"Electrifying The Fleet"
More sustainable propulsion options for the small-scale fishing fleet

Report prepared for
National Federation of Fisherman's Organisations (NFFO)
Future Fisheries Alliance (RSPB, MCS, WWF)
North Sea Wildlife Trusts

Working together to promote sustainable fisheries and address the nature and climate crisis

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Executive summary

The aim of this work is to understand the potential for, and impediments to, the development of hybrid and fully electric propulsion systems in the small-scale fisheries sector (generally considered as vessels of less than 10 m length). Fuel is one of the most significant costs for the small-scale fishing sector, especially vessels using mobile gear such as trawls and dredges. The report considers the availability of electric and hybrid systems and the costs of conversion or implementation and estimates the fuel savings that are possible. The implications of electrification for shoreside infrastructure and support are also considered.

Fishing ports in three regions of the UK were visited in order to interview fishermen and others involved in the industry and to make a visual assessment of port infrastructure and the small-scale fleet (generally under 10 m) assemblages in Yorkshire, Devon and Orkney. The over 10 m fleet which mostly consists of vessels using mobile gear and travelling significant distances was deemed to be out of scope for this investigation. It is widely acknowledged that all sectors will have to play their role in meeting net zero and within the fishing sector this will include decarbonisation as part of the solution. Generally, fishers were receptive to the idea that in the future, where possible, propulsion systems need to move away from purely fossil fuel options. Data were gathered on how engines are used on fishing boats of different types and what current fuel usage is. It was clear that there is significant potential for the development of electrical and hybrid propulsion systems for inshore static gear vessels (potters, divers and netters). Although there are no ‘off the shelf’ packages for fishing vessels, suitable technology is available, for example in the recreational sector, that could be adapted. For mobile gear vessels (trawlers and dredgers), because of their continuous high power requirements and lower energy density of currently available batteries, it appears that electrification is unsuitable for now.

If the fishing fleet does adopt more electrical propulsion solutions, rural ports’ electrical infrastructure will need to develop to support this. Some thought is required with regard to upstream electrical infrastructure and exploration of renewable energy options. Government support in the form of legislation, grants and training for both onshore and at sea components of the industry will be essential to assist in transitioning from fossil fuels to low carbon solutions.

Key findings

- Pure electric propulsion, running off batteries, is currently only feasible for some of the smallest boats which have the lowest power and endurance requirements. This is primarily due to the weight and volume of the batteries needed for higher power and/or longer periods, although the cost of such batteries may also be a barrier.
- Hybrid technology shows promise for static gear fishing, due to the variation in engine power that is used during a day at sea. For some vessels with some usage patterns, at least a 20-30% saving in fuel and emissions is achievable. There are no “off the shelf” systems available at the moment, but all of the necessary technology exists today. Many fishers showed interest in switching the next time they change their engine, if the switch is affordable.
- Hybrid systems would not be of significant benefit to boats using mobile gear, because of their need for high engine power most of the time means there would be no gain in efficiency.
- We suspect that significant energy and emissions reductions could result from a change in licensing to focus less on the length of vessels. The current system encourages inefficient short but wide boats, in order to maximise the deck area that is available without exceeding a length threshold that would increase the license cost.
- In the future (by 2050) it will be necessary for the fleet to decarbonise if the UK is to meet its climate commitments. We believe that this will probably happen either through an

improvement in battery technology, or through the production of alternate fuels using renewable energy. The first of these possibilities would have significant implications for port infrastructure, as a small scale fishing fleet charging overnight would require orders of magnitude more power than most harbours have available at the moment.

- We believe that the rising cost of energy is likely to lead to changes in fishing behaviour, and that the optimal solutions will vary from one location to another reflecting local energy supplies and the small scale fleet assemblage. Detailed study of this was beyond the scope of this report.

Recommendations

Needed for fishers

- Research into potential impacts of cumulative efficiency tweaks (propulsion system, boat shape, fisher behaviour) that can have immediate impacts on fuel use.
- Financial support from government will be required to assist fishers with the capital cost of switching to lower carbon propulsion systems.
- A model should be developed that fishers or suppliers can use to find the best combination of engine, generator and battery to design a hybrid system for a particular vessel (either new or retrofitted).
- Further research should be conducted to monitor the engine use of a variety of static gear boats over several days or weeks, in order to gather more robust data on the potential for electric or hybrid drives.
- These data could be used to design a few exemplar vessels to demonstrate to fishers the potential for electrification. At present there is only one small Seafood Innovation Fund supported fully-electric catamaran in Brixham that is serving as a trailblazer. A select few early adopters in ports around the country could be funded to switch to a hybrid system.
- Consideration could be given to the development of partially-funded “starter packs” consisting of a very small-scale (under 6 m) boat with electric engines for new entrants interested in inshore fishing as a career.

Policy and research needs

- A study should be made of licensing rules to examine whether a licensing regime that placed less emphasis on vessel length and power – while still accomplishing licensing objectives – would result in significant fuel savings by encouraging more efficient hull forms.
- Knowledge of electrical propulsion systems (pure, hybrid and auxiliary, including battery systems) should be incorporated into the syllabus standards for marine engineering and engine maintenance courses.
- Government should fund and encourage research into the development of low carbon propulsion systems that are suitable for small scale fisheries and workboat applications. In the short term this means implementing hybrid systems for small craft, to move the concept from “innovation” to “off the shelf”. In the longer term there is a need for improved battery technologies or alternative sustainable fuels if small fishing boats are to be enabled to make their contribution to the nation’s net zero target of 2050.
- Harbour authorities should consider allowing for future electrification needs when conducting routine infrastructure works and upgrades (for example, if installing new trunking in a pier, it should be sized for larger cables).
- Efficiency is going to be key to the development of alternative propulsion systems for small scale vessels. Fishing vessel builders, regulators and designers need to anticipate this.

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Most of all, we thank all of the individual skippers and fishfolk who gave up their time to help us understand how their needs may evolve in a more sustainable world.

1 Introduction

We live in an age of environmental crisis. The recent IPCC Sixth Assessment Report[1] reminds us of the urgency of decarbonizing human activity, and the UK has a legislative target to reach "net zero" greenhouse gas emissions by 2050 and in Scotland by 2045. Awareness is growing that one area in which individuals can have a significant effect on their own carbon footprints is in their diet, with food accounting for 28% of household carbon footprints globally[2]. Concern has been growing, in particular, at the high carbon emissions cost of catches landed by some vessels in the small-scale fishing fleet. For example, catching and landing 1 kg of lobster may involve the production of up to 10 kg of CO_2 equivalent[3] by the time fuel use, transport and bait have been taken into account. This is higher than all major land-based foods except for beef[4], and it compares unfavourably with larger and more efficient offshore fisheries. Indeed, the European average across all fisheries is thought to be only 1.7 kg CO_2-eq per kilogram of landed fish and invertebrates[5], which is lower than most land-based animal foods. The sea, and the fishers who depend upon it have a role to play in continuing to provide healthy and nutritious food and enhancing UK food security. Reducing their carbon consumption is a contribution that the fishing community can make towards combatting climate change and reducing the impact that we are already seeing on marine ecosystems.

There is, then, an imperative for small-boat fisheries, which are of such socio-economic importance, to reduce their carbon footprint, both for the sake of global climate and to improve their acceptability as food suppliers with an increasingly carbon-conscious public.

A note on the definition of "small-scale fishing vessel" by Jerry Percy
There is no finite definition of what 'small scale' means in relation to fishing operations, either nationally or globally. And whilst it is difficult to define, you tend to know it when you see it. In the UK, DEFRA's predecessors introduced a 10 metres and under measurement, primarily on the basis that these smaller vessels had little impact on quota stocks and were therefore left outside of the reporting structure at the time. This divider is no longer relevant in the light of improvements in the efficiency of catching that have little reference to size in many ways and more to do with the equipment aboard. In the EU, the CFP defines smaller scale as vessels of 12 metres and under, not using towed gear but again, it is a somewhat arbitrary figure and varies widely by member state. So "small scale" is always going to be within an envelope of length, although for the reasons given, length is no real descriptor on its own. "Owner on board and landing fresh fish daily" is a definition that better reflects the actual operation of a small scale vessel.

The major source of greenhouse gas emissions in many capture fisheries is fuel[6]. This is also one of the most significant contributors to operational costs, with rising fuel prices placing increasing financial pressure on fishers – and so measures to reduce fuel use and to reduce emissions may align well and be attractive business propositions, so long as sufficient capital is available and the payback times in initial investment are acceptable.

Small scale and beach-launched fleets are the poster child of those supporting sustainable fisheries. However, we have seen the demise of local beach-launched fleets in places such as Filey and Cove over the last 20 years. These vessels are naturally effort-limited by weather restricting the ability to launch

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[1] https://www.ipcc.ch/assessment-report/ar6/

[2] https://www.carbonbrief.org/in-depth-qa-the-ipccs-sixth-assessment-on-how-to-tackle-climate-change

[3] CO_2 equivalent, or CO_2-eq, is a measurement which includes all greenhouse gases (GHGs), expressed in terms of the equivalent mass of CO_2 which would produce the same effect. In practice, for fisheries, nearly all of the total is CO_2.

[4] https://interactive.carbonbrief.org/what-is-the-climate-impact-of-eating-meat-and-dairy/

[5] Parker RWR, Blanchard JL, Gardner C, et al (2018) Fuel use and greenhouse gas emissions of world fisheries. Nat Clim Chang 8:333–337. https://doi.org/10.1038/s41558-018-0117-x

[6] Gephart, et al (2021) Environmental performance of blue foods. Nature 597:360–365.

and constrained to a locality by speed and capacity: their low power and small size generally restricts them to local fishing (~20 miles radius from port) and short trips, as well as the use of static gear (pots, hooks and nets) that cause minimal physical disturbance to the seabed.

There have been significant increases in effort from the small-scale static fleet in recent years and the evolution of “fast workers” that will service several hundred pots/creels per day. Since the 1960s there has been a steady increase in engine power in under 10 m new-build vessels from around 50 kW to 120 kW (Figure 1a).

By shifting to a renewable source of fuel such as renewable electricity or green hydrogen, there is an opportunity to significantly reduce the carbon cost of the small-scale fishing sector. This has the potential to support traditional small-port, small-vessel, inshore fisheries in economically vulnerable areas. The lower cost of running electric or hybrid systems in the small-scale sector could support the potential for low impact, low intensity fishing as a way of life. Many supporters of, and people in, the industry are fully behind the transition of fishing to net zero and reductions of environmental impacts such as fuel and noise pollution. It is unlikely that all fishers will be able to jump directly from diesel/petrol to electric or hydrogen propulsion. However, there is likely to be a range of options from retro-fitting older boats with electric engines or hybrid systems to having a low power ancillary electric motor for low speed operations. It is likely that there are a range of solutions specific to budget, boat size, fishing method, location and power requirements.

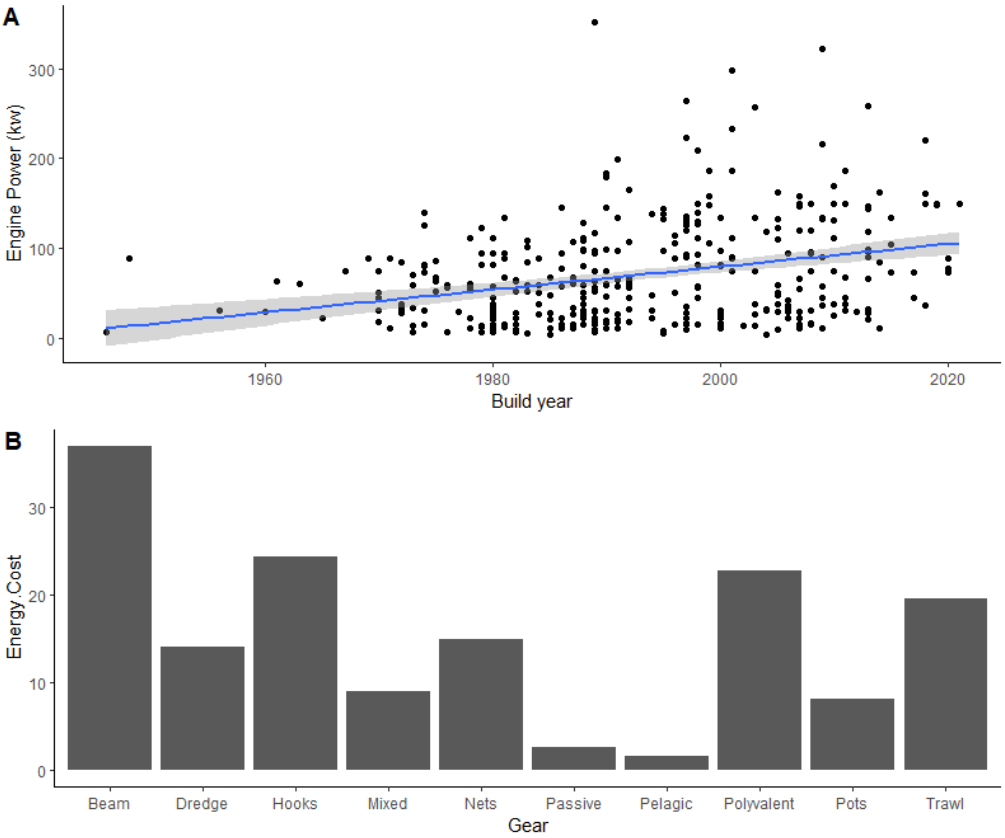

Figure 1: (a) Increase in engine power over time in the <10 m fishing sector[7]; (b) Energy cost ratio for different fisheries - i.e. the ratio of the energy required to catch seafood to the calorie content of the food[3].

For this report, we aimed to understand the needs of small boat fisheries based on interviews with skippers in three different locations – the Yorkshire coast, Devon, and Orkney – and to look at the

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[7] https://www.gov.uk/government/statistical-data-sets/vessel-lists-10-metres-and-under

options for full or partial decarbonization, both now and in the future. Section 2 gives an overview of the three fleets that we studied. Section 3 touches briefly on the context in the wider picture of national decarbonisation, and Section 4 gives a summary of the current state of relevant technologies. Section 5 relates what we learned from speaking to fishers, and in Sections 6 to 8 we describe what we think is possible now, and what will be possible in the future. Section 9 suggests further research required. Finally, Section 10 summarises our recommendations.

1.1 The 2022 energy crisis

In early 2022, for a variety of reasons including the global economic recovery from the COVID-19 pandemic and the Russian invasion of Ukraine, energy prices have risen at a rate unprecedented in recent decades. As of March 2022, the monthly averaged price of red diesel in the UK was 96 p/l[8], with reports of the spot price in Bridlington hitting 130 p/l — and it may rise further. Electricity prices have also risen. Most of this report was prepared before these events, and interviews with skippers were conducted when the price of diesel was around 65p/l. As such, we have not studied the most recent increases in detail. It is safe to assume that recent increases in the cost of energy will make improvements in efficiency even more worthwhile.

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[8] https://ahdb.org.uk/fuel-prices

2 Characterisation of case study fleets and their landings

2.1 Overview

The fishing fleet assemblage in any port is a function of its history, local ecology, fisheries regulation, and infrastructure. We chose three regions of the UK where fishing is an important part of the local economy and identity, but that have quite different backgrounds. The fleet assemblages reflect these differences: for example, Devon has a diverse mix of vessels targeting crustaceans and whitefish while Orkney and Yorkshire lean heavily towards potting (Table 1).

Table 1: Under 10 m fleet assemblages (registered fishing boats) in the regions that were used for fieldwork. Data sourced from the MMO.

	Number of vessels		
Vessel type	Devon	Orkney	Yorkshire
Angler	24	2	0
Diver (scallops)	3	5	0
Dredger	10	0	5
Netter	55	1	3
Potter / creel boat	33	37	84
Trawler	46	3	0
Total	**171**	**48**	**92**

2.2 Yorkshire

The fishing fleet along the Yorkshire coast (Staithes to Withernsea) has traditionally consisted of a mix of beach-launched vessels (Filey, Flamborough, Hornsea and Withernsea) and larger harbour-based boats (Staithes, Whitby, Scarborough and Bridlington), with about 60% falling into the “Under 10 m” category. The larger ports act as collection points for the catches from smaller towns with beach launched fleets along the Yorkshire coast. Bridlington is regarded as the “Lobster Capital of Europe” with around £10 million worth of landings of crab and lobster per year.

As is probably the case with many smaller fishing ports, until thirty years ago, the fishing fleet was dominated by boats targeting whitefish, with some smaller boats catching lobsters and crabs with static gear. Historically there was an element of seasonality, with fish being preferred in winter and crustaceans in summer. Around the mid-late 1990’s, especially in Bridlington, there was a rapid shift from quota species to non-quota lobsters and crabs (Figure 2). It is likely that this was due to a shortage of quota for inshore fishing vessels, legislative changes, decommissioning schemes, and stock depletion, but it may also have been due to the opening up of lucrative European (and for a short while later Chinese markets) for crab and lobster and the development of easy border crossing, storage and processing infrastructure and transportation links to Europe. The result was a rapid expansion of the fleet and significant investment in new vessels. Today, large vivier lorries routinely visit Scarborough and Bridlington to collect full loads of live lobster to the EU where live crustaceans attract premium prices.

Most of the Yorkshire ports now targets crustaceans year-round, with a quiet period after Christmas when the weather can be poor and prices low. Catch diversity is a little higher in Scarborough, where scallops are the third most abundant species landed (see the Appendix for details of landings). Scallops are processed elsewhere rather than in Scarborough itself. Crabs may be sent to the EU, across the UK or processed locally (e.g. Venture Seafoods[9]).

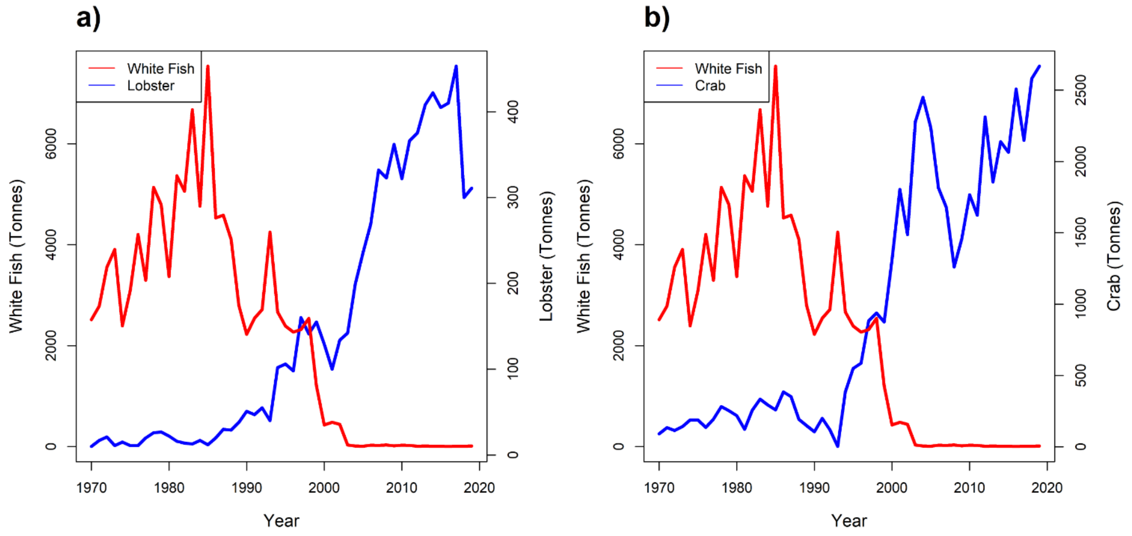

Figure 2: The shift in landings in Bridlington from whitefish to crustaceans between 1970 and 2020. Figures kindly provided by Dr Mike Roach of the Holderness Fishing Industry Group.

Until around 2000 there were daily fish auctions in Bridlington, Whitby and Scarborough. Lobster and crab have always been landed directly to landing companies for a price governed by supply and demand that changes with the season, generally being low in summer and higher in winter (particularly around Christmas).

2.3 Brixham and Plymouth

Brixham and Plymouth have a diverse under 10 m fleet including trawlers, dredgers, potters and netters targeting a diverse range of species. The under 10 m fleet is a little overshadowed in Brixham by the significant number of over 10 m fleet of beam trawlers and scallop dredgers that have come to dominate the port in recent years – 32 over 20m vessels and around a dozen under 10 m, some very small. The fishing fleet in Plymouth has its own pontoon area close to the fish quay. This port has seen an increase in scallop landings since 2014 and decrease in crabs and sardines. There are a larger proportion of whitefish vessels in this region than in the other two visited with over half the fleet comprising trawlers and netters. There is perhaps more flexibility in the fleet here than elsewhere as the mobile gear boats often have the facility to use beam trawls or dredges while the netters may also use pots on occasion. There are significant numbers of angling vessels in this region, some working professionally and targeting bass.

It is likely that the fishing industry in this region benefits to some degree from the influx of affluent tourists in the summer who will seek out locally caught seafood.

2.4 Orkney

Demersal landings (mainly haddock) made a small but valuable contribution to Orkney fisheries prior to the early 2000s, and are again increasing slightly, but shellfish typically represent in excess of 98% of total landed quantities over recent years. Creel fishing predominates, for which the most valuable target species are brown crab (high volume and value) and European lobster (low volume, high value). Velvet crab landings are also significant, serving European export markets, and green crab are also targeted depending on other species' availability.

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[9] https://www.ventureseafoods.co.uk/

King scallop are a further key species. Previously there have been 2-3 small dredge vessels fishing out of Orkney, but the current scallop fishery is predominantly by hand-diving. Other fishing activities include potting for whelk and a summer long-line fishery for mackerel.

Almost three quarters of the fleet comprises under 10m vessels, and most of the larger vessels are in the 10-12m category. Together these vessels characterise the inshore fleet. Significant landings are also taken by offshore crabbers targeting brown crab in waters to the west of Orkney. Key ports for shellfish landings are Stromness, Kirkwall and Tingwall on the Orkney mainland, and Pierowall in Westray. Creel fishing takes place throughout the island group, however, and the ports in the outer islands are all important to the fishery, as are St Margaret's Hope and Burray[10].

Lobster, velvet crabs and scallops are largely sold live. There are a number of UK-based vivier trucks which visit Orkney on a weekly basis to transport shellfish to continental markets. Most velvet crabs and around 60% of lobsters leave by this route, while the rest of the lobster catch is air-freighted to markets in Scandinavia and Europe. Dived scallops are mainly sold live to the restaurant trade in the UK, with the remainder sold for processing. Around 80% of the brown crab caught and landed by local vessels is processed at co-operative factories in Stromness and Westray. The rest is shipped live by vivier trucks.

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[10] https://rifg.scot/storage/region/Orkney-Sustainable-Fisheries-Ltd.-Management-Plan-2017-2.pdf

3 Policy background

3.1 National electrification

The UK has a target, set in legislation, to reach net zero greenhouse gas emissions by 2050. This will require the phasing out of nearly all fossil fuels and their replacement either with electric alternatives, or with alternative fuels that can be produced using renewable energy and do not cause net CO_2 emissions. Candidates for the latter approach include hydrogen, methanol, ammonia, and others, which all have individual advantages and disadvantages for any given application. Full evaluation of these options is beyond the scope of this report, save to note that none are available yet (but see a brief comment on hydrogen in Section 4.4).

The current policy drivers in the UK are encouraging electrification of those things that can sensibly be electrified: cars, home heating, etc. This generally results in an immediate drop in emissions, and also means that emissions associated with that energy consumer will continue to fall as UK electricity generation decarbonises further. This general trend towards electrification is likely to require upgrades of electricity transmission and distribution networks across the country during the next thirty years.

Vehicles that need very high power or a very long endurance present a greater challenge for electrification. This is because of the relatively low energy density of batteries compared to liquid fuels – i.e. they carry less energy per m^3 or per kg, and so less “fuel capacity” can be installed in a given size or weight constraint. With current battery technology we are unlikely to see electric HGVs, airliners, or deep-sea shipping. Inshore fishing vessels are harder to be certain about, as there is a wide range of power and endurance requirements; see Section 6.1.

3.2 Increasing cost of fuel and diesel duty rates for fishers

In the period from 2010 to 2021, the annual average price of red/blue diesel has risen by 41.4% from 46.4 p/l to 65.6 p/l [11]. Over the same period the price of diesel at the pump for domestic consumers rose from of approx. 110 to 130 p/l [12]. For fishers with large engines and/or who steam for long distances, fuel is one of the largest costs, and so this has represented a squeeze on finances. While it is impossible to predict fuel prices into the future, it seems likely that the price will climb higher — as, indeed, it has already done in 2022.

Following the 2020 Budget, the UK government consulted on whether current users of red diesel should be allowed to keep this entitlement from 2022. A decision was made that the fishing industry could continue with red diesel[13], although shoreside port equipment such as forklifts must now pay fuel duty at the full rate. This discussion created concern in the industry, and if the entitlement to red diesel were to be removed in the future, then the business case for more efficient propulsion would become much stronger – indeed, it might be necessary for many fishing businesses to remain viable. Many under 10 m fishing businesses using towed gear (trawls, dredges) would go out of business overnight if they were required to use white diesel.

Whether pushed by a pricing mechanism or by more direct regulation, if the UK is to hit its 2050 target for decarbonisation it will be necessary for fishing fleet to stop or substantially reduce its use of diesel. It is wise, then, to anticipate the challenges.

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[11] https://ahdb.org.uk/fuel-prices

[12] https://www.racfoundation.org/data/uk-pump-prices-over-time

[13] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/966132/Summary_of_responses_to_the_red_diesel_consultation.pdf

4 Technology overview

In this section we consider two approaches to more sustainable propulsion: pure electric drives, or diesel-electric hybrid systems which use a combination of a diesel generator, a battery, and at least one electric motor/generator. If the drive is purely electric, there is an obvious reduction of the carbon footprint. But even for hybrid drives there can be a significant fuel saving because the diesel component is never required to idle or to run flat out: instead, it is either off or running at its most efficient speed (rpm).

We will look here only at that which is possible now or in the immediate future; for possible future developments, see Section 8.

For both pure electric and hybrid options, the introduction of electric propulsion offers the following advantages:

- Smoother and more accurate control of the vessel due to precise speed control and swift thrust reversal.
- Reduced operation noise and vibration.
- Straightforward electrification of auxiliary onboard equipment.

Pure electric systems also offer:

- Simplification of the drivetrain, thanks to wide implementation of direct-drive permanent-magnet synchronous motors and power electronic controllers (i.e. gear boxes can be are not required in many cases). Most diesels have a 2:1 reduction
- Reduced maintenance and repair cost, due to a reduction in the number of moving parts and the lower-maintenance nature of electrical systems compared to internal combustion engines

4.1 Summary of battery technology

In most modern technology, use of lead-acid batteries has been superseded by Lithium-ion batteries because of their superior performance, longevity, and reduced size/weight. A Li-ion battery is about a quarter of the weight and size of a lead battery for the same performance.

Table 2: Comparison of lead acid and Li-ion battery performance[14]*. DoD = Depth of discharge.*

Characteristic	Lead Acid	Lithium-ion
Power density	40 Watts per kg	125 Watts per kg
Cycle Life	200 @ 100% DoD	2800 @ 100% DoD
Useable energy	50%	80%
Temperature sensitivity	Degrades at > 25°C	Degrades at > 45°C
Voltage per cell	2 V	3.2 V
Maintenance requirements	Every 3 months	Annual

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[14] https://datacenterfrontier.com/energy-storage-lead-acid-lithium-ion/

The leading battery technology for electric boat propulsion is therefore Lithium-ion, similar to all other modern electric drive designs such as those used in electric cars. Their typical key characteristics:

Specific energy (gravimetric energy density)	100 – 265 W·h/kg
Specific power (gravimetric power density)	~250 – ~340 W/kg

Lithium marine batteries cost £100-1,000 per kWh of capacity. This cost is a combination of the cost of “raw” battery cells and that of a high-IP-rating enclosure with embedded battery management electronics. The “raw” cell cost is currently slightly less than £100 per kWh, having dropped by a factor of five over the last decade.

There are many types of batteries based on Li-ion conductivity which differ in the material matrices used in their design. Three main types employed for electric power drives are:

- Lithium Nickel Manganese Cobalt Oxide, $LiNi_xMn_yCo_zO_2$ (NMC): the highest energy and power densities, but relatively expensive and considered the least safe among the three tyles.
- Lithium Titanate, Li_2TO_3 / $Li_4Ti_5O_{12}$ (LTO): shortest charging time, and most charge/discharge cycles (i.e. longest lifetime). Seen as the safest Li-ion technology, but suffers from relatively low energy density.
- Lithium-Iron-Phosphate, $LiFePO_4$ (LFP): moderate energy and power density, with low cost.

Fire safety concerns that were raised by earlier generations of Li-ion batteries have largely been answered in newer generations via improvements in battery chemistry and the embedded electronic battery management systems.

Ambient temperature is an important factor strongly affecting operation of Li-ion batteries. The output performance of all types drops drastically at low temperatures (less than -5˚C) due to slowdown of the chemical reactions involved. However, this effect is reversible and the power is normally restored once a battery has been warmed up. For charging, the lower temperature limit is stricter and more than 5-10˚C is normally required. These seemingly significant limitations can be often reduced by the heat generated inside the batteries during charging or discharging process, if proper control from a battery management system is provided. The upper temperature limit is +35-45˚C for all regimes of operation; higher temperatures result in non-reversible degradation and hence a reduction in lifetime.

These temperature constraints have been solved in electric cars by integrating air or (usually) liquid heat management systems within the battery packs. Forced cooling appears to be a necessary feature in all prospective ultrafast charging batteries.

4.2 Summary of electric motor technology

AC motors in combination with variable-speed power electronic drives are normally used for electric power drives. These motors are based on mature technologies and have high (more than 90%) efficiency. There are multiple designs of these motors, but they can be broadly classified into two main groups: synchronous and asynchronous, based on rotor synchronism with the frequency of AC power supply.

The **asynchronous motor** (also known as induction motor) is the most popular general industrial motor, largely due to its low cost, compact size and robust design. It is available in a wide range of powers and its energy efficiency is 90%+ in premium models. However, this type of motor is not dominant in the marine propulsion area. This is mainly because its nominal rotation speed is usually too high for direct drive applications. Hence, a gearbox between the electric motor and propeller shaft is required, which increases cost and lowers the efficiency of the drive train.

The **synchronous motor** is also characterized by high energy efficiency, exceeding that of premium induction motors by a few percent. It can be operated at low rpm and allows for precise control over the rotation speed, making it well suited for direct drive applications. Historically its main disadvantages have been a relatively high cost and large dimensions. However, the size issue has been largely eliminated in synchronous motor designs which use rare-earth permanent magnets. Currently, these motors appear to be the most popular in marine propulsion applications.

4.3 Summary of hybrid systems for marine use

The use of diesel-electric transmission is not new in larger vessels. A classic diesel-electric drive train consists of diesel-based electrical generator(s), electrical control units, electric propulsion motor(s) and power controls/converters. Typically, a number of smaller generators are used in place of a single one, so that some of them can be stopped when little power is required. Over the last hundred years, the application niche of diesel-electric propulsion has become well defined: it becomes beneficial when the ship has a significant amount of auxiliary electrical load, or when its propulsion system operates at low power for a considerable proportion of time. Examples of high auxiliary load are ships using dynamic positioning with thrusters, or cruise ships with large hotel loads. Examples of ships that run at low power for much of the time are tugs, and vessels on rivers (which operate at high power when moving upstream and at low power when moving downstream). In fishing vessels, the auxiliary electric load is typically low. Therefore, to benefit from a conversion to diesel-electric propulsion, a vessel should spend a significant proportion of its sea time at propulsion loads that are a fraction of the maximum.

At partial load any diesel engine runs with significantly reduced energy efficiency, leading to energy losses in a classic diesel system. In contrast, in a diesel-electric system, the diesel driving the generator is always operating at its maximum efficiency point, so the propulsion at all power levels becomes equally efficient (Figure 3a). However, there are energy losses due to the extra energy conversion steps (mechanical->electrical->mechanical) in diesel-electric propulsion, which reduces the overall efficiency of the hybrid system. If these additional losses are overcompensated by the reduced fuel consumption of gensets either running at their max efficiency spot or stopped, there is a saving in energy and fuel consumption. Hence, the operation region where diesel-electric hybrid propulsion is more efficient than the mechanical diesel propulsion is the smaller green area shown in Figure 3b.

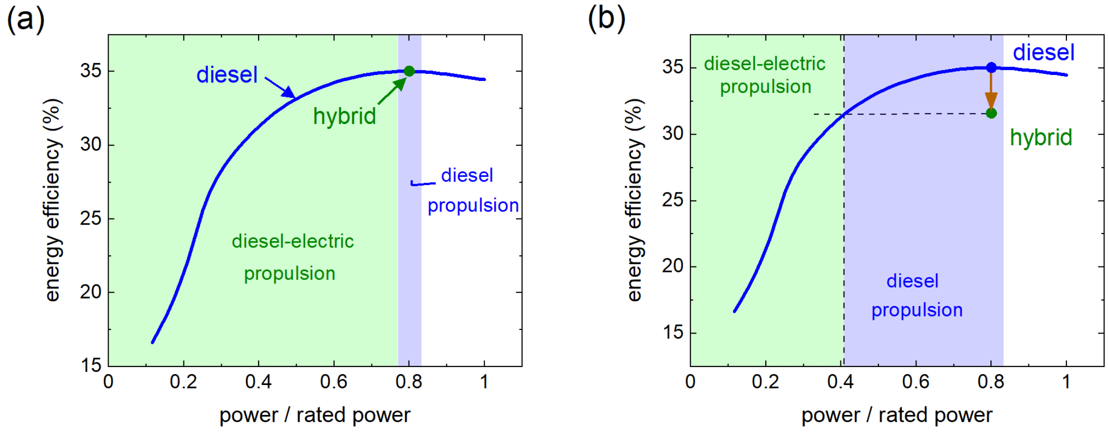

Figure 3: (a) Diesel engine energy efficiency curve, showing maximum near 80% of rated power. The genset is always operating at this maximum efficiency. If the hybrid energy conversion losses are ignored, the hybrid operation (green area) is more energy-efficient at all power levels except 80%. (b) Reduction of the hybrid power efficiency due to the energy conversion losses leads to the shift of the hybrid operation region (green area) into lower power range. At higher power, the direct diesel propulsion (blue area) becomes more efficient.

The diesel-electric concept has traditionally been realised by replacing the main diesel with several generators that can be switched on/off independently in varying numbers to cover the whole range of power needed for operation. A more suitable option for smaller boats is to replace the diesel engine with a single generator and a battery pack. In this case, the excess energy generated during low-power operation is stored in the batteries. This stored energy can be subsequently used either for pure electric propulsion, or for a power boost when full power is required. If for a particular vessel there is no requirement to operate at full power for an indefinite period, the availability of this electric boost means that the power of the generator can be reduced compared to the engine that it replaces. For examples of this cycle in a fishing context, see Section 6.2.1.

There are two main approaches to hybrid drives: parallel and series. Their layouts are illustrated in Figure 4. In the series system, the propulsion torque is provided exclusively by an electric motor, which can be powered by a genset or batteries, or a combination of both. The motor power rating should be at maximum propulsion power needed for the boat, while the power rating of genset can be reduced from that value. In a parallel system, the propeller shaft can be driven by the electric motor or the diesel engine or a combination of both. The electric motor and (depending on requirements) the diesel can both be specified at reduced power rating, because they can work together when full power is required. Since the electric motor is also used as a generator, its use as a motor can be powered only from the batteries and not from the diesel, unless a second motor/generator is included in the system.

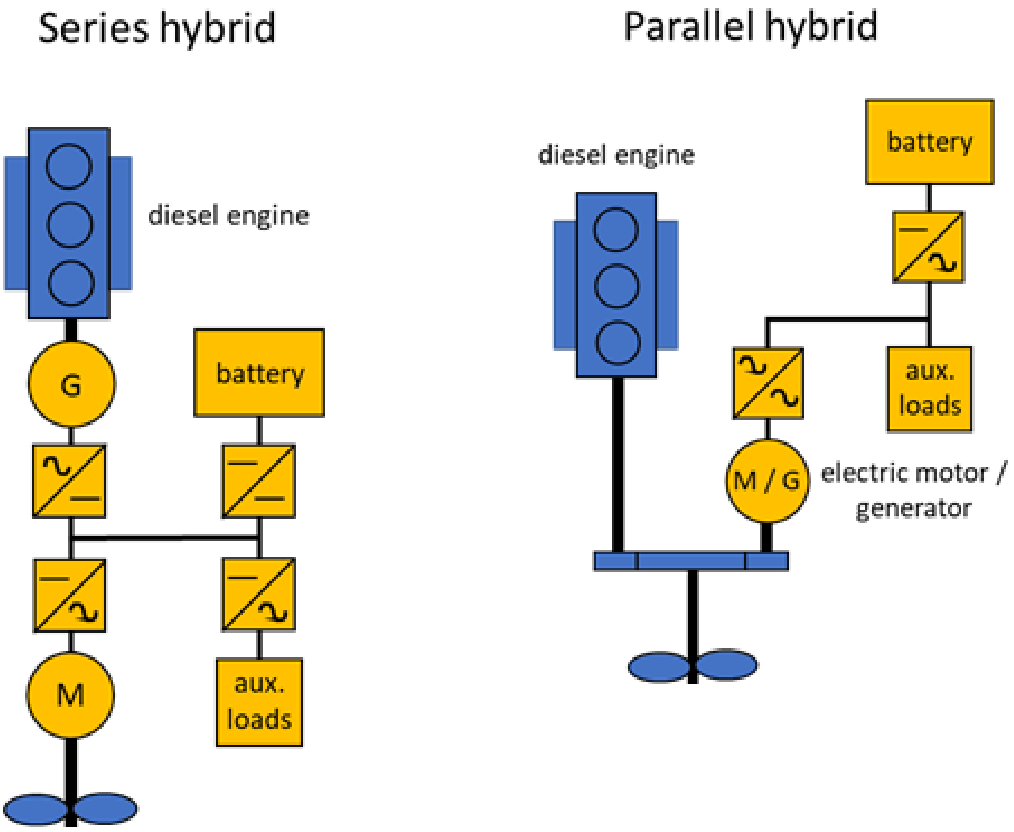

Figure 4: Schematic diagrams representing series and parallel hybrid systems. In a series model the diesel engine drives a generator (G) that provides power to charge a battery or an electric motor (M) that rotates the shaft. In the parallel hybrid system both the engine and the electric motor can turn the shaft.

A parallel system *may* have a lower capital cost, if only a single motor/generator is used, but it requires a more complex drive system. On the other hand, it benefits from increased efficiency at high power settings because the power from the diesel is not converted before reaching the propeller.

A hybrid propulsion system needs to be designed specifically for the usage patterns of a particular vessel or class of vessels. This optimisation will include the power ratings of the diesel engine and electric motor, the size of the battery, and the choice of a series or parallel arrangement.

4.3.1 Hybrid power using separate drive systems

A further option which may be preferred for some vessels is to use two entirely separate systems: a conventional diesel drive for high power, and a small electric drive system for efficiency and economy at low power. The electric system's battery might be charged by the diesel engine as an auxiliary load. The advantage to this approach is that each system, or at least the diesel, can be an off-the-shelf product, and indeed the electric drive could be retrofitted to a vessel with an existing diesel. This approach may be of particular interest to boats using outboard engines.

4.4 Hydrogen for marine use

Hydrogen is a possible alternative fuel which may be used in the future as a way to store energy. It is attractive because it can be produced by electrolysis using only electricity and water, and hence it can be entirely renewable. Hydrogen produced this way is known as "green hydrogen". When hydrogen burns, combining with oxygen in the air, the only waste product is water. Hydrogen is potentially better than other options because rather than simply burning it, it is possible to use it in a fuel cell to produce electricity – although this is currently expensive.

In the future we may see hydrogen used either as a renewable fuel to replace diesel in hybrid systems (see for example the small hydrogen internal combustion engine developed by OakTec[15]), or – with the use of fuel cells – as a way of "storing electricity" with a much higher energy density than current battery technologies. However, only limited steps have been taken towards marine use so far.

Experimental work in Orkney has focused on using excess renewable electricity which the grid cannot handle to make hydrogen, and then using this in a fuel cell on the pier to provide "cold-ironing" power for lighting and heating on ferries. This was seen as a first step as it avoids the need for Maritime and Coastguard Agency approval for installing the system on the vessels themselves. A more recent project intends to test and demonstrate various ways of using hydrogen on board an operational vessel[16].

In some circumstances, hydrogen can be injected into a conventional diesel engine to improve its efficiency – at the cost of extra equipment and needing to refuel with both diesel and hydrogen.

For the purposes of this report, we see hydrogen as a possible future fuel, especially in locations that have excess renewable energy generation – but not as something that is ready to be adopted in the immediate future.

4.5 Previous attempts at alternative propulsion for small vessels

CalMac already run hybrid-powered ferries on short sea crossings in Scotland, where the alternating duty cycle of power at sea and idling in port makes for significant fuel savings[17], and there is a battery electric car ferry in Denmark on a 12-mile route[18]. Offshore wind operator Ørsted will shortly begin trialling crew transfer vessels with hybrid drives, that are able to recharge their batteries directly from the wind farms using specialised mooring buoys[19]. However, these vessels are all at somewhat larger scales (35-60 m) than those we are interested in.

Low-carbon propulsion is less developed in under 10 metre vessels. Nevertheless, we have found several early examples of electric and hybrid propulsion in boats of sizes similar to those found in the small-scale sector. Most of them have been developed as one-off demonstrators or testbeds in the last few years, and hence should not be used as indicators of costs. Further details of previous attempts at developing vessels with alternative propulsion systems are given in Appendix B.

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[15] https://www.oaktec.net/technologies/

[16] https://www.emec.org.uk/press-release-maritime-decarbonisation-to-cruise-forward-in-orkney/

[17] https://www.cmassets.co.uk/project/hybrid-ferries-project/

[18] https://www.bbc.co.uk/news/business-50233206

[19] https://orsted.co.uk/media/newsroom/news/2021/01/ctvs-are-innovatively-transformed-in-preparation-for-hornsea-two-construction

5 Interviews with fishers, harbour masters, and engineers

5.1 Interview approach

Fishers were contacted directly on the quay, via local fisheries associations and personal connections, and interviews were conducted on the quayside or on board vessels. It was often necessary to travel some distance to meet interested fishers. Several fishers that we approached on the quayside declined to be interviewed. We also interviewed harbour masters in Yorkshire and Plymouth. Interviews lasted between 45 and 90 minutes and were free flowing and wide ranging to make the maximum use of the significant expertise of the fishers that we met.

Figure 5 Team members discussing potential for fleet electrification with fishers on the quayside from Brixham and Plymouth

Table 3: Skippers of small scale fishing vessels interviewed at each location

Gear	Devon	Orkney	Yorkshire
Angler	1	0	0
Diver	2	2	0
Dredger	2	0	0
Potter	2	8	10
Trawler	3	0	0
Total	**10**	**10**	**10**

Although discussions were broad-ranging, we were specifically interested in these key questions:

- What do you fish for and how?
- How powerful is your engine?
- What is your weekly fuel use?
- How far / for how long do you travel to get to your gear/grounds?
- How many hours a day do you fish?
- What is your daily pattern of work and engine use when at sea?
- How do you feel about the potential for electrification?
- How much would it cost you to install a new engine?

In addition to 1:1 interviews with skippers, we spent time surveying harbours in each area identifying what species each of the boats we encountered were likely to be targeting and the fishing methods in use (Table 1).

Generally, fishers were receptive to the idea that in the future, where possible, propulsion systems need to move away from purely fossil fuel options. However, this move will need to fit within the financial constraints of fishing businesses. Outcomes of conversations with fishers around the questions asked are summarised in the sections below.

5.2 Characterisation of how boats are used

Boats use their engines differently depending on what fishing gear they are using. Boats using static gear will leave port and head for their grounds to spend the rest of their time moving short distances between strings of pots or nets. The number of pots that can be hauled in a string is limited by available deck space. The time taken to reach their gear is rarely more than 2 hours, although some will travel further to access crabs offshore. Most potters transit to their fishing grounds at around 70-80% of full power in order to reduce fuel costs and avoid undue wear and tear on their propulsion system. The number of strings of pots (creels) worked in a single day can vary between 10 and 30 depending on the number of pots on each string, boat size and creel size. Each string of pots or set of nets can take around 15-20 minutes to process. Some fishers maximise their efficiency by setting fleets of pots very close together so that they can easily work their way along their gear allowing the boat to be pulled along by the hauler.

Boats using mobile gear (trawls and dredges) may travel further afield (e.g. from Brixham to Liverpool bay for scallops). In the past fishermen were driven by the mantra “If you don’t go you won’t know” and would steam for significant distances, but the price of fuel is impacting on their fishing strategies, with skippers choosing to fish closer to home. In these boats there is little variation in the required engine power used during a fishing cycle, especially for boats using scallop dredges or beam trawls. The engine will be running at full speed or just below it whether transiting to/from their fishing grounds or fishing their gear. For boats using otter trawls then some efficiencies can be made by using the prevailing tide while fishing.

5.2.1 Reliability as a safety concern

When at sea in a motor vessel, loss of power can be a threat to life. Interviewed fishers explained this has a number of implications of relevance to this report:

- Mariners, including fishers, will never turn off their engines at sea unless absolutely necessary (e.g. for vital and urgent repairs). This may reduce confidence in hybrid power systems which do not keep a minimum of one diesel engine running continuously – although this may be mitigated if there is a substantial battery reserve (enough to get home).
- Many fishers favour older designs of diesel engine over newer types which are more efficient, because of a perception of greater reliability and ease of maintenance. Typical exemplars of the older type are engines built by Gardner, which have not been produced new since the 1990s but are still in widespread use[20]. They are larger and run at lower speeds than more modern designs, which is seen as giving them a longer lifetime. Several fishers suggested that they would rather recondition and rebuild an old Gardner engine than buy a new diesel.
- There is a perception among some fishers that electrical components in the drivetrain – whether these be an engine management unit on a modern diesel, or a complete electric propulsion system – are inherently unreliable and when they malfunction cannot be fixed with basic tools, and hence undesirable for the reasons above. Other fishers told us that there was a period in which this was true, but that it is no longer the case. We are unable to comment on this objectively without a reliability survey.

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[20] https://gardnermarine.com/

- Reliability is less of a safety concern for boats with two engines, although an unreliable engine is still a business risk.

5.3 Need for training and development

In discussions with fishers in the three locations it became clear that there is a shortage of qualified marine engineers and many of those that are active are approaching retirement age. There is a perception among some under 10 m skippers that marine engineers favour working on larger vessels. There is a need to develop the workforce and enhance their knowledge of alternative propulsion systems. The syllabus and requirements for training engineering officers (Fisheries) provided by the Marine Safety Agency were last revised in 1995, and hence assume diesel/petrol propulsion[21].

Several fishers mentioned the difficulties that new entrants face in progressing from working as crewmen to the stage where they can purchase their own vessel. This is one of the causes of an aging population of fishers, which will present future challenges to the industry. One potential opportunity that was suggested to us is the concept of “starter packs” of a small (6 m) boat with pure electric engines for new entrants to the industry, assisted by grant funding. The low kW power of electric pure vessels could help keep costs down for licencing (currently £350 per kW) or a separate licencing scheme could be tailored to a specific mew entrants scheme. This could be a catalyst for the development of a fleet where skippers are comfortable with and knowledgeable about electrical propulsion systems.

5.4 Analysis of reported engine power and fuel use

Skippers’ responses about the types of fishing activity undertaken were combined with data from the MMO on the installed engine power of their vessels for the analysis shown in Figure 6. Median power for mobile gear vessels is 112 - 132 kW (depending on activity type), which translates to 6.5 – 15.0 kW per meter LOA (length overall). For boats using static gear these figures are markedly lower, at 38 – 64kW and 4.0 – 7.3 kW/m LOA.

Vessels using mobile fishing gear such as trawls and dredges need powerful engines to pull the gear through the water, while static gear boats (using pots and nets) only need enough power to cruise to and from their fishing gear. Some modern potters have invested in larger engines to allow them to travel faster and work more gear in a day. These are commonly known as “fast workers”, and they can range from small beach-launched boats to larger harbour-based vessels with tri-hull designs.

Boats with static gear may use a significant amount of auxiliary power for their haulers while on site. Most boats use units with capacity up to 1.5 tonnes. We were informed by a fisher that this can require a hydraulic power unit with a 28 kW demand at full load. In most cases this is powered by a clutch onto a main engine, but in principle an electrically-powered hydraulic unit could be used.

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[21] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/303059/MSA_Exam_CoC_Fishing_Eng.pdf

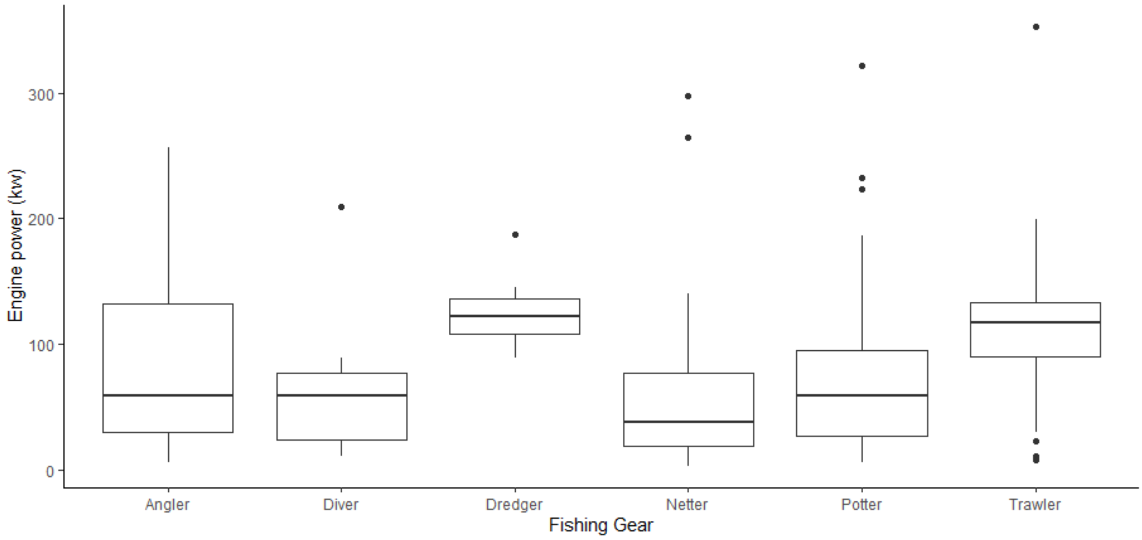

Figure 6: Variation in engine power by gear type on inshore fishing vessels of less than 10 m. Engine power from MMO data, vessel type by direct observation, conversations with skippers, internet searches and from marinetraffic.com where available. The thick horizontal line represents the median value, the box the 25 and 75% quartiles, the vertical lines the 95% range and the dots any values outside the 95% range.

Hull shape is also linked to engine power, with single hull vessels generally being less powerful than catamarans or trihull designs of the same length (Figure 7). We cannot necessarily conclude that the power requirement is determined by the hull form, however: this correlation may simply reflect the fact that the multihull vessels tend to be newer and that engine power has increased over time (Figure 1a).

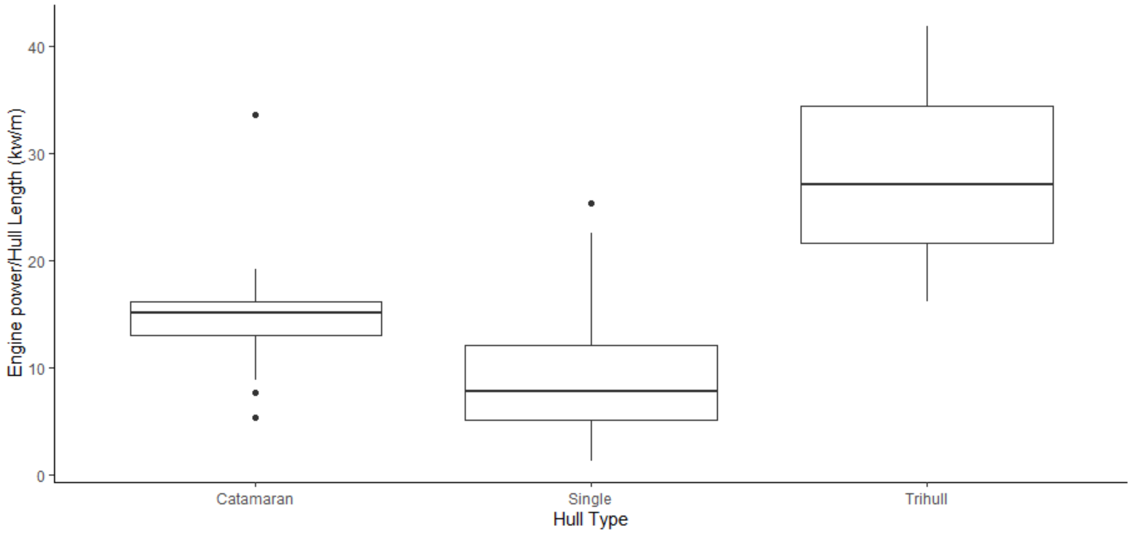

Figure 7: Engine power per unit length (kW/m LOA) by hull type of inshore fishing vessels using pots. The thick horizontal line represents the median value, the box the 25 and 75% quartiles, the vertical lines the 95% range and the dots any values outside the 95% range.

In the same way that boats with different types of gear show clear differences in engine power, there are significant differences in how much fuel they use (Figure 8). This is a function of both the differences in engine size, and the gear-specific ways in which fishers operate (see section 5.2). Vessels working mobile gear (trawls and dredges; medians are 683 and 2400 litres per week respectively) use significantly more fuel than those deploying static gear or divers (223 and 400 litres per week respectively).

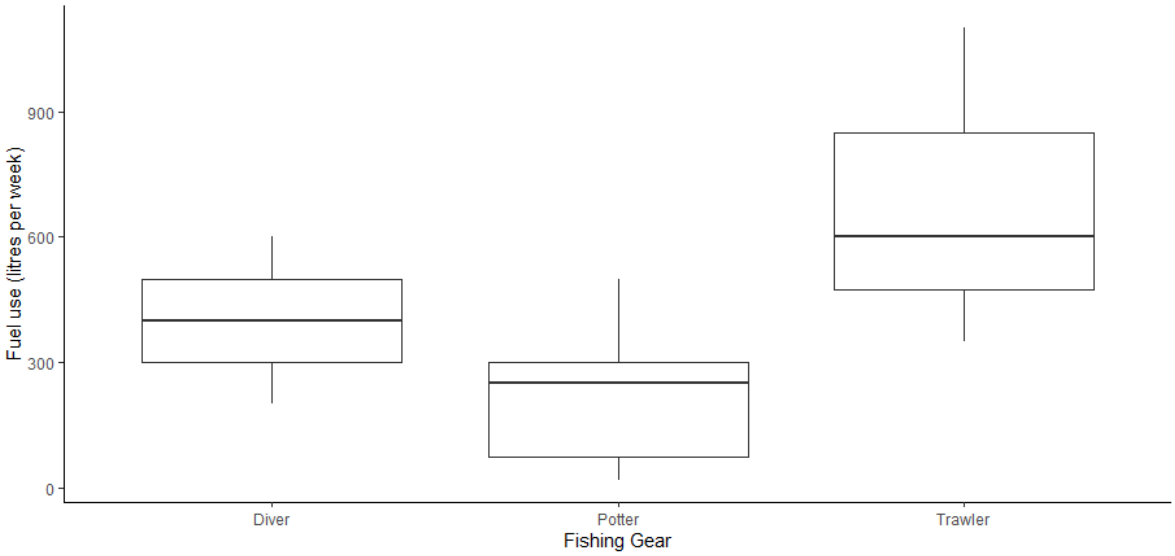

Figure 8: Fuel use by fishing vessels using different fishing gears. Data are estimates provided by skippers. The thick horizontal line represents the median value, the box the 25 and 75% quartiles, the vertical lines the 95% range and the dots any values outside the 95% range. Boats using mobile gear were combined in the Trawler category.

5.5 Issues facing harbours and ports

For harbours, potential changes to vessel propulsion leads to questions as to the necessary infrastructure. Pure electric propulsion will require recharging facilities in ports, which raises a range of issues including,

- Making safe electrical connections to vessels
- The need for boats to pay for electricity and thus a need for metering, whether at shared or designated berths. In most locations because power demand when alongside is minimal it is currently included at a flat rate as part of berthing fees.
- Electrical supply to ports, both within the ports themselves and in terms of grid infrastructure upstream

Most of the harbours that we visited are considering installing floating pontoons for their fishing boats, largely on grounds of safety (perhaps reflecting the increasing average age of small-boat skippers). In Whitby, Scarborough, Kirkwall and Brixham, the marinas already host a mix of recreational and fishing vessels. Moving fishing boats from quays to pontoons would make safe electrical connections easier, but other engineering solutions are probably feasible too. Having easily accessible electrical connections on the quayside could allow fishers to reduce fuel use by hooking up and switching engines off as soon as they come alongside.

In locations where boats are moored offshore, there is potential to hook them up to buoys that provide power. Jebb Smith Ltd have been developing the “oasis marine power buoy system”[22], generally for larger vessels but there is potential for the development of a smaller version that might look something like their (unpowered) Mara Buoy (Figure 9).

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[22] https://oasismarinepower.com/

Figure 9: The Mara buoy developed by Jebb Smith Ltd.[21]

For most rural harbours it is unlikely that port authorities have planned for significant increases in electricity demand. For example, Bridlington harbour commissioners recently upgraded their electricity capacity, at significant cost, to increase capacity by about 10% — but this is much less than would be required for full electrification. Such works have a significant lead time, and if fishing fleets electrify in the future it will take time and investment for harbours to respond.

Grid capacity outwith the harbour gates is also of potential concern, although this should be seen in the context of the general electrification of heat and transport across the country (see Section 3.1) and hence as part of a general need for grid reinforcement.

If boats adopt alternative, renewable, fuels instead of electrifying, then this may also have infrastructure implications for harbours – although the principle of a shared fuelling station is unlikely to change greatly from the status quo.

6 Findings: What's possible now

6.1 Pure electrical propulsion using Lithium-ion batteries

The limiting factor for pure electric propulsion, with current technology, is the weight (and potentially the cost) of batteries, which dictates the time for which the necessary power can be delivered – or to put it another way, the amount of "fuel" that can be carried.

As such, pure electric power is currently only suitable for boats using static gear and travelling short distances from harbour to their fishing grounds. This is likely to indicate smaller vessels, as per the Dart Deputy in Brixham (see Section 6.1.2), because the larger sub-10m boats tend to make longer trips *and* require more power.

The need to charge a boat overnight using the existing power supplies available in ports places an additional limit to the size of battery that can realistically be used. The highest capacity supply commonly available is likely to be approx. 7 kW (that is, 32A 1-ph @230V), suggesting a maximum battery capacity of 84 kWh to be charged in 12 hours. Once again this points to smaller vessels, as they will need smaller batteries, and it will also place a practical limit on the number of electric boats that can be supported in any given harbour. See Section 8 for a view of how these limitations might be addressed in the future.

The best way to install heavy high-capacity batteries in some vessels is likely to be to use them in place of ballast. However, many modern GRP vessels have their ballast sealed within the resin of their keels, and hence it would be impractical to remove and replace. Additionally, while batteries are heavy, their density is lower than that of lead and so achieving the same mass of ballast would require more room. It seems likely that there will be a need to design hulls specifically to integrate batteries for electrical propulsion, and hence there is limited scope for retrofitting any but the smallest craft.

By making some significant assumptions, we can estimate the limit of what is currently feasible:

We assume that the governing limitation is the maximum weight of the battery pack that can be installed on the vessel. We assume that this is 1.5 and 3 tonnes for under 7m and under-10m boats respectively. Assuming a propulsion power requirement of 50 kW and 100 kW respectively, the full-power operation time on a full charge is limited to around 4 h in both cases (calculated using a 125 Wh/kg energy density for the battery). The actual duration for a day at sea would be longer provided that the boat is not operating at full power continuously, with the actual figure for maximum endurance depending heavily on the operation pattern of the boat.

From these calculations it seems clear that currently suitability of pure electric drive is limited to those vessels that operate with relatively low power, close to their home port.

6.1.1 Example calculation

For numerical evaluation, boats with stationary gear from the lower-power end (25-35 kW) of the distribution (Figure 6) have been selected. A typical operation pattern consisting of 2 hours of full-power steaming and 6 hours of fishing at 20% of nominal power has been applied.

A battery of 72.5 – 101.5 kWh capacity and weight of 580 – 812 kg would be required. The cost for this is estimated as £9000 – £12700 at the most optimistic £125 per kWh. If the operation pattern is expanded to 4 hours of steaming and 8 hours of fishing, the battery pack parameters are increased to 125 – 175 kWh with a weight of 1000 – 1400 kg, costing £15600 – £21900.

6.1.2 Market options

There are dozens of companies offering electric propulsion solutions for low- and medium-power vessels (under 100 kW and 1000 kW respectively, see Section 10). Most of them are new but there are several well-established marine engineering companies, such as Bellmarine[23], that are expanding their business and have recently developed electric propulsion systems. However, most of this development is for leisure craft, where some “off the shelf” packages are being offered. For small-scale professional craft, the electric propulsion market is still in its early development stage and is represented largely by individual case studies.

Hence, some cost estimations can be made based on the offerings made in the leisure sector. These are limited to the pure electric propulsion, since hybrid propulsion is virtually absent in leisure craft. Two companies are currently dominating the UK leisure boat conversion market: e-Propulsion and Torquedo, with ~2000 electric motor installations in total by 2021. We have located just few examples of the fishing boat conversions by these and other companies, and only 1-2 of these boats are used for fishing after the conversion. Thus, the cost of the conversion to electric propulsion is specific to each case.

Case study: the recent conversion of a 6.6 m fishing catamaran vessel “Dart Deputy” (intended for close-range lobster potting) by Two Brothers Ltd. of Brixham to pure electric propulsion[24]. The conversion was funded by a grant and delivered by e-Propulsion. The total cost of the solution comprised two 6 kW motors powered by a 40 kWh Li-ion battery pack was £24k, with £16k being the battery cost. The battery pack weight is 360 kg. In this case the motor and battery costs were £500 per kW and £400 per kWh respectively. It is estimated that replacing the old diesel with a new diesel would have cost £8k, so under current “leisure boat” market prices, the conversion to electric propulsion appears to be 3 times more expensive than a diesel engine replacement.

Figure 10: The "Dart Deputy", a small potter in Devon with pure electric drive (Sergey Rybchenko).

Assessing the pricing information available across the whole range of <100 kW electric propulsion motors and marine battery suppliers, the lowest-range figures are around £150 per kW for an AC motor (complete with power electronic drive and propeller) and around £125 per kWh for Li-ion battery (equipped with electronic management system). Battery pack size varies between installations, but

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[23] https://www.bellmarine.tech/en/products-page/

[24] https://fishingnews.co.uk/features/brixham-boats-trial-electric-outboards-and-eco-gear/

taking 4 hours of full-power operation per single charge as a minimum requirement for a fishing boat (equivalent to longer at lower power), the corresponding battery pack cost of motor power becomes (4 x £125) £500 per kW. Thus, the lowest total electric propulsion cost can be estimated as (£150 + £500) £650 per kW of motor power (or power on the propeller shaft). This is to be compared to the £300-400 per kW cost for a diesel/petrol engine replacement. Thus without considering the cost of set up replacing a diesel engine with an equivalent electric engine and batteries would be about twice the cost.

6.2 Hybrid diesel-electric propulsion

Hybrid diesel-electric propulsion is suitable for larger boats travelling further from the harbour, when their pattern of operation allows for benefit compared to diesel propulsion. The operation pattern of boats using static gear has been identified as suitable because it is characterized by combination of periods of full steaming and long periods of slow manoeuvring or idling. The fishing patterns/methods that involve continuous operation at full power (mobile fishing gear) will see no benefit through switching from diesel to diesel-electric propulsion.

Hybrid systems must be designed for the intended vessel, or type of vessel, and the envisaged usage pattern. This entails optimising the relative power of diesel engine(s) and electric motor(s), the capacity of the battery, the choice of a parallel or series hybrid, and so on. We believe that hybrid propulsion of one form or another could benefit most boats using static gear using currently available technology. One factor limiting adoption is likely to be the availability of capital and the subsequent payback time in reduced fuel consumption.

6.2.1 Example calculations

In this calculation we ignore energy conversion losses for simplicity; in reality performance would be slightly worse. We assume a required power of 100 kW, from the high end of the range of static gear boats. We adopt an operation profile consisting of 4 hours of full-power steaming plus 8 hours of fishing at 20% of full power. The resulting saving in fuel compared to a simple diesel arrangement is estimated at 42% — although if energy conversion losses are included this fuel saving would be somewhat less. A more accurate evaluation of fuel economy for any vessel would require a precise characterisation (fuel consumption vs power and speed) of the diesel engine and its overlap with the propeller load curve.

The exact operation scheme of the hybrid system is sensitive to the size of the battery pack selected. Figure 11 shows examples of the operation of a hybrid system through a day consisting of 2 hours of steaming, followed by 8 hours of fishing activity at 20% load (to allow for manoeuvring and hauler use), followed by a further 2 hours of steaming. The three battery capacities shown correspond to holding 5%, 10% and 20% of the energy that would be used by 12 hours at full power: in this case 60, 120 and 240 kWh respectively. For the 5% and 10% options the generator is always either at full power or off. With the 20% pack, we illustrate that the generator could be run continuously at 50% power — suggesting that a smaller generator could be used instead, although this would place a limit on how long full power would be available for. In the 5% and 10% cases the battery starts the day uncharged. In the 20% scenario the battery starts partially charged, perhaps representing a scenario where it can be topped up in port.

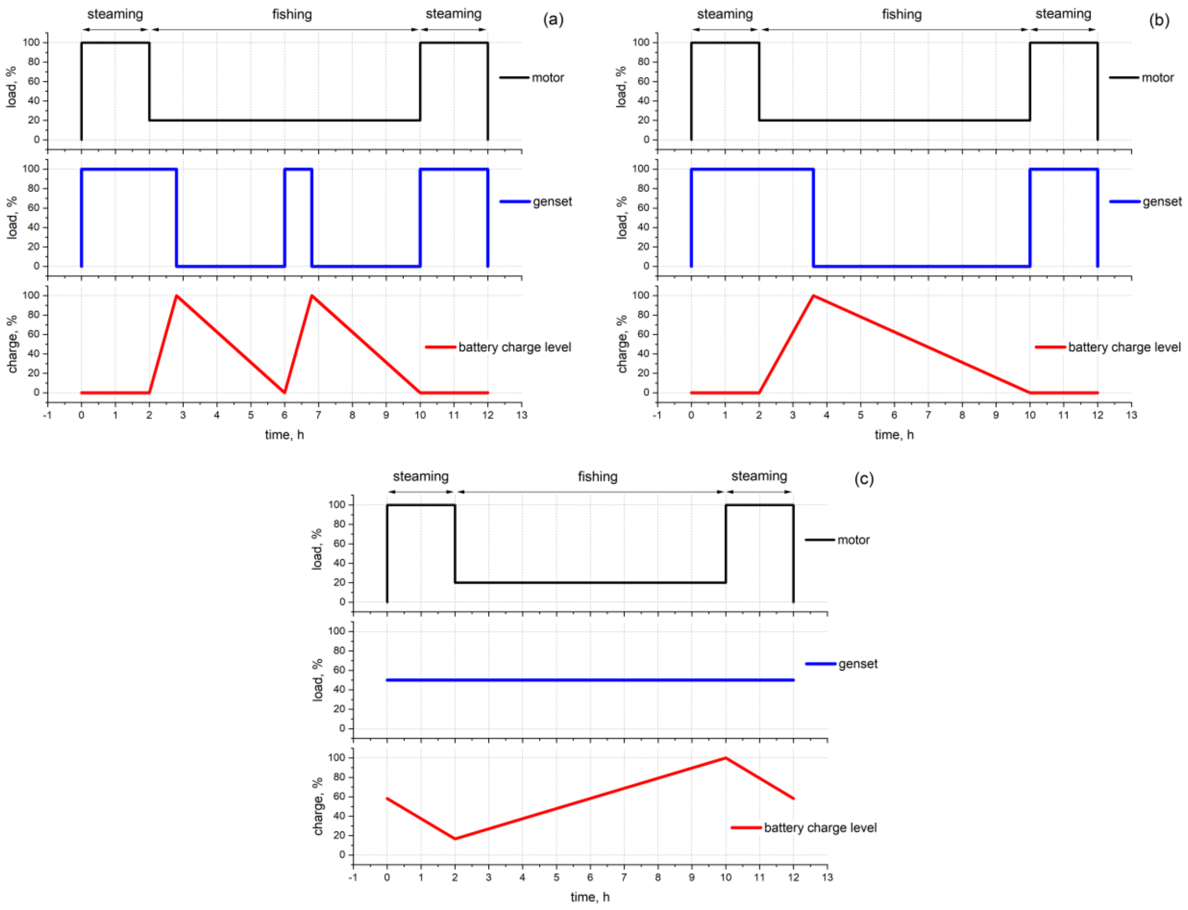

Figure 11: Operation schemes of diesel-electric hybrid scheme with battery capacities corresponding to (a) 5%, (b) 10% and (c) 20% of the energy that would be used by 12 hours at full power. With the 20% pack, we illustrate that the generator could be run continuously at 50% power. In the 5% and 10% cases the battery starts the day uncharged. In the 20% scenario the battery starts partially charged, perhaps representing a scenario where it can be topped up in port.

6.2.2 Market options

A developed market for hybrid electric propulsion systems for the under 10 m fishing fleet does not exist; traditionally this type of propulsion has been used in much larger ships. However, a number of individual pilot case studies indicate that the hybrid propulsion idea is being tested on smaller vessels (see Section 4.5). Several companies in the EU have been identified that offer a full hybrid propulsion solutions (Bellmarine-Transfluid) or components (TEMA, Hydrosta) in the power range of interest. In the UK, the Hybrid Marine company has offered diesel-electric retrofit solutions since 2008, although it appears that no projects in the fishing sector have been completed by them. Pricing information could not be obtained from these suppliers.

In the absence of pricing information for integrated systems, we have provided cost estimates for hybrid systems based on the cumulative cost of the major components (Table 4), to allow comparison. We caution the reader that the data in Table 4 does not include any of the costs of controls or system integration, and it is unlikely that an individual boat owner could buy a hybrid system off the shelf at these prices. Actual system costs for early adopters are likely to be significantly higher and would require support in the form of financial incentives.

For hybrid systems, there are two design options: in parallel and in series (see Section 4.3). For each, the size of the battery pack and the power rating for motor, generator and diesel engine can be tuned in several ways to fit a particular operation pattern. Table 4 shows costs per kW of propulsion power in a series and a parallel hybrid system, with the three sizes of battery pack shown in Figure 11. When compared to the traditional mechanical propulsion, all electrical components represent an extra cost associated with the hybrid system. This results in about twice the cost per kW in hybrid systems as compared to the mechanical ones.

Table 4: Major parts costs per kW of propulsion power for several battery sizes, expressed as the percentage of the energy that would be used by 12 hours at full power. In the 20% case the power of the diesel engine is reduced by 50%. The AC motor/generator price includes power electronic drive/converter; the battery pack price includes battery management system. The diesel engine is costed at the same level independently of whether it is used as a direct drive or as a part of a genset. These parts costs do not include controls or system integration, and the actual system costs for early adopters are likely to be significantly higher.

Cost per kW of propulsion power>	AC Generator	AC Motor	Battery	Diesel engine	**Total per kW**
Mechanical propulsion (benchmark)				£300-400	**£300-400**
Series with 5% battery storage	£150	£150	5%*12h*£125=£75	£300	**£675**
Series with 10% battery storage	£150	£150	10%*12h*£125=£150	£300	**£750**
Series with 20% battery storage	£150	£150	20%*12h*£125=£300	£300*50%=£150	**£750**
Parallel with 5% battery storage	£150	----	5%*12h*£125=£75	£300	**£525**
Parallel with 10% battery storage	£150	----	10%*12h*£125=£150	£300	**£600**
Parallel with 20% battery storage	£150	----	20%*12h*£125=£300	£300*50%=£150	**£600**

In general, the parallel hybrid is a cheaper option since (in its simplest form) it requires only one motor-generator. However, the difference becomes less important in configurations involving large battery packs.

6.3 Auxilliary electric engines

For some vessels there could be the opportunity to partially decarbonise by adding an auxiliary electric motor. Many modern static gear vessels have powerful diesel inboard or petrol outboard engines to get them to their fishing grounds quickly, but once there this power becomes redundant. A small electric outboard that is enough to keep the vessel on station and heading into wind could perhaps encourage skippers to change behaviours and even switch main engines off with likely significant saving in fuel (See the LEWAS project in Section 9). However, current vessel registration and licensing processes that MMO implement do not have the provisions to factor in the addition of an electric outboard power source to a commercial fishing vessel[25].

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[25] Personal Communication from Michael Coyle (Head of Compliance and Control, MMO)

7 Findings: Other observations

7.1 Regulatory issues on battery safety

We understand that the major issues raised by the MCA with regard to safety are around battery installation and operation. Issues highlighted by MGN-550[26] include the potential for minor defects in a lithium-ion cell to result in a fire hazard and the toxic nature of chemicals inside the batteries. There can be significant differences between Li-ion batteries by manufacturer and it is essential that the battery management system is aligned with the particular characteristics of any batteries installed. Li-ion batteries are more complex than conventional lead-acid batteries and specific measures and monitoring are required to avoid damaging them. MCA recommendations are that Li-Ion batteries are maintained in a fire-proof temperature-controlled compartment that has good levels of redundancy. Given the fact that there are very few electrified fishing boats in the UK using Li-ion technology, current MCA guidance is that their installation and usage will require a risk-based approach specific to each situation. If there are significant shifts toward electrification in the small scale fishing fleet, there will be a requirement for skilled engineers who can assess the appropriate and safe hybrid system for a given vessel using specific gear.

7.2 Impact of licensing arrangements on vessel efficiency

The motor fishing vessels of the mid 20th century were generally longer than an equivalent class today, with an efficient hull form designed to make the most of the limited engine power available. Changes to this design have been guided by a range of factors, perhaps primarily convenience and efficiency for fishing (e.g. the change from side to stern trawling). However, one determinant of boat design has been licensing. One of the factors determining the type and cost of a fishing license in the UK is the length overall (LOA) of a vessel, and hence hull forms have changed to give less priority to hydrodynamic efficiency and more to maximising the deck area available within a given length. The speed lost by having a shorter boat has been partially regained by using more powerful engines, which burn more fuel.

We recommend a further study, bringing in expertise in naval architecture and fishing policy, to examine whether a change in licensing regime that placed less emphasis on length, while still achieving the licensing objectives, would result in substantial fuel savings.

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[26] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/882850/MGN_550_Electrical_Installations_-_Guidance_for_Safe_Design__Installatio....pdf

8 Possible Future Scenarios

Small boat fishing fleets will need to decarbonize by 2050, and this means that they will need to stop using fossil fuels. In Section 6 we reported that except for the smallest and least powerful boats, fishing close to home, full electrification is not practical with current technology – and nor, in the short term, would the port infrastructure be in place to support it if it were. Diesel-electric hybrid drives, while offering significant fuel savings to some craft and being a worthwhile step forward, will not fully decarbonize them. What, then, does the future look like? What might things look like in 2050, and how might harbours prepare?

The contents of this section are necessarily speculative; it represents the views of the authors as to what could happen, and it may be proved wrong. In it we present two possible scenarios: one of electrification, and one of an alternate, renewably-sourced, fuel. After presenting these two visions we will briefly discuss possible changes to the industry.

8.1 Full electrification

In this scenario, improvements in battery technology make it feasible for most or all small fishing vessels to be powered by pure electric drives. This is unlikely to be accomplished with Lithium-ion batteries, but two alternative technologies which might suffice are in development: Sodium-Sulphur (Na-S) and Lithium-air (Li-air).

Sodium-sulphur is new but already in use for utility-scale applications, but most installations operate at high temperature (300-350°C) which probably makes them unsuitable for marine use in their current form. However, recent research[27] has demonstrated a room-temperature battery with an energy density of 946 Wh/kg, around 7 times that of Li-ion, so there may be potential for it to develop into a viable option.

Lithium-air batteries are at an earlier stage of development, but by using atmospheric oxygen as one of their electrodes they have the theoretical potential to have a similar energy density to petrol or diesel, at 12000 Wh/kg. This is a theoretical maximum value, but early research in Japan[28] has recently demonstrated a Li-air battery providing 500 Wh/kg – already about 4 times that of Li-ion – in lab conditions, and this density is likely to be greatly improved before the technology is ready for commercial use.

Assuming that a new battery technology becomes available with a higher energy density than Li-ion, and that it is suitable for use in small boats, this could permit full electrification of inshore fleets. Battery capacity will probably still be a critical factor, at least at first, and thus it may be critical for vessel designs to aim for efficiency.

This is the scenario with the greatest impact on port infrastructure, because of the need for charging. The power that would need to be delivered to allow any but the smallest vessel to fully charge overnight is an order of magnitude greater than that which is currently available in ports as shore power.

Grid upgrades should be seen in the context of national electrification of heating and transport (Section 3.1) and hence of grid upgrades probably being necessary throughout the country in any case. However, the grid upgrades needed for electric cars are likely to be comparatively modest, because they will not all need to charge at the same time. The movements of fishing boats are governed by common factors such as tides and weather, which means that a future electric fishing fleet *would* all need to charge simultaneously. This would impose a heavy load on the local electricity grid, and sufficient capacity may not be available in networks servicing rural or small-town harbours.

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[27] https://doi.org/10.1016/j.ensm.2018.11.031

[28] https://www.sciencedaily.com/releases/2022/01/220120140724.htm

A possible solution is for a private power system within the port. A large battery bank could be charged continuously at relatively low power, from the grid and/or from local renewable energy sources in the port. The battery system could then discharge over a few hours to provide the higher power needed to charge electric vessels, without requiring major grid upgrades. Fishers might buy shares in the system and operate it as a cooperatively owned facility.

Although it is aimed at infrastructure in major ports, National Grid have recently developed an online tool to help port managers and harbourmasters assess their likely peak power demands based on an assessment of their assets[29]. In response to increased prevalence of battery-electric ferries for passengers and tourism on the west coast of Scotland, a new project has just started at Strathclyde University that is developing a toolkit to evaluate shore-side infrastructure for rural communities[30]. There is some potential synergy between the likely need for increased electrical availability for vessels in fishing harbours and the need for more electric vehicle charging points in harbour carparks[31]. With the reduced need for shoreside space, as vessels have switched from mobile to static gear, in many fishing ports large open areas on the quayside that used to be net mending areas are now council or harbour authority car parks. Cars are generally parked in these places during the day, while small scale vessels are berthed overnight meaning that power dem

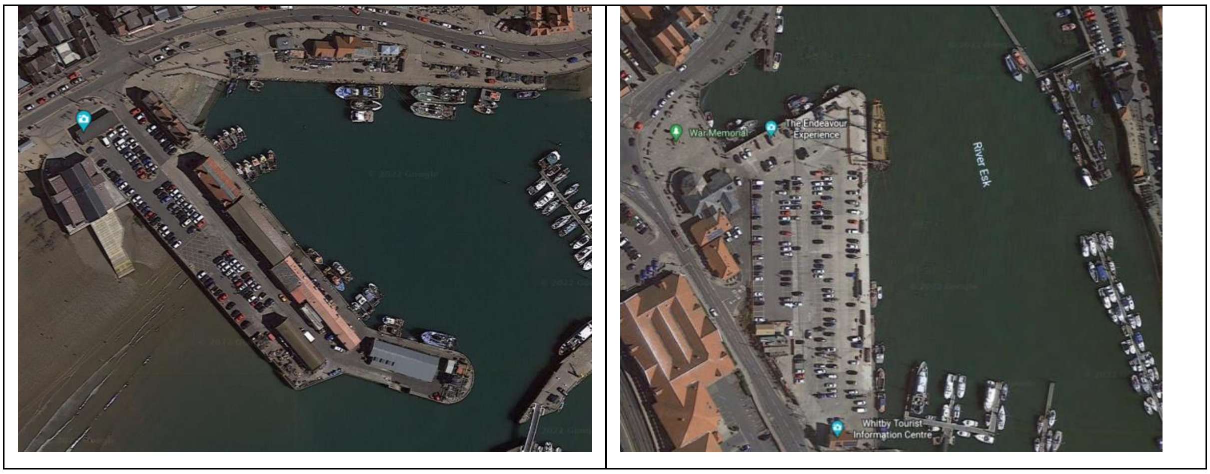

Figure 12: Illustration of how car parking has replaced net mending areas in Scarborough and Whitby (source: Google earth)

8.2 Alternative fuel

In this scenario, the supply of petrol and diesel is replaced by something else – something which is a pumpable fuel but can be made from sustainably-available materials in a renewable energy. This fuel could be a bio-diesel made from crops; it could be methanol produced with renewable electricity; it could be hydrogen made from electrolysis of water, or it could be ammonia produced from that sustainably-sourced hydrogen (although the last one is unlikely for small craft due to the need for cryogenic storage).

All of these fuels would have a lower volumetric energy density than diesel, so the same size of tank would probably give less range. In some cases it might be possible to continue using existing engines with adjustments, but in all cases (except perhaps hydrogen – see below) it would be better to use a hybrid system, with the new fuel instead of diesel.

Hydrogen could be used to power a generator in a hybrid setup, just like diesel, but it is also possible to use hydrogen in a fuel cell to produce electricity much more efficiently. A fuel cell system could

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[29] https://www.nationalgrid.com/stories/journey-to-net-zero-stories/new-online-tool-will-help-uk-ports-transition-net-zero

[30] "Connected Places Catapult: A toolkit to evaluate shore-side infrastructure requirements for rural islanded communities"; contact Lewis Hunter (lewis.hunter.100@strath.ac.uk)

[31] https://kempower.com/information-center/news/worlds-first-electric-boat-hpc-charger-in-norway-is-designed-manufactured-by-kempower/

perhaps allow for a fully electric drivetrain, with all the maintenance advantages of not using an internal combustion engine, using a hydrogen tank and fuel cell instead of a battery. Fuel cell technology is, however, very expensive at the moment.

For most of these potential fuels, port infrastructure could remain roughly as it is now. The exception, again, is hydrogen. A hydrogen filling station could work in a similar manner to diesel today (albeit with rather different hoses and connectors, for the fuel must be delivered at pressure). But it might also be possible to generate hydrogen on site from mains electricity or on-site renewables. Detailed investigation would be needed to see if this was feasible at sufficient scale for a given harbour.

8.3 Possible changes in fishing behaviour

Whether one of the scenarios above comes to pass, or whether something else happens, the general trend of rising energy prices is likely to continue. This is because, with the scale of the necessary national and global transition to low carbon / renewable energy, such energy is likely to be in short supply for the foreseeable future.

Increased energy costs – of petrol and diesel in the short to medium term, and of electricity or another fuel in the future – are likely to have profound impacts on the behaviour and business choices of fishers. Based on our interviews, some grounds or species are already only fished when catches are high because of the cost of getting to them. With recent increases in fuel costs, fishers are already targeting grounds closer to home. This will (and, we are told, already does) result in more effort on grounds around busy ports such as Brixham, which increases the pressure on local stocks. In the longer term we may see fishers relocating to base themselves close to less busy fishing grounds, in order to minimise transit times. This could result in a revival of small local fishing harbours and a reversal of the tendency of fleets to consolidate in a few ports. If this happened, it would of course have implications for infrastructure: for harbours and/or launch facilities, for landings, and for fuelling or recharging.

High energy costs will also introduce pressure on vessel design, making it desirable to have an efficient hull form and a lower-powered engine. Reducing the power that is needed (and hence the battery capacity required) may be the key to getting off diesel and converting to electric propulsion. We may see changes that favour propulsion efficiency over deck space, or a move towards longer vessels for a similar deck area. Much will depend on the licensing regime – see Section 7.2.

In a world of high energy prices, the future of mobile gear seems uncertain. It may be that more small-scale fishers currently using trawls and dredges will consider switching to static gear (nets and lines) so that they can downsize their engines.

Ultimately, the whole-system effects of the changes suggested here would be complex, are likely to be specific to a given region, and will depend on social and cultural issues as much as anything technical. As such any detailed predictions are beyond the scope of this report, but it may be helpful to consider specific location(s) in the future through a holistic “transition engineering” approach[32].

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[32] Krumdieck S (2019) Transition Engineering: Building a Sustainable Future. CRC Press

9 Further research

In order to assess the accurate fuel economy figures for the case of diesel-electric hybrid propulsion for a variety of vessels further study is required. The lack of accurate data for low-power diesel engine performance and its overlap with the boat propelling curves and hull speeds prevents an accurate evaluation of fuel economy. For each vessel design, these data are critical to allow the choice of the most efficient version of hybrid propulsion (series or parallel hybrid) and scaling factor of the diesel engine. Mapping the required characteristics for a number of typical engine/boat combinations would allow the development of a generic model that could be applied to small scale fisheries. To achieve this for any vessel the diesel engine should be equipped with torque, speed (rpm) and fuel consumption monitors and run over typical operating pattern(s). The cost of fitting the necessary systems to monitor engine use in order to optimise the design of a bespoke hybrid system would be around £7000 per vessel.

Some initial investigations into workboats for the aquaculture sector (LEWAS: Low Emission Workboat for the Aquaculture Sector) by Maline Marine Ltd using this technology suggested that the simple act of monitoring engine performance and fuel consumption more closely results in 25% saving on fuel use[33]. This aligns with studies of consumer behaviour in response to the availability of smart meters – engaged consumers will use real-time information to reduce their overall consumption[34].

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[33] LEWAS (Low Emission Workboat for the Aquaculture Sector), Maline Marine Ltd. Contact Chris Dunn (c.dunn@malingroup.com; 01412 213075)

[34] Batalla-Bejerano J, Trujillo-Baute E, Villa-Arrieta M (2020) Smart meters and consumer behaviour: Insights from the empirical literature. Energy Policy 144:111610.

10 Key findings and Recommendations

- Pure electric propulsion, running off batteries, is currently only feasible for some of the smallest boats which have the lowest power and endurance requirements. This is primarily due to the weight of the batteries needed for higher power and/or longer periods, although the cost of such batteries may also be a barrier.
- Hybrid technology shows promise for static gear fishing, due to the variation in engine power that is used during a day at sea. For some vessels with some usage patterns, at least a 20-30% saving in fuel and emissions is achievable. There are no “off the shelf” systems available at the moment, but all of the necessary technology exists today. Many fishers showed interest in switching the next time they change their engine, so long as the switch is affordable.
- Hybrid systems would not be of significant benefit to boats using mobile gear, because of their need for high engine power most of the time.
- We suspect that significant energy and emissions reductions could result from a change in licensing to focus less on the length of vessels. The current system encourages inefficient short but wide boats, in order to maximise the deck area that is available without exceeding a length threshold that would increase the license cost.
- In the future (by 2050) it will be necessary for the fishing fleet to decarbonise if the UK is to meet its climate commitments. We believe that this will probably happen either through an improvement in battery technology, or through the production of alternate fuels using renewable energy. The first of these possibilities would have significant implications for port infrastructure, as a fishing fleet charging overnight would require orders of magnitude more power than most harbours have available at the moment.
- We believe that the rising cost of energy is likely to lead to changes in fishing behaviour, and that the optimal solutions may vary from one location to another. Detailed study of this was beyond the scope of this report.

10.1 Recommendations

- Financial support from government will be required to assist fishers with the capital cost of switching to lower carbon propulsion systems.
- A model should be developed that fishers or suppliers can use to find the best combination of engine, generator and battery to design a hybrid system for a particular vessel.
- Further research should be conducted to monitor the engine use of a variety of static gear boats over several days or weeks, in order to gather more robust data on the potential for electric or hybrid drives.
- This data could be used to design a few exemplar vessels to demonstrate to fishers the potential for electrification. At present there is only one small SIF funded fully-electric catamaran in Brixham that is serving as a trailblazer. A select few early adopters in ports around the country could be funded to switch to a hybrid system.
- A study should be made of licensing rules to examine whether a licensing regime that placed less emphasis on vessel length – while still accomplishing licensing objectives – would result in significant fuel savings by encouraging more efficient hull forms.
- Consideration could be given to the development of partially-funded “starter packs” consisting of a small-scale (under 6 m) boat with electric engines for new entrants interested in inshore fishing as a career.
- Knowledge of electrical propulsion systems (pure, hybrid and auxiliary, including battery systems) should be incorporated into the syllabus for marine engineering and engine maintenance courses.

- Government should fund and encourage research into the development of low carbon propulsion systems that are suitable for small scale fisheries and workboat applications. In the short term this means implementing hybrid systems for small craft, to move the concept from “innovation” to “off the shelf”. In the longer term there is a need for improved battery technologies or alternative sustainable fuels if small fishing boats are to make their contribution to the nation’s net zero target of 2050.
- Harbour authorities should consider allowing for future electrification when conducting infrastructure works (for example, if installing new trunking in a pier, it should be sized for larger cables).

Appendix A: List of websites showing examples and data relating to electric engines

Websites with full information:

- https://plugboats.com
- https://www.nauticexpo.com/cat/alternative-engines-propulsion-systems-DA.html
- https://www.nauticexpo.com/boat-manufacturer/electric-thruster-21599.html

Specialized on one or two suppliers:

- https://www.mitgroup.co.uk/sector/marine/electric-propulsion/#1601302963853-4a70e9eb-9b72
- https://www.bellmarine.tech/en/products-page/
- https://www.vetus.com/en/electric-propulsion.html
- https://www.vetus.com/en/electric-propulsion-product-information

UK main suppliers:

- https://www.epropulsion.com/
- https://www.torqeedo.com/en
- https://www.hybrid-marine.co.uk/

Pricing info:

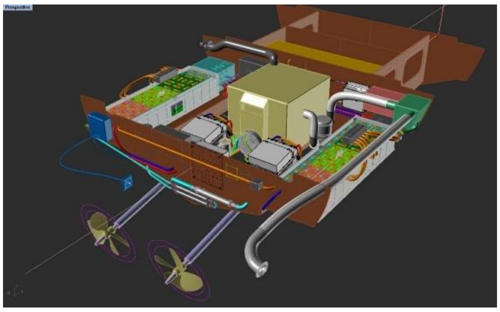
- https://www.buy-transfluid.com/bellmarine/
- https://www.vetus.com/en/catalog-request
- https://plugboats.com/electric-inboard-boat-motors-guide-over-150-motors/

Appendix B: Examples of vessel propulsion electrification projects

10.1.1 Hybrid recreational cruiser / recreational fishing boat

https://www.passagemaker.com/technical/changing-world-hybrid

The Rhea 850 Electric developed by Rhea (France, 2014) is based on their Rhea 850 diesel-propulsion model. This is a diesel-electric series hybrid incorporating: two 145 kW electric motors, a 38 kWh battery pack and a Volvo D3-130 diesel generator (90 kW). It has not been a commercial success due to its high price.



10.1.2 Electric small-scale ferry

https://www.voyagerboatyard.co.uk/evoyager.html

Plymouth Boat Trips, in cooperation with an electric car parts company, a local boatyard and two universities, has produced a pure (battery) electric 12-passenger ferry. This is a demonstration project, using batteries designed for electric cars and with a significant amount of grant funding. The ferry operates continuously during its working day, making 15 trips across the local bay on a single charge. e-Voyager appears to be the first such vessel to have been approved by both the MCA and a Classification Society for passenger use.

10.1.3 Hybrid pilot boat

https://www.mitgroup.co.uk/casestudies/leader-hybrid-case-study/
https://www.goodchildmarine.co.uk/boats/orc-136-hy

“Leader” is the UK’s first hybrid-powered pilot boat, built for the Port of London Authority in 2019. She has a length of 14.4m and uses a parallel hybrid arrangement with two 75 kW motors, two 300Ah batteries, a 50 A charger, and a 400 hp / 300 kW diesel engine to give a top speed of 19 kn. She was built by Goodchild Marine Services Ltd in Norfolk, who now offer the design to other buyers.

10.1.4 Hybrid fishing boat

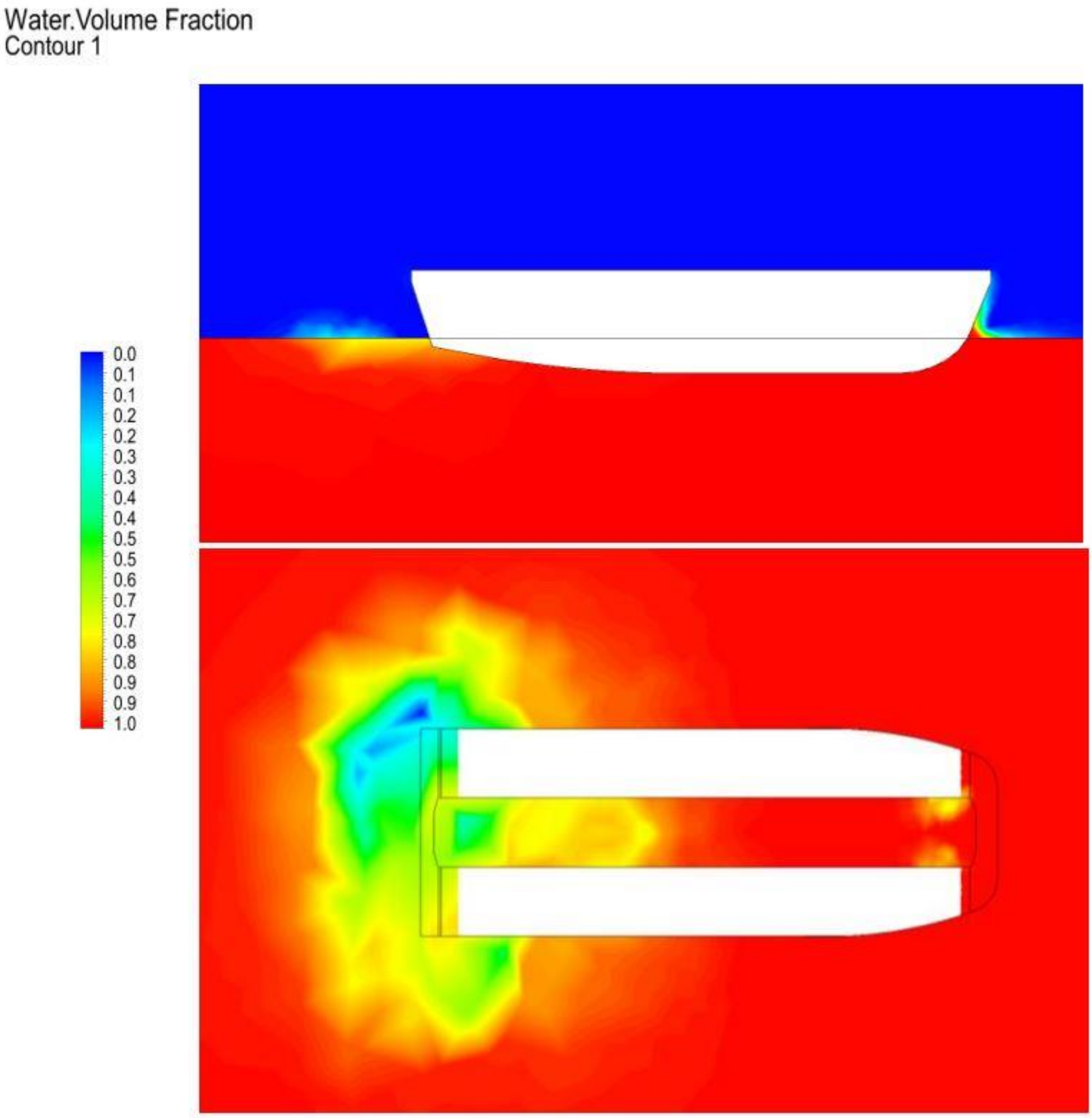
https://www.vesselfinder.com/news/3890-Selfa-Elmax-1099-The-Worlds-First-Electric-Fishing-Vessel
https://maritimecleantech.no/project/first-electric-fishing-vessel/

The 11 metre fishing boat “Karoline” was developed by Selfa Arctic AS (Norway) and Siemens for Norwegian fishing company Øra AS in 2015. This boat is described by her owners as the “World's First Electric Fishing Vessel”. Little information is available about this boat’s performance, but the same designer has begun work on a successor “Sundsbøen”. This boat is to be a series hybrid with a large 195 kWh lithium battery pack and 50 kW diesel generator. The vessel is designed to operate solely on battery power over a 10 hour period, and to charge overnight by plugging into the electrical grid. She will hence burn no fuel in normal operation, but by having a generator on board she will not be range-limited by her battery capacity when making longer passages.

10.1.5 Electric workboat

https://www.shetnews.co.uk/2022/04/20/project-to-create-fully-electric-boat-gathers-pace/

Malakoff Engineering are currently developing an 8 m catamaran workboat with a £30000 grant from the UK government’s transport research innovation grants scheme. The designers say that the boat is not designed for speed or good looks, it’s mainly to see what we can achieve under electric power.


Water.Volume Fraction
Contour 1
0.0
0.1
0.1
0.2
0.2
0.3
0.3
0.4
0.4
0.5
0.5
0.6
0.7
0.7
0.8
0.8
0.9
0.9
1.0

Appendix C: Species landings by under 10 m vessels by port

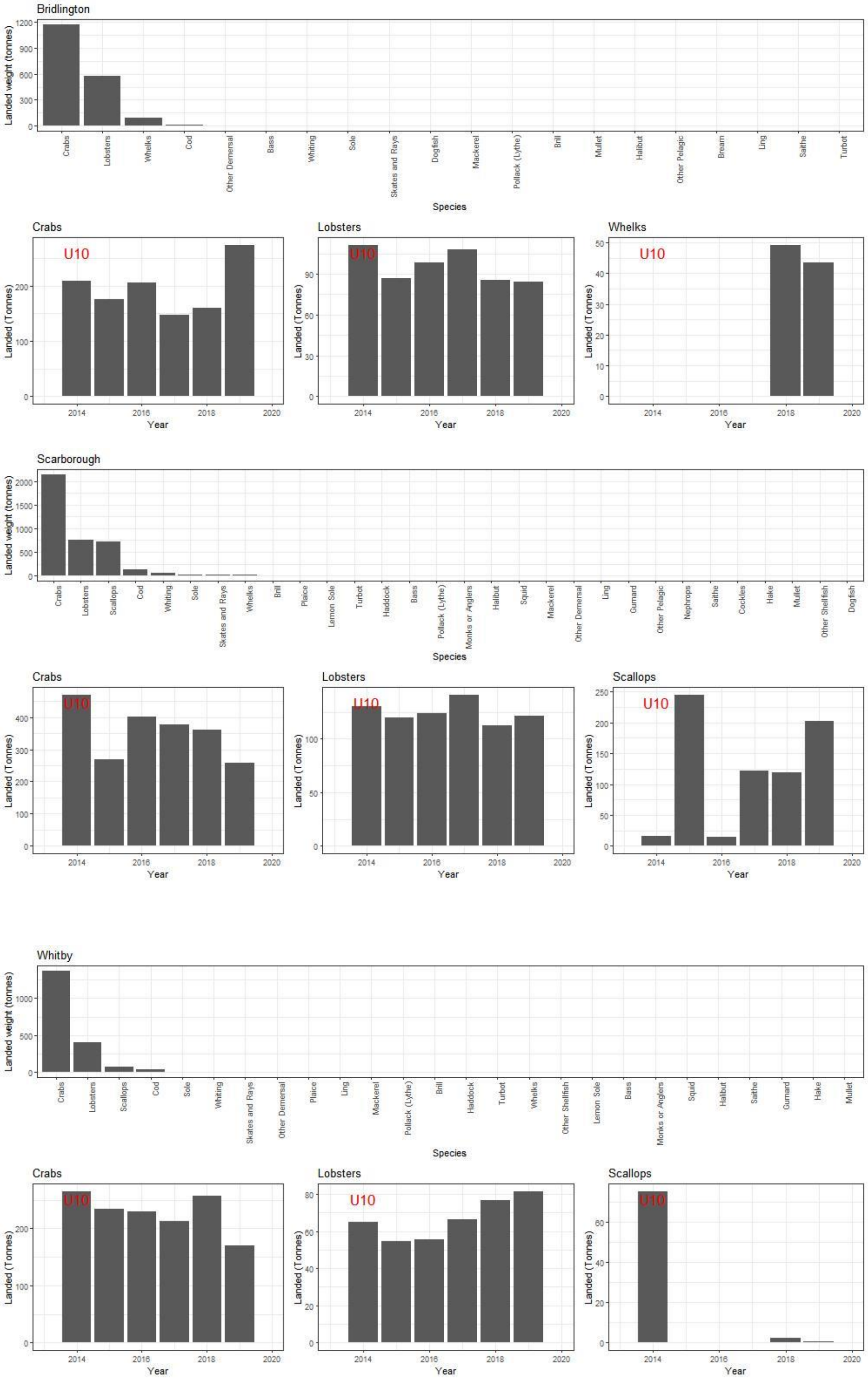


Figure 13: Landings profiles for Yorkshire ports visited during field work (Bridlington, Scarborough and Whitby). The top figure for each port shows the total landed between 2014-2020. Where there is no bar above a particular species this indicates that small quantities were landed at some point during this period. The three lower figures illustrate the annual landings in this period for the three most important species in each port (MMO Data).

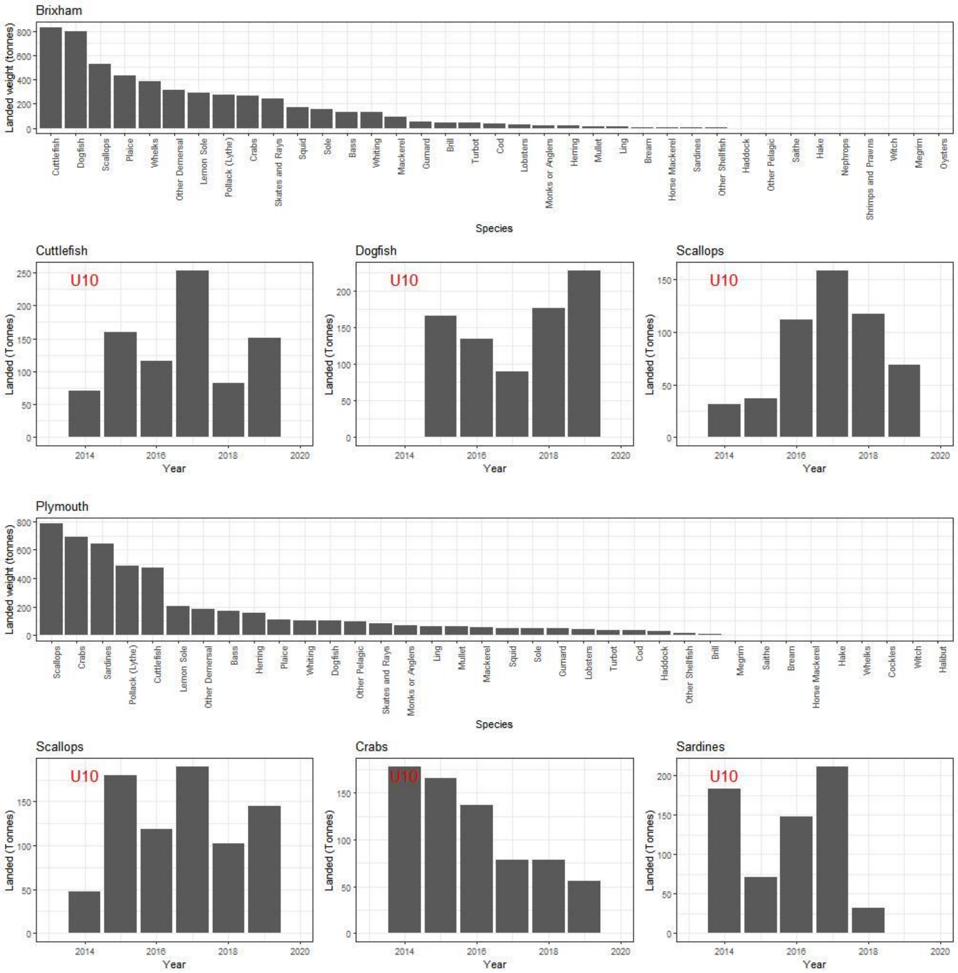


Figure 14: Landings profiles for Devonshire ports visited during field work (Brixham and Plymouth). The top figure for each port shows the total landed between 2014-2020. Where there is no bar above a particular species this indicates that small quantities were landed at some point during this period. The three lower figures illustrate the annual landings in this period for the three most important species in each port (MMO Data).

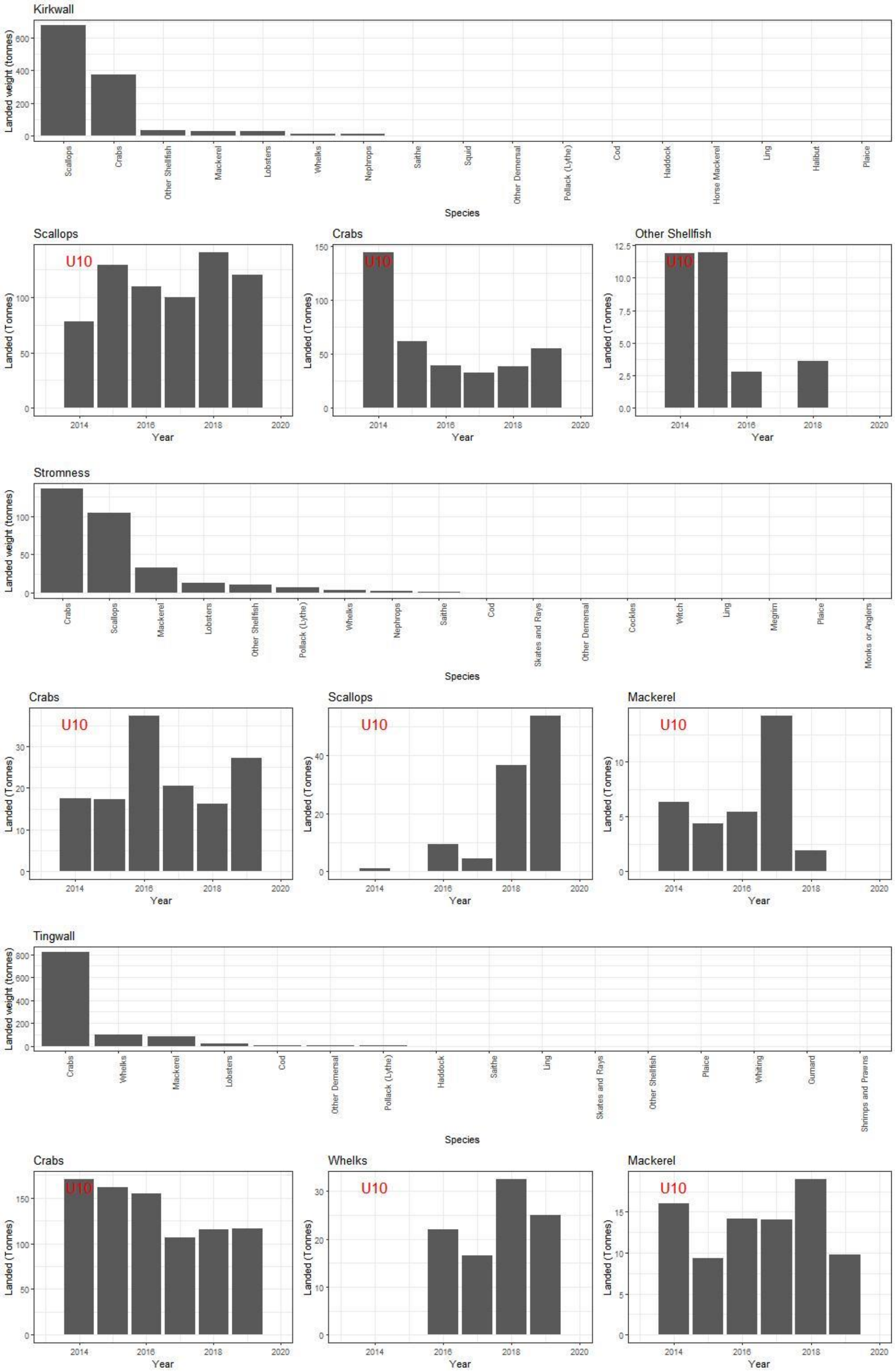


Figure 15: Landings profiles for Orkney Islands ports visited during field work (Kirkwall, Stromness and Tingwall). The top figure for each port shows the total landed between 2014-2020. Where there is no bar above a particular species this indicates that small quantities were landed at some point during this period. The three lower figures illustrate the annual landings in this period for the three most important species in each port (MMO Data).