentive for skippers to be more concerned about energy use. Some skippers are already very savvy about fuel economy and will tow with the tide etc., whereas others exhibit very little awareness.

In the more-distant future, one correspondent wondered whether it would be necessary to always have a vessel out in the ocean (burning fuel) 'searching' for fish, when technology is advancing so quickly. They postulated that in the not-too-distant future, greater use of semi-autonomous drones (both flying and in the water) might allow fishers to detect pelagic fish shoals from a distance, to direct fishing effort, and perhaps even deploy autonomous capture devices without the need for expensive vessels.

5.3 Technological changes: barriers and enablers

Many of the pilot projects for new technologies originate from countries other than the UK. With regard to the adoption of new technologies, interviewees suggested a number of legislative, and logistical barriers that need to be overcome before the UK will witness widespread uptake in the fishing industry. In addition, several important enablers were proposed.

Vessel building codes and tax disincentives. It was suggested that recently introduced MCA (Maritime and Coastguard Agency) regulations aimed at controlling NO_x and SO_x emissions may have perverse consequences, making the achievement of 'zero carbon' fisheries especially difficult. From 1st January 2021 any commercial vessel where the keel was laid down on or after that date and which is intending to operate within the North Sea Emission Control Area, is required to be fitted with a diesel engine which complies with the IMO MARPOL Annex VI Tier III standard. The problem is that Tier III and conventional engines are not equitable price wise – and there was a rush of new building before the new regulations came in. Most (non-Tier III) fishing vessels constructed in 2020 or 2021 will still be in use in 2050 when the UK is aiming for 'Net Zero'. In other words, legislative decisions taken now may have heavily diminished our ability to meet mitigation targets in 15-30 years' time, because of the slow renewal rate of vessels in the UK fishing fleet. It was suggested that to promote significant change and enhance turnover in the fleet, a directed scrappage or decommissioning scheme might be needed. Similarly, there are currently tax incentives in the UK to buy a second-hand vessel over building a new one – which can be thought of as being counter-productive in terms of reducing emissions and improving safety, i.e. a 12% writing down allowance for a second-hand engine, but only 6% for a new engine.

Concern was raised that statutory building codes, which specify the standards for vessel or engine construction and are overseen by MCA, might be applied unilaterally in the UK, but not elsewhere in Europe as a result of legislative misalignment following Brexit. Vessel construction costs could be higher and therefore present a competitive disadvantage to UK constructors/operators, and create problems given that many UK fishers choose to buy second-hand vessels from elsewhere in Europe, especially from the Netherlands. Similarly, concerns were raised about different legislative burdens in different parts within the UK, and whether the rules will be applied consistently across the Devolved Administrations. Already, there are different (earlier) carbon emission reduction targets in Scotland compared to the rest of the UK, and it is possible that vessel building codes might also diverge.

At present, some of the proposed technologies are not really supported by the MCA (Maritime and Coastguard Agency) on health and safety grounds, so any new design would be subject to a lengthy and expensive proving process. In accordance, with "Fishing Vessels (Certification of Deck Officers and Engineer Officers) Regulations 1984" some vessels currently do not require an engineer onboard, but many of the newer technologies might necessitate this. It was suggested that government might need to invest in 'demonstrator projects' to help offset development costs, but particularly to help navigate through any legislative obstacles, as a 'proof of concept'.

Logistical constraints. Given that space is highly limited on most fishing vessels, energy-density (i.e. the amount of energy that can be released by a given mass or volume of fuel) is often an important consideration, as is the space required to accommodate any additional equipment.

The energy density of a fuel partly determines how applicable the fuel is for certain vessel types and operations. Because of its low volumetric and gravimetric densities, employing batteries to propel deep-sea operations is challenging and for most cases simply not feasible or realistic given current battery technologies. LNG has around 40 % lower volumetric energy density than diesel, roughly the same as LPG. When also accounting for the storage system, LNG has roughly 1/3 the volumetric energy density as diesel. Liquid hydrogen, ammonia and methanol have even lower volumetric energy densities – around 40–50% of LNG. Biodiesel is the only fuel which is close to matching the energy density of diesel (Figure 13).

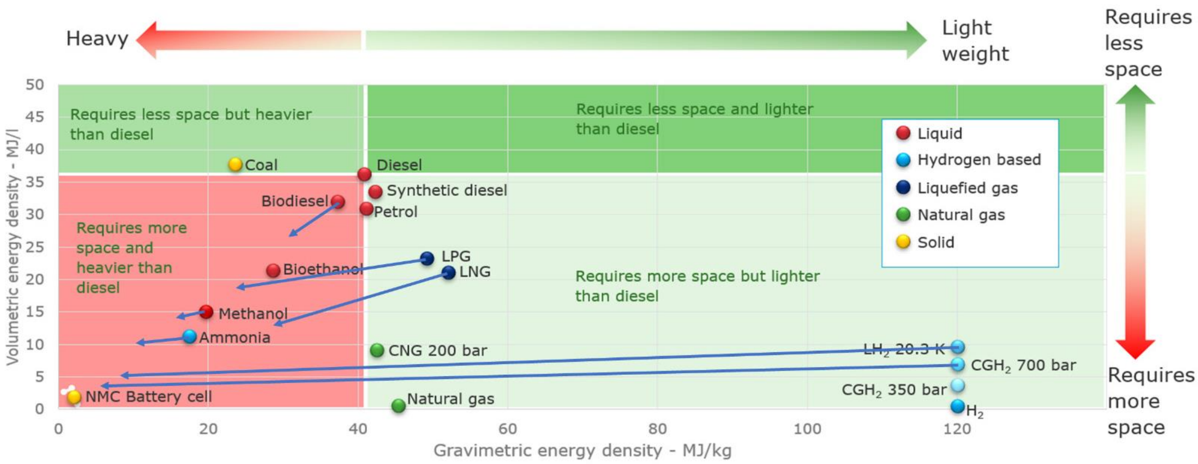

Figure 13. Energy densities for different power systems. The arrows represent the impact on density when taking into account the storage systems for the different types of fuel (indicative values only). From DNV GL (2019).

Vessels might need to be radically re-designed to accommodate certain fuels, as retro-fitting might otherwise take away space from the fish room, which is not what is usually wanted (i.e. resulting in a smaller hold for fish). Similarly, some Tier III engine types employ Selective Catalytic Reduction (see above), necessitating a large storage tank for urea (known as Ad-Blue), and this has proven unpopular because of the additional space requirements.

Tanks required to store gaseous hydrogen would be huge, but less so if the hydrogen is liquefied. This in itself creates challenges as it requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is −252.8°C. Consequently, fishing vessels might be poorly suited for full hydrogen-propulsion. Furthermore hydrogen remains very expensive and there is limited guaranteed supply. Most hydrogen available at present is ‘grey hydrogen’ i.e. extracted from natural gas (methane) using steam reforming but in this case, relevant technologies do not capture resulting emissions, instead they are released into the atmosphere. To move toward zero carbon emissions will necessitate an increase in the supply of ‘green hydrogen’, i.e. extracted using a method that does not produce greenhouse gas emissions. Green hydrogen is most commonly produced using a device called an electrolyser. Electrolysers use electricity to split water into hydrogen and oxygen. The key is that the electricity that powers the electrolyser comes from renewable sources, such as wind and solar.

Health and safety concerns. A number of different health and safety concerns were raised with regard to the various new propulsion options. Some of these would require additional on-vessel expertise and training in order to ensure safe operation. For battery-powered electric fishing vessels the main concern is about range and reliability, as a flat battery at sea could have much more severe consequences than would be the case on land. Batteries (at least with current technologies) are typically very heavy, and this weight could present a stability issue for small fishing vessels.

Hydrogen is very flammable and can cause fires and explosions if not handled properly. Hydrogen gas has a very broad flammability range – from 4% to 74% concentration in air, and from 4% to 94% in oxygen – and keeping air or oxygen from mixing with hydrogen inside confined spaces is therefore very important. LNG is not flammable or explosive in its liquid form which means converting natural gas to LNG is one of the safest ways to transport energy. LNG is stored and transported inside double-walled or double-hulled containers to keep it cold and to reduce the risk of a leak.

Ammonia is less flammable than methane or hydrogen and constitutes a lower, but not ignorable, explosion risk. However, ammonia is highly corrosive as well as extremely toxic, and it is therefore considered essential to be able to control all leakage scenarios in order to design and operate a safe ship. Having alkaline as well as corrosive properties, ammonia will corrode galvanised metals, cast iron, copper, brass or copper alloys; hence, careful material selection is required. Pressure vessels used for storage of ammonia may explode when exposed to high heat. Ammonia is transported in the liquid state; therefore, it must either be compressed or refrigerated, or some combination of the two. Fully refrigerated ammonia storage tanks contain liquid at –33°C at atmospheric pressure.

Onshore facilities. Harbour-side space for additional bunkering facilities could be very limiting at certain UK ports. For example at Brixham in Devon, there is no obvious place where a tank, suitable for storing LNG, HVO, ammonia or hydrogen could be located. Delivery systems (usually a road tanker making occasional visits to the harbour-side) might also have to be reconsidered, and it might be that for certain fuels, bunkering is only available through specialised facilities and hubs, e.g. the national hydrogen highway network on the Thames and the Tees Valley Hydrogen Transport Hub (see above).

Large-scale use of electric propulsion would also necessitate considerable investments in ports and harbours. In many fishing harbours electricity infrastructure was said to be woefully inadequate; there are currently virtually no charging points and voltages would be insufficient. The Department for Transport have recently launched a consultation that invites views on the deployment of 'shore power' and specifically the provision of shoreside electrical power to a docked vessel while its engines are shut down. Such facilities (up to 1000 kW) exist for large vessels (e.g. cruise liners) in Norway, and could be feasible in the UK, but so far have not made sense economically. For example, Aberdeen is currently building a new part to its harbour – but no 'shore power' is included. The Department for Transport has suggested that rolling-out 'shore power' will bring private investment, encourage new careers, create thousands of jobs, boost economic growth, and revitalise coastal communities. So far, there has been little conversation with the fishing industry.

A further obstacle to the roll-out of electric charging points for fishing vessels in some ports is that vessels often tie up side-by-side due a lack of space (as is the case in Brixham). Electric charging would require each vessel to have an assigned independent berth.

Financial risk and reward. Undoubtedly among the biggest barriers to the adoption of low carbon technologies is the financial risk that this might present, especially if the technology is unproven. For the highly profitable Scottish pelagic fleet, where vessels are renewed on a 10-year cycle, there might be more risk appetite or at least sufficient adaptive capacity to resolve difficulties where these arise. For other parts of the UK fleet, risk appetite will be much lower, as poor investment decisions could affect profitability for many decades to come.

Stakeholders suggested that very few vessel owners have the financial resources that could be directed towards research and development. If they intend to build a new vessel, they need something that they know what will work for many years into the future, and that will not reduce their competitiveness. Consequently, there will always be a tendency to piggyback on existing 'tried and tested' technology. Nobody is prepared to shoulder the risk of going first.

Full de-carbonisation is not something that the fishing industry can achieve on its own. The market for new fishing boats is an order of magnitude smaller than the automotive or aviation sectors. These industries have been supported by sustained research investment over many decades, whereas the fishing industry has received very little attention.

Several stakeholders recommended new schemes to provide financial support to fishers or vessel builders in pioneering low-carbon technologies. When some of these technologies have been commercialised (and the regulatory hurdles have been surmounted), then other fishers will be willing to follow suit. It was suggested that government might need to invest in 'demonstrator vessels' to help offset development costs, where fishers would have the opportunity to try these out and see how they should be operated (under dispensation). In return, fishers would be asked to report back and evaluate the situation, which would include the use of logbooks to monitor their fuel use, in addition to catches and other relevant data.

5.4 Pathways to emission reductions: operational changes

While novel developments in technology and fuel methods may well be the most obvious candidates when pathways towards Net Zero carbon are being considered, their development is also, to a large extent, external to fisheries. Within fisheries, emission reductions could also be achieved through a set of operational and/or behavioural changes in the way that fishing activities are carried out (Figure 14). Such 'operational pathways' have the advantage that they may be more practicable in the short- to mid-term, leading to significant fuel savings and hence emission reductions. By themselves, such operational changes are unlikely to be sufficient to bring emissions completely down to Net Zero; nevertheless, they are expected to facilitate this transition until the time when alternative fuel types or propulsion methods become more available, or importantly become more affordable in the future.

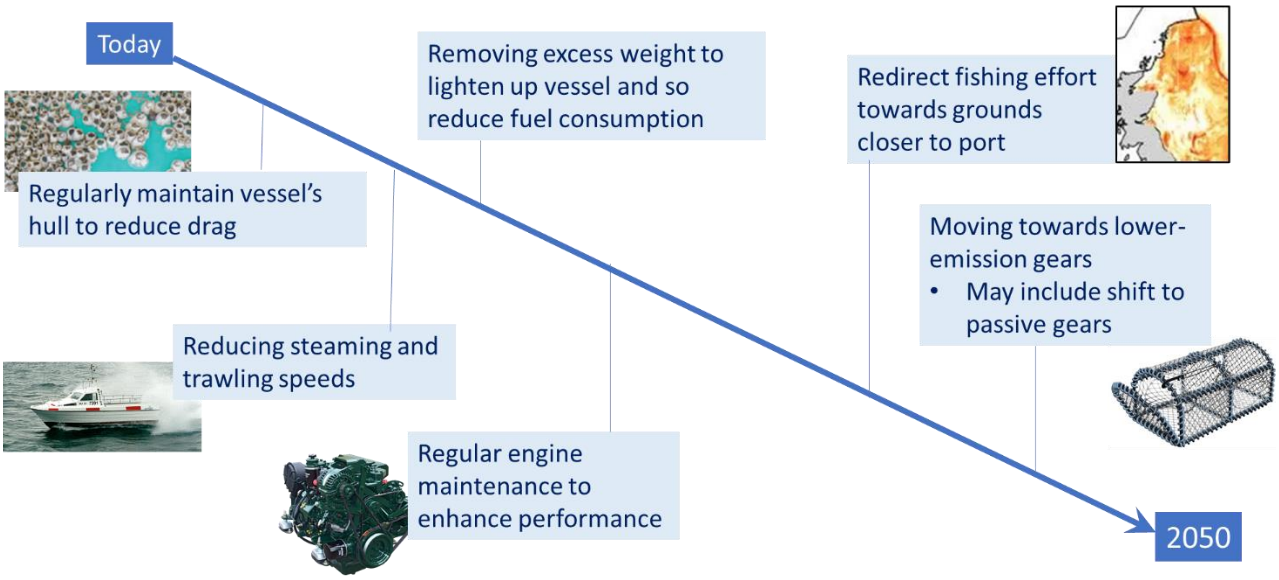

Figure 14. Pathways towards zero-carbon fisheries through operational changes within fisheries.

In the past two decades, high volatility in fuel prices has already led to fisheries of the UK (Curtis et al., 2006; Abernethy et al., 2010) and other countries (e.g. Netherlands: Poos et al., 2013) having to adapt, partly through operational changes to remain profitable (or else face economic hardship: Abernethy et al., 2010). Curtis et al. (2006) in particular looked at options for improving fuel efficiency in the UK fishing fleet, and interviewed fishers on ways they were adapting their operations. Based on these and other studies (Parker et al., 2018; Kristofersson et al., 2021), pathways that may lead to reduced emissions through operational changes (largely via fuel use reduction) include:

- *Regular maintenance of the vessel's hull to reduce drag*. Maintaining as little friction as possible between the hull and the water improves fuel efficiency. More marine growth implies more friction, and an increase of over 30% in resistance has been noted in cases where the hull has been left to foul. Rough paintwork can also increase friction (Curtis et al., 2006).
- *Regular maintenance of the engine.* This can enhance performance by ensuring the engine runs efficiently. Badly worn or faulty components, such as a blocked fuel filter may lead to greater costs from lost fuel efficiency than from replacing components, and will lead to higher emissions.
- *Removing excess weight, either from the vessel or from the gear*. Emissions may be reduced by lightening the vessel from excess weight, and so reducing the fuel consumption. The weight of the gear may also be reduced, particularly in the case of beam trawlers that traditionally carry heavy gear; this may be achieved through changes in the chain mat size and reducing beam length.
- *Modifying the fishing gear.* There are many ways in which fishing gear may be modified to reduce emissions. In trawl or net fisheries, lighter twine may be used, a smaller net, or a net with wider mesh; the weight of trawl doors may also be reduced (Curtis et al., 2006). Vessels may also switch from single to pair trawling. In beam trawlers, wheels rather than shoes may be used at the end of the beam to reduce friction on the seafloor, although many beam trawlers have already implemented this change. In general, such gear changes need to be carried out correctly so as not to impact the fishing performance adversely and ensure they lead to real benefits.
- *Completely changing the gear.* As shown above, different gear types are typically associated with widely differing average emission levels. Accordingly, fuel costs and levels of carbon emissions may be reduced by changing gear choice towards lower-emission gear types. This includes increasing use of passive gears (including nets, pots, traps, hooks and lines).
- *Reducing steaming and/or trawling speeds.* As long as this does not significantly hamper fishing success, reducing the speed can be a way to reduce fuel use and hence emissions that requires little or no added cost. This may be done both during steaming, and trawling; the latter might require (some) modifications in the gear being towed.
- *Redirecting fishing effort towards grounds closer to port.* If long steaming distances can be reduced by moving effort to fishing grounds closer to the port of landing, fuel usage and hence carbon emissions will be reduced. This does require that fishing opportunities closer to port are indeed available, which may be compromised by competing uses of the marine environment and by designated marine protected areas, that may be equally important for carbon neutrality. Fishing closer to port has already been an earlier way for fishers to adapt to high fuel prices (Abernethy et al., 2010)
- *Changing the landing port closer to the grounds.* Alternatively, fishers or vessel owners may change their landing port to the nearest port to fishing grounds and so reduce fuel usage and costs, and therefore carbon emissions (and may only infrequently visit the original home port). Such changes in the port of landing have already been observed in UK liners and netters, in response to earlier periods of high fuel prices (Curtis et al., 2006). Note that while this could imply that carbon emissions are transferred to land freight, the latter is usually more efficient when compared to a steaming fishing vessel.
- *Avoiding going to sea in bad weather.* Fishing in stormy weather not only incurs higher physical risk to fishers, and is generally (at least above a threshold) associated with lower catch rates (Sainsbury et al., 2021); but it also implies (often considerably) higher fuel usage. Carbon emissions may be reduced by avoiding going to sea in adverse weather conditions.

While on first appearance, many of the above described, 'operational pathways' to reduce carbon emissions in fisheries appear straightforward to implement, they often do incur various up-front financial costs, which may form a barrier to adaptation (Suuronen et al., 2012). There may be a more or less lengthy period of time before returns on initial investment are achieved. These changes may also require some level of experimentation on alternative options. More research is needed into these, and other potential, 'operational pathways' for carbon emission reductions in UK fisheries, to facilitate informed decisions and appropriate investment and implementation.

5.5 Operational changes: initiatives already taking place

It is likely that the emission reductions achieved so far within the UK fleet in recent decades, have at least partly come about through a mixture of operational changes such as those described above. Indeed during the ten stakeholder interviews held with industry for this project, representatives highlighted a number of initiatives towards reduced emissions through operational changes that are already taking place.

Vessel maintenance: a priority. For vessel owners and skippers, good maintenance of vessel and engine is generally seen as a necessity, not only to meet inspection requirements, but also to ensure the vessel is workable and safe while out at sea. However there are limits to this, especially if budgets are constrained, as vessel maintenance often requires the vessel to be out of the water (e.g. for hull cleaning or repairs), and not being able to go fishing for a more or less extended period of time.

In a few cases, having a very efficient engine may not necessarily lead to reduced fuel use – as some fishers might actually increase their speed, and this tends to undo any fuel savings.

Modifying fishing gear, and removing excess weight. Most fishers are interested in tweaking their gear including making it lighter. The motivation is either so that it catches better or so that it reduces fuel consumption, or both (in both cases, this would favour emission reductions but the latter *per se* is generally not the immediate motivation). When replacing gear, fishers will generally assess what is available and are interested in novel developments. There are, however, limits to what can be achieved with current materials and technologies.

Within the UK beam trawl fleet, all vessels at least in southwest England use wheels now, rather than conventional beam shoes that slide over the seabed. This creates a lighter contact with the seafloor which not only implies less impact on the seabed and benthic fauna but also reduces fuel use and hence emissions. Over the years, rockhopper gear applied to demersal trawls has also become lighter and more fuel-efficient.

A new system of beam trawling, the SumWing system (Box 4), is currently being trialled by an entrepreneurial skipper in the south west, as a means of potentially saving significantly on fuel cost. This new way of fishing, developed in the Netherlands, uses a beam that is much lighter-weight than a conventional beam, and that is aerofoil shaped (similar to a plane's wing) in a way that allows it to be towed at a controlled height in the water column, so pulling the trawl net. The fuel savings result from the reduced weight and from far less contact with the seabed.

In a recent, collaborative project between science and industry, trials were carried out on trawl modifications that were aimed at reducing bycatch of non-target species. In addition to the improved selectivity, it was also found that the modification led to a reduction in fuel use.

However, while many modifications to fishing gear are clearly happening, completely changing the gear appears to occur at most sporadically, including vessels switching from active to passive gear types (see below, under 'Barriers').

BOX 4. Novel beam trawl design: the SumWing trawl

The wing trawl system, or Sumwing beam trawl, is a method of beam trawling where the traditional beam is replaced with a 'wing' style of beam, without any beam shoes at the ends (HFK Engineering, 2009). The beam is aerofoil shaped, which creates lift as it is towed through the water in a similar way to an aeroplane wing. It is designed to skim about 60 cm above the seabed, with a standard beam trawl net behind it. The gear was originally developed in the Netherlands beam trawl fleet where the gear was often combined with the pulse trawl system. Recently (not applying the pulse trawl) it has also started being picked up in UK fisheries. Trialling this gear has been an initiative by a skipper in the south west who is keen on innovation, especially with the aim of reducing fuel use. The success will depend on whether the gear will indeed fish well, and will not result in much loss of time. A potential added benefit of this gear might be that, by its lighter weight, negative impacts to the seabed and benthos might be reduced.

Changing port to be closer to the fishing grounds. Theoretically, steaming times could be reduced either by fishing closer to home port, or by changing the landing port to one closer to the fishing grounds. In practice, stakeholders we interviewed indicated that fishing closer to home ports is rarely possible, opportunities being very limited; however there were many cases where fishers are changing their landing ports to be closer to the fishing grounds.

In the south west, Brixham skippers in 2021 lost the ability to swap quotas internationally with EU member states, and now retained quota for area VIIa (Irish Sea) which they would have previously swapped for VIIe (Western Channel) quota. With their main grounds now moved to the Irish Sea, they would sometimes still land in Brixham, but now more so in Milford Haven, avoiding a steaming distance of over 150 nautical miles.

A further example is in the North Sea, where North Shields fishers – partly as a result of northward distribution shifts of their target species – no longer have their main fishing grounds along the northeast English coast, but rather off Shetland, or even off the Norwegian coast. Many of these fishers no longer fish from North Shields but now do so from Peterhead, which greatly rationalises their steaming distances and fuel costs.

5.6 Operational changes: barriers and enablers

Interviewees highlighted several barriers and challenges to operational changes that would theoretically favour emission reductions, and moreover suggested several other potential operational changes in the way of fishing.

Gear modification: barriers and enablers. As expressed by one stakeholder, "innovations are always welcome; gears that make fishing more economic make sense – the challenge is aligning economics with practice." Decisions about gear choice are often made at the point of vessel replacement; where budgets allow, the choice will generally be for better gear design, more effective trawl doors, etc., to favour more efficient and economical fishing.

In pelagic fisheries, a way to improve efficiency that is starting to be considered, might be through steerable trawl doors, so changes can be made to settings while out at sea, potentially during fishing operations. This is beginning to be taken up and might be mainstream within 5 years. However, this and other major gear changes require a large investment.

There are some challenges still in effectively introducing the SumWing trawl (described in Box 4) as it was originally developed in the Netherlands to be used with pulse trawling, but in the trial fishery in the UK (where the latter fishing method is banned) the intention is for it to be used in combination with a chain mat (which is heavier). More adaptation will be needed to fully develop it for ways of beam trawling that use a (possibly lighter) mat. As a fully new development, trials are being carried out in the Netherlands on the use of (intermittent) jets of water (rather than pulse) to enhance catch rates, and this might prove compatible with a SumWing trawl.

Sometimes, legislative restrictions can preclude a gear from being modified legally. In scallop dredges, gear specifications are very prescriptive, which does not allow much room for the fisher to 'play' with the gear, even if this could help reduce fuel or drag. Here, changes to the legislative framework would be needed to facilitate the development and adoption of lighter, lower-emission gear.

Challenges with switching gear, including to passive. Fully changing the fishing gear can be problematic for a fisher or fishing company. This is not only because most fishing vessels are purposely built for certain gears (e.g. a beam trawler cannot simply be turned into a gillnetter), but also because certain species that fishers or companies have quota for, are caught by certain gears (and quota may be associated with specific gear types). Where species are caught by multiple gear types, the quantities and proportions in which species are caught by these gears can be very different. As a result, fully switching between gears is seen rarely, especially if a fishery is reasonably lucrative.

It should be noted that passive gears are not, necessarily, fully passive – either in terms of emissions or in terms of environmental impact. Fishing effort by passive gears would have to be increased very greatly if similar quantities of fish were to be caught as in active gears. One stakeholder cited a study by the Commission, where it was estimated that if passive gears were to be used to catch the whole North Sea sole quota instead of beam trawlers, numbers of static nets would have to be increased by some 1300% – with potentially detrimental bycatch effects on sensitive species such harbour porpoises. A mixture of passive and active gears might be considered more appropriate than 'flipping a switch' from active to passive. While passive gears do supply many small-scale, specialised markets, their use alone "would make it very hard to feed the nation."

Reducing speed and success of fishing. Reducing the speed may be seen as sometimes counteracting the success of fishing. However towing with the tide can be a means of maintaining speeds compared to the ground but using less fuel. Overall, skippers need to balance maximising the fish they are catching, in a way that maximises the price (where timely delivery to port may be essential – especially if a specific 'factory slot' is to be met), with any possible savings that may be achieved through reducing steaming or trawling speeds. In many cases, this balancing act works out in favour of higher speeds and against reducing speed.

Opportunities for fishing closer to home port. With multiple and increasing, competing human uses of the marine environment (including offshore windfarms, aggregate extraction, gas and oil, underwater cables and pipelines) and improved environmental protection (MPAs and Highly Protected Marine Areas), there are very limited opportunities for redirecting fishing effort closer to port. Instead, competing demands for space mean this is more likely the other way around, and fishers may have to steam longer distances. Concerns on reducing fishing opportunities close to home port were expressed by most stakeholders we interviewed, e.g. it was stated that "people would love to fish closer to home if they could, but that is not an option."

In one fleet segment, the Scottish pelagic trawlers, there are opportunities to plan fishing trips close to home port, by ensuring they have access to fishing opportunities in local waters around Shetland while their target species (particularly mackerel) reside there. Their fishing trips may be less than a day. If stationed in Shetland, these vessels have to steam only 6–12 nautical miles out of the harbour, and also if based in Peterhead, they are still less than 50 nautical miles away.

Bad weather: staying in port or going out fishing? This consideration is highly dependent on vessel size: generally, larger vessels (or those with stronger engines) are better able to withstand heavy weather. The large, pelagic trawlers in the Scottish fleet can go out in virtually any weather; as they generally have short fishing tows, poor weather is generally of limited concern. An incentive for a larger vessel to go out fishing with poor weather is that if it is the only one that can go out fishing, its catch will fetch the best price. Thus any decisions about whether to stay in port or go out fishing in bad weather will depend on considerations around opportunity, risk, economics, etc.

Further suggested operational changes. Several stakeholders suggested the use of sensors that accurately monitor fuel use, as a means of helping to identify where fuel savings may be possible, and also of raising awareness of fuel use. Some fishers already monitor their fuel use more closely, and trial different ways of towing (e.g. with the tide) to economise on fuel use. Other interviewees, however, indicated that most decisions on fuel use happen when planning the trip, rather than while out at sea.

By and large, fishers have limited opportunities within which they can operate. They will mostly fish in ways that have proven for them to be profitable; and will only digress to some extent. If using slightly more fuel results in much greater catches, they might instead be incentivised to do so. If using far more fuel results in slight increases in catches, they will not do so, and likewise if reducing fuel use results in major drops in catches this is unlikely to take hold. However both the prices of fuel and those of fish change continually, so the way in which fisheries operates with regards fuel efficiency will also respond accordingly.

5.7 Pathways to emission reductions: policy changes

To help the UK fishing fleet to "evolve" from its current state – which as seen above, is still relatively carbon-intensive – to Net Zero, this report recommends that UK Fisheries Administrations develop policy specifically targeted at emission reductions in fisheries. This could include policy measures aimed at achieving 'quick-wins,' i.e. leading to specific, targeted reductions in emissions in the short-term (but likely insufficient for fully achieving Net Zero), as well as long-term measures required to completely move towards Net Zero carbon. Expanding such policy frameworks to be inclusive of aquaculture might also be considered. Ideally, policy measures should be designed not to focus purely on 'top-down' measures which add pressure to a sector that is already challenged, and which is key to coastal communities around the UK, but instead to include sufficient support, research and innovation, and targeted investment to be beneficial to a fishing sector that will combine prosperity with reductions in emissions, and ultimately carbon neutrality.

Below, we discuss potential 'managerial pathways' of policy towards reducing carbon emissions in UK fisheries and moving towards Net Zero carbon (Figure 16). Importantly, these are introduced here as theoretical options – and *not* as established policy. This section, as was the case for the two previous sections on 'pathways for emission reductions', aims to stimulate dialogue and facilitate discussions within and between policy, industry, science, NGOs, and other stakeholders.

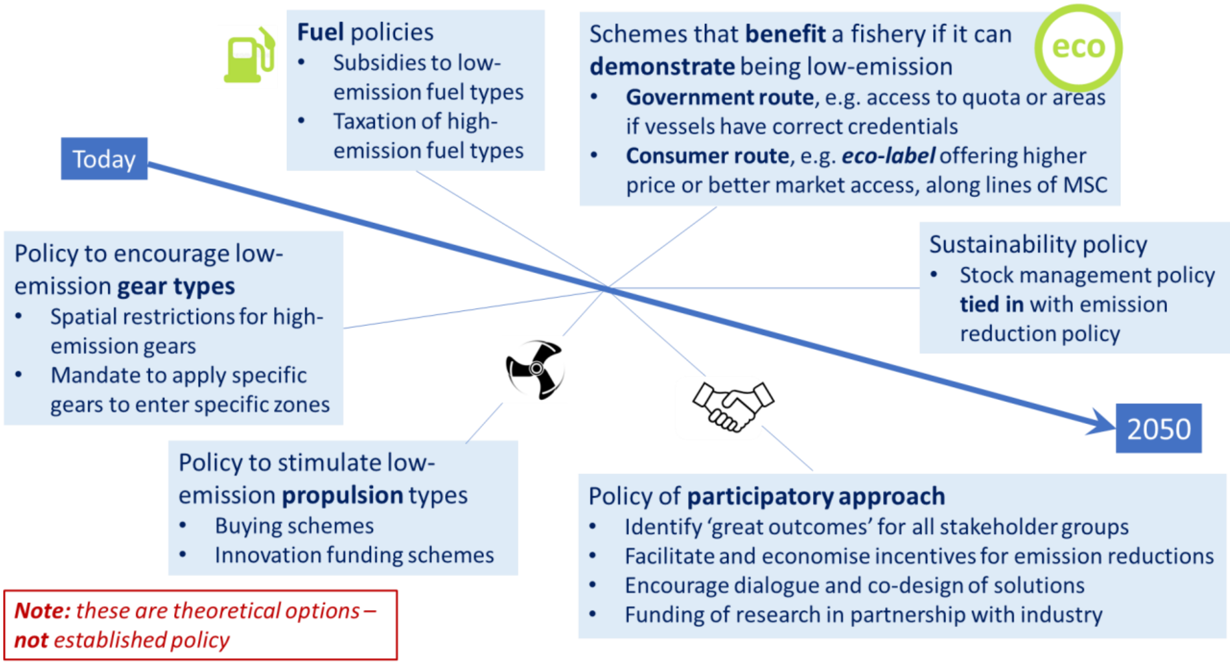

Figure 15. Pathways towards zero-carbon fisheries through potential managerial changes, presented here as theoretical options that may be considered by policy.

Policy towards low-emission gear types. One set of policy measures may be designed to encourage *low-emission types of fishing gear.* Such a policy would reflect that there are clear differences in average carbon emissions between different gear types; however, a careful selection of appropriate 'performance criteria' would be needed (emissions per vessel, per kg fish landed, per value landed, or per sea-faring job). Potential measures could include spatial restrictions for certain (high-emission) gears; it could also include a mandate to apply specific gears to enter specific zones for fishing. Policy may also be designed to encourage a potential switch to passive gears.

For many fishers, however, there may be major constraints that prevent a complete switch towards either passive gear, or otherwise an entirely different, lower-emission gear type. Policy may therefore also be designed to encourage modifications *within* the gear types in use that reduce emissions. This could include stimulating gear modification towards, e.g. lighter or thinner twine in the net, wider mesh, smaller overall net size, or lighter or shorter beams – aimed at reducing potential cost barriers to implementing these modifications.

Policy stimulating low-emission propulsion types. This would be a set of policy measures where low- or zero-emission propulsion types or technologies are stimulated. Many of the novel propulsion technologies currently still come at very high cost, prohibiting their implementation on fishing vessels; buying schemes might make their initial installation more affordable (it is expected that the prices of low-carbon technologies will drop, but not in the immediate future: Parker, 2021).

Alternatively, innovation funding schemes could help develop low-carbon solutions for fishing vessels, and make these more affordable in the medium term (and various such projects are currently under way through the Seafood Innovation Fund). Projects could aim to improve hull hydrodynamics, the propulsion system, and/or reduce electricity or thermal energy consumption.

Some specific policy could focus *initial interventions* on a few fleet segments that currently are particularly carbon-intensive yet are also crucial for sustaining livelihoods, helping these to adapt to lower-carbon solutions (e.g. moving towards biofuels in the short-term). This could achieve 'quick-wins' while not penalising these fleet segments excessively.

Fuel policies. Policy around fuel in fisheries could work along broadly similar lines as terrestrial policies around fuel in road transport. On one hand, subsidies may be provided to preferred, low- or zero-carbon fuel types. On the other hand, this could involve taxation on, or removal of subsidies from, fuel types that may be considered 'high-emission'. The dynamics of which subsidies may be considered to be either subsidised or taxed, will have to be carefully assessed and evolve over time.

Policy schemes that benefit a fishery if it can demonstrate being low-emission. Carbon emission reductions in fisheries are likely to be incentivised if schemes were to be put in place that could benefit a fishery, if it could demonstrate being 'low-emission' (through criteria that will have to be carefully established). Such schemes could work through either:

- a *government route,* such as access to quota or specific areas if vessels have the correct 'low-carbon' credentials; or through
- a *consumer route*, such as an eco-label that offers a higher price for products or access to specific, desired markets. This could be along lines similar to the Marine Stewardship Council (MSC) certification scheme for environmentally, ethically and responsibly sourced seafood products (Agnew, 2019).

Stock management policies supporting emission reductions. If fisheries resources are at high abundance levels, then the catch per unit effort (CPUE) will also be high – and so the same quantities of fish may be obtained at lower emission levels. Thus, policies aimed at reducing emissions may not only do so through investment in new technologies and changes in the operation of fishing (i.e. purely carbon emission focussed policies), but also through aiming at achieving high abundances of fish or shellfish stocks (i.e. stock productivity focussed policies).

Policy of participatory approach. It is well known that a close working relationship between policy and governance, science and the fishing industry is beneficial to environmental, societal, and economic sustainability (Mackinson et al., 2011). Likewise, a participatory approach will be essential for all stakeholders involved when striving towards emission reductions.

To start with, such a participatory approach could identify 'positive outcomes' for all stakeholders involved, even if the specific motives for achieving these may be (slightly) different between each stakeholder group – be these reductions in costs, practical considerations, enhancing sustainability, or contributing to carbon emission-associated targets *per se*. Accordingly, it will be important to identify, facilitate, and economise incentives for different stakeholders that may lead to a shared outcome of emission reductions (Mackinson et al., 2017). The participatory approach should aim to encourage dialogue, collaboration and co-design between industry, science and governance when seeking emission-reducing solutions. A further, important means is through funding of research in partnership between science and industry.

5.8 Potential policy changes: industry perspectives

UK fisheries are highly diverse with some parts of the fleet being highly successful, adaptive and competitive, but with other parts of the fleet segments operating within narrow profit margins or in some cases even at a loss. As a result, slight changes in policy might have negligible impacts for some fisheries, but have serious consequences for others. In the interviews with industry representatives, we asked for their perceptions with regard to the various, potential policy options described above and in particular, what policy or managerial options they would either be supportive of, or would see as creating major barriers or challenges.

Feedback on policy options towards low-emission gear types. Interviewees were consulted about their views on potential policy schemes aimed at promoting low-emission gear types, through either: *(1) spatial restrictions to high-emission gear types, (2) a possible mandate – in order to enter specific zones, where only low-emission gear types would be allowed; (3) a scheme that would facilitate lower-emission modifications within a gear type; or (4) any other gear-related potential policy schemes.*

With regards (1) *spatial restrictions* (i.e. making area access conditional on the use of specific low-emission gear types), stakeholders expressed that while theoretically possible, this should be seen against a background of already existing, and ever more tightening "squeeze" in fisheries due to increasing competition with other uses of the marine environment (e.g. windfarms, marine protected areas, cables, extraction sites etc.). Therefore, such spatial restrictions would be seen as a very hard "stick".

With regard to (2) policies around *mandated* options, this might be seen more as a "carrot", but it would mainly work if there was not access (or very limited access) in the first place, although it might then conflict with other objectives. In case of mandated options for entry into specific areas, these would have to be fair (e.g. applicable to all nations); fairness across the board would make any "stick" easier to swallow. If considered, then discussions between fishery administrators and fishers might need to take place in the context of Fishery Management Plans (FMPs), and it should be clear how it would contribute to meeting the objectives of the Fisheries Act (including the Climate Change objective). Stakeholders considered that decisions should be implemented based on dialogue, rather than as siloed decisions.

Policy schemes (3) aimed at facilitating *lower-emission modifications within a gear type*, were viewed upon favourably, and would likely be taken up. A small number of motivated fishers are already trialling this, but a scheme may indeed be needed to incentivise the uptake of lower-emission gear more widely across the fleet. Financial support would probably be needed to facilitate further trials aimed at developing new gear and demonstrating initial 'proof of concept.' There is usually keen interest in the sector in such initiatives, e.g. through fisheries-science partnerships.

It was further recommended (4) that a dedicated programme may also be needed to stimulate more wide-spread *adoption* of efficient gear across the fleet. This is because experience has shown that the uptake of new measures can be very low; either because fishers are not quick adopters of new methods if these have not yet been 'proven' to work more widely, or even because new methods may not legally be allowed yet, under current technical regulations.

Feedback on policy options towards low-emission propulsion types. We asked industry stakeholders for their thoughts and perspectives about potential policy schemes aimed at promoting low-emission propulsion types, through either: *(1) subsidies and schemes helping to build new vessels; (2) retrofitting existing vessels, that employ novel propulsion technologies; or (3) having mandatory vessel building codes and standards that require vessels to be low carbon*.

Responses varied but as a general rule, "carrots" were widely preferred above "sticks". With regard to subsidies or schemes to (1) *build new* (low-emission) vessels or (2) *retrofit existing* vessels, it was suggested this should be subject to constraints to avoid over-capacity, e.g. being managed via conditions such as like-for-like replacement of vessels without increasing total engine power. In this way, progress might be achieved fairly quickly. It would be needed to both build new vessels and retrofit old vessels – for reasons of safety, continuity, and sustainability (acknowledging sustainability issues also with scrapping old vessels).

Several stakeholders felt there is currently a lack of incentives for new builds in the UK, unlike elsewhere such as in the EU, hence British companies tend to buy second-hand vessels from other fleets in the EU (e.g. Netherlands, Belgium), which reportedly do give loans that stimulate innovation.

On the question of (3) *mandatory vessel codes and standards*, it was understood that mandatory codes are likely to change in the future, as is happening in the automotive industry; but that any such change should happen at the right pace in line with technology development, and in particular with how price and feasibility development on the market. Again, it was felt there should be a level playing field across the devolved administrations, so that fairness is assured across all (where it was noted some imbalances may already exist). Finally, mandatory codes should be level across the UK and EU, or otherwise financial disadvantage might result; and to avoid the latter, also the pace of change should be similar.

We also enquired about (4) whether *initial intervention* should focus on some fleet segments that currently have particularly high carbon emissions, as a priority, or on the other hand, on those fleet segments already low in carbon emissions, as added stimulus. It was felt that responsibility should be right across the industry – not for one part of industry over the others – everybody should make an effort. Still, for some fleets such as the beam trawlers there may be greater incentives because reducing emissions would also have significant benefits in reducing costs.

Feedback on fuel policy options. Interviewees were asked for their perspectives on: *(1) potential subsidies to low-emission fuel types; or on (2) taxation (or removal of subsidy from) high-emission fuel types*; and how potential preferred policies on these might be different in the *short (1–5 years), medium (5–10 years) and long term (10–30 years)?*

There was consensus that fuel subsidies (or taxation) form a difficult topic. It is generally understood that government should be moving away from subsidised fuel, however currently all businesses in UK fisheries are based on the assumption of current fuel prices – and that dropping subsidies would cause economic shocks to the sector, with unforeseen consequences. Rising prices of fuel, the biggest outgoings at present, could lead to other costs being squeezed, e.g. crew wages, maintenance and safety costs. Thus, any changes would need to be done in a stepwise way, because "if fuel subsidies would be removed now, there would be no industry left". Given that, as a food producing industry, fisheries is already carbon efficient compared to agriculture, but is also a highly stressed industry, stakeholders highlighted that a policy penalising it through removal of current fuel policy without available alternatives would not necessarily deliver the desired policy outcome.

One stakeholder noted that in a perfect world, subsidies for lower emission would be favoured, where fishers would move to low emission with assistance and could see benefits in terms of efficiency as well as clean running. Unfortunately, alternative fuels such as biodiesel or other biofuels are currently in short supply, are often more expensive that traditional diesel, and their sourcing may not necessarily be environmentally sustainable (e.g. if sourced from palm oil).

In summary, it was suggested that alternative fuels – sustainable sourced – would have to become much more widely available to fisheries at reasonably competitively pricing, and that technologies would have to progress possibly in a stepwise way before any significant changes to current fuel policies would be recommended.

Feedback on policy that would benefit a demonstrably low-emission fishery. Views from industry was sought on potential policies in support of: (1) *an eco-label offering a better price or better market access if a fishery can demonstrate being low-emission* (similar to MSC certification); or (2) that would make *access to quota or specific areas be (partly) dependent on whether vessels have the correct 'low-carbon' credentials*.

Responses included that an eco-labelling scheme such as MSC, which has had a huge impact on fisheries management globally that would not have happened otherwise, might be interesting. However, it was also thought that a scheme such as MSC would, in the near future anyway, be expected to include an element of low-carbon emissions, in a similar way to how human welfare has become included recently in addition to ecological sustainability. While some would prefer a separate "low-emissions ecolabel", others would be concerned about making things too complicated for markets and consumers, and having "so many labels on a box of fish that you can't see the product" – and therefore would rather see this integrated in an existing ecolabel such as MSC.

If an ecolabel route were to be selected, then adhering to this would likely be more important for access to markets than in order to obtain a price premium; for example, that most UK supermarkets now demand MSC certification. This means that for some sectors an ecolabel has become a necessity (a "stick", rather than a "carrot"). For other sectors, having an ecolabel would be of less importance. Most catches of scallop dredgers go abroad, to various European countries where buyers do not demand an ecolabel at present. In case of the large pelagic sector, catches are mostly sold as 'bulk fish' to developing world markets (e.g. in Africa), again where an ecolabel is not required. Even so, there is still likely to be interest for companies to be seen as "good citizens", caring not just about ecological sustainability and social responsibility but also about emissions – a strong reputation does matter for access to markets and business success.

While potential policies on an ecolabel were seen with mixed but mostly favourable views, policies that would make quota emission-dependent would be seen as a very tough "stick" – as it would imply another licence condition in addition to many others, that if not fulfilled would preclude a vessel from fishing. It was seen that this could be a stimulus for innovation due to the necessity to adapt; but also that it would be very complex to implement and (partly due to the multiple metrics for emission levels) could become highly divisive. Interviewees emphasised that fishers invest heavily in obtaining FQAs (Fixed Quota Allocations), and may have borrowed money based on their FQA holdings; it would be very harsh if these were taken away from people. It was considered this might be an option in case of some of the 'liberated' quota currently looked at by Defra as a result of Brexit, to deliver behaviour change; however, stakeholders found that "existing quota should remain FQA based."

Fisheries stock management included, or separate from emission policies? Feedback was also provided on the question, should emission policies *primarily focus on stock abundance preservation, or on technological or operational innovation?* This related to the consideration that reducing emissions (per quantity of fish landed) could not only be achieved through investment in new technologies and changes in the operation of fishing (i.e. carbon emission focussed policies), but also through a high abundance of fish or shellfish stocks (i.e. policies aimed at a successful stock management system). Interviewees agreed that both can contribute to emission reductions, however generally felt that policies aimed at emission reduction, and those aimed at stock preservation are best kept separate. It was felt that sustainable fisheries management is best left as it is – with its internationally agreed systems of total allowable catches, quota allocations and many existing systems in place to preserve and manage transboundary and other internationally shared stocks; inclusion of emission measures might just "muddy the waters." It was felt that technological and operational pathways on emissions *per se*, would be more relatable and understandable, and easier to implement than if combined with fisheries stock management.

Feedback on participatory approach. Dialogue would not only enhance buy-in, but would also lead to more informed decisions more likely to be at the appropriate level; and would avoid 'siloed decision-making.' It was felt that top down, centralised command and control has in the past led to perverse outcomes. A participatory approach was seen as crucial ("a no-brainer").

Stakeholders were not only "strongly supportive" or "extremely strongly supportive" of the participatory approach, but also expressed interest in collaborative industry-science projects aimed at pioneering new technologies and/or operations of fishing. These could refer to trials with novel propulsion systems, fuel types, or the transition to electrics, but also innovations to fishing gear that could lead to significant emissions savings. This interest was expressed across the board, by stakeholders across different devolved administrations, from producer's organisations representing offshore and inshore, pelagic and demersal vessels, from the largest and most modern vessels to the numerous inshore fleets.

There was particular interest in more joined-up conversations, not only between industry and Defra, but also with DfT and BEIS where collaboration and investment projects with the maritime sector are already in place, but were perceived not yet to include fisheries to the extent needed. Better links with boat builders would moreover be beneficial. It would also be beneficial to include discussions on ports, and the required facilities in ports necessary for the transition from fuel-intensive to Net Zero technologies.

6 Next steps

This study has shown that carbon emissions in UK fisheries are still substantial but also that significant emission reduction has taken place at least since the turn of the millennium, demonstrating that progression in emission reduction can be achieved. In order to further reduce emissions towards Net Zero, the 'roadmap' provided consisting of potential technological, operational and policy changes, may serve to inform government, industry, and science. Through the inclusion of stakeholders' knowledge, expertise and experience, it is hoped this work will stimulate workable solutions and collaborative partnerships that help achieve these aims, and may inform policy choices that minimise disruption and optimise the long-term environmental, industry and societal benefits.

Building on this study, a workshop was scheduled for 24 March 2022 aimed at presenting key findings from this study and encouraging dialogue between different parts of UK government including Defra, BEIS, DfT and Defra's Arm's Length Bodies (ALBs), and with presence from different Devolved Administrations as well as representation from industry. Spanning across these government bodies and stakeholders, the workshop is aimed at open dialogue on questions including (1) What is currently being done to work towards reducing carbon emissions in fisheries? (2) What suggested tools and changes are needed and feasible to put in place? (3) Where are the evidence gaps and what are the emerging views on priorities for research? Based on the workshop, plans and priorities are to be developed for further research on how to move forward in achieving the UK target of Net Zero carbon emissions.

As one priority for future research, it is recommended that a reconstruction of past trends in emission reductions back to 1990 is carried out – which is the 'benchmark' year against which the 2035 UK target is compared (i.e. a 78% reduction in emissions compared to 1990). This will allow us to assess the level of progression in reductions already achieved – and to accurately quantify what level of further reductions will be needed to meet the 2035 target.

Looking ahead, it will be important to estimate the associated costs and benefits that are required to achieve emission reductions, under various scenarios such as either newbuild of a vessel, or retrofit of an existing vessel. Ideally, this should take account of price differences between different fuel types – acknowledging the major challenges in predicting future fuel prices, let alone those of novel fuel types. A full cost-benefit analysis could not be achieved here and was beyond the project's scope.

For meeting future emission targets in UK fisheries, it is suggested that participatory industry-science research projects are designed on questions including fuel efficiency, practicability of alternative propulsion types, gear efficiency and making gears lighter, and many of the other themes described in this study as potential technological and operational changes. Collaborative research aimed at finding practicable solutions are looked upon highly favourably within the fishing industry and might be a way forward beneficial to industry, science and policy.

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8 Technical annex

8.1 Description of methodology for estimating carbon emissions

This section includes a fuller description of the underlying data and methodology used to calculate carbon emissions by the fishing fleets of the UK and other European countries, as well as for different fleet segments within the UK fleet. For the former, data were primarily sourced from the EU Scientific, Technical and Economic Committee for Fisheries (STECF, Joint Research Centre, Ispra, Italy: STECF, 2019). For the latter, data were primarily based on annual surveys of the UK fishing fleet, carried out by Seafish ('Seafish Surveys': see https://www.seafish.org/insight-and-research/fishing-data-and-insight/uk-fishing-fleet-survey/; noting that the Seafish Survey data also provide the annual UK input to the EU-wide data call by STECF). The economic and fuel use data for UK and wider EU fisheries, sourced from STECF and Seafish, were then combined with (fuel type-specific) conversion factors provided by the Department for Business, Energy & Industrial Strategy (BEIS), to convert total fuel use data into estimates of greenhouse gas emissions.

Compilation of data for fishing fleets across Europe

To identify similarities and differences between the UK and EU Member States' fishing fleets, data was collated from the Scientific, Technical and Economic Committee for Fisheries (STECF) 2019 Annual Economic Report on the EU Fishing Fleet (STECF, 2019), and its underlying datasets. This provides an overview of the structure and economic performance of the EU fishing fleets, based on data provided annually by each of the Member States. In particular, information was selected on the total numbers of vessels, total fisheries landings, economic value of landings, and fuel use for each country, for the years 2015 to 2018. Table 4 shows the number of fishing vessels registered for various EU Member States in 2018. Data for 2019 was incomplete as the UK is no longer an EU Member State, hence has no longer reporting obligations to STECF.

Table 7. Countries included in the analysis comparing emissions by the UK and other European fishing fleets, with the total numbers of fishing vessels registered in 2018 (STECF, 2019).

Country	Vessels	Country	Vessels
Belgium	70	Latvia	322
Bulgaria	1864	Lithuania	147
Croatia	7731	Malta	938
Cyprus	806	Netherlands	721
Denmark	1707	Poland	830
Estonia	1718	Portugal	7887
Finland	3235	Romania	167
France	6629	Slovenia	134
Germany	1362	Spain	9207
Greece	14234	Sweden	1175
Ireland	2051	United Kingdom	6118
Italy	12146	*All included*	*81199*

Compilation of data for the UK fishing fleet

The annual UK Fishing Fleet Surveys conducted by Seafish were the main sources of data used to compile information on the UK's fishing fleet between 2015 and 2019 (Quintana et al., 2020). The surveys are focussed on the health of the UK's fishing sector, both in terms of the economic performance of the fleet itself and on the social impact it has on coastal communities. The results help both industry and policy makers to understand the challenges and opportunities the fleet faces as well as the impact of fisheries management measures.

Using the Seafish fleet segmentation criteria, the entire UK fleet was grouped into 32 segments based on physical characteristics of the vessels, activity level, gear used, species targeted, and areas fished. Of these, 29 segments were retained for the analysis (following exclusion of vessels registered but inactive, and of low-activity vessels). Table 5 provides a brief description of the fleet segments assessed here.

Table 8. UK fishing fleet segments and definitions, as followed in the present study, with the main fishing areas and numbers of vessels registered in 2019. The definitions of fleet segments follow those used in the annual UK Fishing Fleet Surveys conducted by Seafish (Quintana et al., 2020).

Main gear type **Fleet segment**	**Vessel Length**	**Engine Size**	**Main Fishing Area**	**Number of vessels (in 2019)**
Beam trawlers				
North Sea beam trawlers, under 300kW	10m+	<300kW	North Sea (IVabc)	14
North Sea beam trawlers, over 300kW	10m+	>300kW		7
South West beamers, under 250kW	10m+	<250kW	English Channel (VIIde), Bristol Channel (VIIf) and Celtic Sea (VIIg)	22
South West beamers, over 250kW	10m+	>250kW		26
Demersal trawlers and seiners				
North Sea/West of Scotland demersal trawlers	<24m	<300kW	North Sea (IVabc) and West of Scotland (VIab)	18
North Sea/West of Scotland demersal trawlers	<24m	>300kW		26
North Sea/West of Scotland demersal	>24m			42
North Sea/West of Scotland demersal pair trawl seiners	10m+			23
North Sea/West of Scotland seiners	10m+			14
Irish Sea demersal trawlers	10m+		Irish Sea (VIIa)	11
Demersal trawlers in South-western waters, 10-24m	10-24m		Celtic Sea (VIIgh), English Channel (VIIde) and West of Ireland (VIIbcjk)	54
Demersal trawlers in South-western waters, 24-40m	24-40m			14
Demersal trawlers/seiners under 10m	<10m		All regions	167
Nephrops trawlers				
North Sea nephrops trawlers	10m+	<300kW	North Sea (IVab)	66
North Sea nephrops trawlers	10m+	>300kW		72
West of Scotland nephrops trawlers	10m+	<250kW	West of Scotland (VIab)	60
West of Scotland nephrops trawlers	10m+	>250kW		25
Irish Sea nephrops trawlers	10m+	<250kW	Irish Sea (VIIa)	36
Irish Sea nephrops trawlers	10m+	>250kW		29
Dredgers				
Scallop dredgers	<15m		Irish Sea (VIIa), English Channel (VIIde), West of Scotland (VIab), North Sea (IVab) and Bristol Channel (VIIf)	188
Scallop dredgers	>15m			76

Pelagic trawlers UK pelagic trawlers	>40m		North Atlantic Ocean (VIIbcjk) North Sea (IVabc) West of Scotland (VIab)	26
Drift and fixed netters Drift/fixed netters Gill netters	<10m 10m+		UK-wide	203 27
Gears using hooks Under 10m using hooks Longliners	<10m 10m+		UK-wide	198 31
Potters and trappers Pots and traps Pots and traps Pots and traps	<10m 10-12m >12m		UK-wide	1219 181 105
Low activity vessels Low activity vessels Low activity vessels	<10m >10m		UK-wide	1542 1494 48

Data on vessel characteristics

For each fleet segment, we compiled a variety of data from the Seafish 'Multi-annual UK fishing fleet estimates 2010-2020' into an Excel spreadsheet. This included:

- *Gear type used.* This includes the following active gear types: beam trawls, demersal trawls and seines, nephrops trawls, dredges, and pelagic trawls (including pelagic seines); and the following passive gears: drift, fixed or gill nets, gears using hooks, and pots and traps. In the case of demersal trawls and seines, a distinction was made between vessels primarily targeting nephrops (i.e. >80% of annual landings), here referred to as 'nephrops trawlers'; and vessels catching a range of demersal finfish or shellfish species (which may also include nephrops), hereafter referred to as 'demersal trawlers and seine rs'.
- *Vessel length*. As is customary, several fleet segments are moreover based on vessel length classes (see Table 5).
- *Number of vessels per fleet segment* (See Table 5). For each of the above.
- *Average days at sea.* Number of days between vessel leaving and returning to port.
- *Total annual landings.* Both weight and value of landings returned to port were recorded.

For the purpose of this study, the 31 different fleet segments were then grouped into nine 'main gear types,' as indicated in Table 3.

In addition, the following data related to fuel use was collated. To calculate the quantities of fuel used, the method applied by Seafish uses the vessel capacity unit (VCU) and days at sea for the year of each vessel to estimate its fuel consumption in litres (Quintana et al., 2020). The metrics regarding fuel consumption included:

- *Total annual fuel use per fleet segment*
- *Total annual litres of fuel used per vessel*
- *Annual fuel cost per vessel*

Importantly, the use of a constant conversion factor implies that year-on-year modifications to vessel engines, which could lead to improved fuel efficiency, are not accounted for in the above method. Seafish are currently investigating ways that may help understanding to what extent conversion factors may need to be adjusted from year to year. Due to confidentiality agreements, the Seafish data was not publicly available for the fleet segment 'UK pelagic trawl over 40 m' for the entire time-series. Where missing, data for this vessel group was sourced from the STECF report.

Conversion of fuel use to greenhouse gas emissions

The Department for Business, Energy & Industrial Strategy (BEIS) produces a set of greenhouse gas conversion factors each year for use by UK and international organisations to report on greenhouse gas emissions. To report the greenhouse gas emissions associated with organisational activities, the carbon emissions must be converted into activity data, such as distance travelled, litres of fuel used, and tonnes of waste disposed.

Table 6 shows the conversion factors used to calculate emissions of three greenhouse gase s: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Additionally, emissions for carbon dioxide equivalent (CO_2e) were calculated, as this value provides the total amount of greenhouse gases emitted from fossil fuel combustion on the fishing vessels. The emissions were calculated by multiplying the relevant conversion factor by the litres of fuel used, assuming that all fishing vessels in every fleet segment operate using marine fuel oil (MFO) for propulsion.

Table 9. Annual emission conversion factors for marine fuel oil (BEIS). For years prior to 2015, no separate values were available, and hence 2015 values were assumed.

Conversion Factor for MFO	CO_2e	CO_2	CH_4	N_2O
2020	3.12204	3.07707	0.00126	0.04372
2019	3.12209	3.07707	0.00126	0.04376
2018	3.10973	3.06495	0.00126	0.04352
2017	3.19065	3.16601	0.00122	0.02341
2016	3.20324	3.17850	0.00123	0.02351
2015	3.17897	3.17850	0.00018	0.00029

For each of the different European countries, as well as within the UK for each of the nine major and 31 fine-scale fleet segments, different 'metrics' were then calculated from the available data sources, each describing the levels of carbon emissions by country or fleet segment in different ways. These included:

- *Total annual carbon emissions* (unit: kt or Mt CO_2e)
- *Average annual emissions per-vessel* (unit: t or kt CO_2e / vessel)
- *Average emissions per-quantity of fish landed* (including shellfish; unit: kg CO_2e / kg fish landed)
- *Average emissions per-value of fish landed* (units: kg CO_2e / € fish landed for country comparisons, and kg CO_2e / £ fish landed for UK fleet segment comparisons).

In combination, these metrics are expected to provide a more holistic picture of the emission levels than if each were only to be assessed on its own; they should also be assessed in the context of the overall characteristics and productivity levels for each country or fleet segment.

Centre for Environment Fisheries & Aquaculture Science

Cefas

About us

We are the Government's marine and freshwater science experts. We help keep our seas, oceans and rivers healthy and productive and our seafood safe and sustainable by providing data and advice to the UK Government and our overseas partners.

We are passionate about what we do because our work helps tackle the serious global problems of climate change, marine litter, over-fishing and pollution in support of the UK's commitments to a better future (for example the UN Sustainable Development Goals and Defra's 25 Year Environment Plan).

We work in partnership with our colleagues in Defra and across UK government, and with international governments, business, maritime and fishing industry, non-governmental organisations, research institutes, universities, civil society and schools to collate and share knowledge.

Together we can understand and value our seas to secure a sustainable blue future for us all, and help create a greater place for living.

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Innovative, world-class science is central to our mission. Our scientists use a breadth of surveying, mapping and sampling technologies to collect and analyse data that are reliable and valuable. We use our state-of-the-art Research Vessel Cefas Endeavour, autonomous marine vehicles, remotely piloted aircraft and utilise satellites to monitor and assess the health of our waters.

In our laboratories in Lowestoft and Weymouth we:

- safeguard human and animal health
- enable food security
- support marine economies.

This is supported by monitoring risks and disease in water and seafood; using our data in advanced computer models to advise on how best to manage fish stocks and seafood farming; to reduce the environmental impact of man-made developments; and to respond to serious emergencies such as fish disease outbreaks, and to respond to oil or chemical spills, and radioactivity leaks.

Overseas, our scientists currently work in Commonwealth countries, United Kingdom Overseas Territories, South East Asia and the Middle East.

Our customer base and partnerships are broad, spanning Government, public and private sectors, academia, non-governmental organisations (NGOs), at home and internationally.

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