Decarbonising the fishing sector

Energy efficiency measures and alternative energy solutions for fishing vessels

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The fishing sector is facing major challenges in the accelerating energy crisis due to its high dependency on a stable supply of fossil fuels at a low price. This report summarises scientific and grey literature, projects and input from expert interviews to provide an overview of drivers of energy use, and identify potential reduction measures and opportunities for using alternative fuels in fisheries. Each measure is evaluated in terms of greenhouse gas emission reduction potential, costs, challenges, and policy options that could facilitate implementation. A timeline lists measures that could be implemented in the short and long term.

The study finds that considerable fuel use reduction can be achieved from fully implementing existing EU regulations (for instance, by rebuilding stocks and allocating fishing opportunities in accordance with Article 17 of the Basic Regulation on the common fisheries policy). To this end, fuel use efficiency and greenhouse gas emissions need to be integrated as an explicit goal of fisheries management, and monitored on the basis of robust data collection.

The introduction of alternative fuels will require major investment in new infrastructure as well as regulatory changes in the short term, but lead to major gains in the long term, with regard to both costs and emissions. It is however important to optimise the choice of fuel and technology for the operational profile of each vessel. In the transition, it is crucial that economic policy instruments, such as taxes, fees and emission quotas, are used wisely to incentivise transition. A ban of fossil fuel use in fisheries by 2050 would give clear incentives and pave the way for the transition – but needs to be accompanied by well-designed funding opportunities for green investments and compensatory measures to minimise the rise in short-term costs. Overall, a systems perspective is needed to achieve an energy-efficient, decarbonised fishing sector, without this causing other environmental impacts.

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Executive summary

Fisheries are today fully dependent on fossil fuels and are increasingly vulnerable to both rising fuel prices and to requirements to reduce their greenhouse gas emissions – the fishing sector therefore needs to follow the societal transition towards improved energy efficiency and decarbonisation, as for all sectors. This report explores the two main pathways to reducing fisheries greenhouse gas emissions and dependency on fossil fuels:

1. reducing fuel use intensity (the volume of fuel used per unit of catch landed); and
2. shifting to alternative, low-carbon fuels.

The aim is to synthesise current knowledge and identify potential measures to reduce the fossil fuel dependency of fisheries, estimate reduction potential and economic feasibility, and describe policy options that could facilitate this transition. The report is based on literature and project searches, expert interviews, additional literature and projects identified from interviews and materials from recent hearings and workshops on the topic.

In terms of current status, the fuel use intensity (measured in litres per kg landed) of different fisheries is highly variable. At the extremes, small and shoaling pelagic fish can be fished extremely efficiently (often at below 0.1 l/kg), whereas crustaceans, depending on the species and gear type, are often at the highest end of the fuel use intensity spectrum (sometimes at over 10 l/kg). Depending on the level of detail studied and methodology used, several insights have been gained on the drivers, development and variability at different scales. The prevalent perception of small-scale fisheries, if defined by vessel length, being more fuel efficient than large-scale fisheries is not supported by the scientific literature; fuel use intensity is determined more by the gear, targeting pattern and other factors than by vessel length. Current data gaps and inadequate data collection methods call for improved strategies for monitoring the fuel use of fisheries to further the knowledge of the current status and improvement opportunities.

The dependency of fisheries on fossil fuels is almost universal, with the minor exception of certain artisanal fisheries, and the use of non-fossil fuels has not yet reached commercial implementation. In this respect, the fishing sector will depend on the development of the shipping sector, which dominates the use of maritime fuels and will determine infrastructure investment by ports. For various reasons, including the recent price rises, liquid natural/fossil gas (LNG/LFG), is not seen as a major future solution for the fishing sector, but it could pave the way for the use of methane produced from renewable low-carbon or carbon-neutral production routes by requiring infrastructure in ports and on vessels. Natural/fossil gas is currently also used to produce some of the more promising future fuels, such as methanol, hydrogen and ammonia, and could facilitate their introduction, but it is central to continue to develop non-fossil, low-carbon and carbon-neutral production routes, to represent full decarbonisation. All alternative fuels are less energy dense than fossil diesel fuel and therefore require larger volumes, which influences the capacity of and life on fishing vessels where space is already limited. Fuels with a low boiling point (i.e. which are gases at room temperature, such as hydrogen, ammonia and LNG/LFG) need to be compressed or liquefied at an energy cost; this energy can however be recovered in cases when on-board refrigeration is needed. In general, the operational profile of the fishing vessel should guide the selection of energy provider and vessel design to achieve the most energy-efficient and lowest-carbon solutions.

A wide range of projects have been undertaken or are ongoing both to improve energy efficiency when using conventional fossil fuels, and to introduce alternative fuels in the fishing sector. In terms of efficiency, many projects focus on the technological development of fishing gear to reduce fuel use. Projects focusing on alternative fuels are often practical in nature, converting one or a few vessels or building port infrastructure for a new fuel type.

Ample opportunities exist to improve the energy efficiency of fisheries, spanning from larger policy changes through measures taken in fisheries management to behavioural changes by the individual fisher on a fishing-trip basis. For this to happen, two important prerequisites are that i) energy efficiency and low emissions be stated explicitly as a goal of fisheries management; and ii) data of sufficient quality be available to be able to measure and follow performance. Fishing policy measures that may be taken include making sure existing policy is implemented (shift to using low-impact gear, decrease overcapacity and improve stock status) or providing economic incentives for the industry to move towards more climate efficient fishing (e.g. by removing tax exemptions on fuel or adding a carbon fee or tax), but could also encompass larger policy changes such as new management targets for fish stocks to optimise for low-carbon seafood from capture fisheries.

Most measures comes with increased costs for the fishing industry at a different magnitude of scale in the immediate perspective (5 years), but are aligned with economic objectives in the longer perspective. Some measures, such as reducing overcapacity and allowing for higher fish abundance, come with improved economy to the remaining industry, but implies social trade-offs in terms of decreased fishing opportunities. Overall, identification of the most efficient measures needs to be tailored to the specific fishery depending on current status. Passive and active gear segments have very different inherent characteristics relating to fishing operations – but all fisheries benefit from healthy stocks and optimised fleet structure; the extent of the benefit depends on the fishing area, country and targeted species.

In terms of enablers and barriers, it is important to acknowledge the limitations of technological measures (e.g. innovations relating to gear, hull or bow design) compared with policy changes (e.g. change in gear use, stock status) – and carefully navigate between long-term needs relative to short-term actions, which need to be aligned. Current CFP legislation may represent barriers to installing alternative energy sources owing to restrictions on kW and vessel sizes. The current CFP may also be an enabler, for instance by enforcing implementation of Article 17 (on allocating fishing opportunities) to favour energy efficiency. Fisher traditions and behaviour can also be important barriers, but become enablers in the transition; training programmes on operating fishing vessels in an energy efficient way – including using alternative fuels – will be required.

Balancing current with long-term economic opportunities, i.e. to overcome the initial costs for the transition with the long-term gains in mind, is a key component in the decarbonisation of fisheries. To this end, the current knowledge is sufficient to make the necessary transition towards improved energy efficiency: decreasing overcapacity, rebuilding stocks and implementing fuel-efficient fishing gears, rather than focusing on further gear innovations within fisheries, can already be done today. However, for full decarbonisation, further societal investment, research and innovation is needed for the increased uptake of alternative fuels in the fishing sector.

Policy options can be seen as packages or strategies that, when combined, steer towards an overarching goal to differing extents. A set of key measures can favour and facilitate the necessary development to invest in low-carbon fishing by:

1. integrating energy efficiency and low emissions as an explicit goal of fisheries management that should be measured and followed up upon;
2. imposing a global ban on using fossil fuels in all maritime sectors by 2050 to provide incentives for innovation and infrastructure development;
3. identifying ways to compensate fishers that invest in emission reduction, for instance by increasing costs for the continued use of fossil fuels (introducing a new tax or fee or phasing out tax exemption) accompanied by relaxed taxes or fees elsewhere, or redirection of funds to green investments, to not increase total costs for fishers, as has been implemented in Norway;

4. implementing already existing policy objectives on sustainable resource utilisation and starting to operationalise quota allocation in accordance with Article 17 in the CFP favouring low-impact gear types;
5. supporting the establishment of infrastructure for alternative fuels in ports and on vessels.

It is concluded that to effectively decarbonise the fishing sector, applying a systems perspective rather than introducing a patchwork of quick fixes is essential. This will mean identifying in the short term what the most efficient measures are to i) reduce fuel consumption in fisheries, while in the longer term also ii) supporting changes to cut the greenhouse gas emissions of fisheries. In this endeavour, it is important to keep in mind that fisheries are part of the food system and should not be treated unfairly compared with other production systems with high non-fossil emissions, such as beef (for instance by taxing only fuels and emissions of fossil origin). This requires overall policy changes to favour fuel use efficiency, such as improving catch efficiency through improved stock status and promoting low-impact fishing gears. At the other end of the scale – the individual fisher – it is crucial to measure and understand the profile of the fishing operation and vessel both for improving energy efficiency and for identifying suitable alternatives to fossil fuels and optimise their operation.

In following the path towards decarbonisation, it is essential not to forget that there are knowledge gaps. One is the contribution of fisheries with benthic impacts to greenhouse gas emissions by impacting sediments and releasing carbon that has been bound to the sediment to the water and potentially to air. Another is the lack of detailed data on fuel use variability, as well as the use and leakage of climate-impacting refrigerants in fisheries, which can be a substantial source of fisheries greenhouse gas emissions. As new knowledge is gained, new policy options will appear. Nevertheless, it is important to resist the temptation today to take the easy path with quick fixes that may risk introducing trade-offs with biodiversity, for instance promoting a fishing method that has lower fuel use, but is associated with a by-catch of sensitive species. Often, policy actions aimed at reducing the greenhouse gas emissions of fisheries go hand in hand with biodiversity targets – such as decreasing overcapacity and ensuring sustainable exploitation of stocks. Both these policy options are also aligned with economic profitability but may come with short-term social implications from the fleet cuts that may be necessary to achieve long-term benefits for all.

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1. Energy use in fisheries

1.1. Fisheries depend on fossil fuels

Global fisheries have been estimated to use approximately 1% of the total oil consumption (Tyedmers et al. 2005), and may thus not seem to be the most important industry to focus on in efforts to reduce global use of fossil fuels. Fisheries, are however fully dependent on fossil fuels and are increasingly vulnerable both to rising prices and requirements to reduce emissions. Firstly, fuel use is the most important variable cost of fishing companies that often determines their overall profitability (e.g., Abernethy et al. 2010). Secondly, fisheries provide important contributions of critical nutrients to human nutrition (Hicks et al. 2019), with opportunities to increase (Robinson et al. 2022). Thirdly, for future sustainable food systems, average environmental impacts of seafood are lower compared to other animal-sourced food (Gephart et al. 2021), in particular the types of seafood with lowest impact and when weighing in the relatively higher nutrition density compared to other animal-sourced foods (Bianchi et al. 2022). Combined, in efforts to reduce use of fossil fuels, with increasing oil prices, and the need to shift to more sustainable diets, it is vital to identify how capture fisheries may continue to supply healthy and sustainable seafood also in the future.

There are many benefits of reducing fuel use in fisheries. Life Cycle Assessment (LCA) studies have shown that fuel use is the single most important driver of greenhouse gas emissions of capture fisheries, as well as many other environmental impacts (see text box on next page). Furthermore, emissions related to production and combustion of the fuel used often dominates not only the greenhouse gas emissions of fishing (60-90% according to Parker et al. 2018), but the entire supply chain to the consumer, unless products are airfreighted to market (Parker 2012, Vazquez-Rowe et al. 2013, Ziegler et al. 2016a, Avadí & Fréon 2013). At the same time, fisheries are almost exclusively operated using diesel or light fuel oils, with the exception of artisanal fisheries operated by manpower or gasoline-driven outboard engines (Parker et al. 2018). The fuel use and greenhouse gas emissions of fisheries is often, with exceptions, correlated to other types of environmental impacts, why reduced fuel use would have wider benefits than reducing costs and greenhouse gas emissions.

> ### Environmental pressures of capture fisheries: More than greenhouse gas emissions
>
> This study is restricted to cover fuel use intensity (fuel use per unit of catch landed) and greenhouse gas emissions of fcapture fisheries and related reduction opportunities. Most of the literature used is based on studies using Life Cycle Assessment (LCA), a sustainability assessment tool that according to the ISO standard should cover all relevant environmental impacts to be able to quantify potential trade-offs. For fisheries, it has however been found that fuel use on fishing boats drives most emission-based environmental pressures, such as acidification, eutrophication and particulate matter. Only toxicity-related pressures may have more important drivers, such as construction of vessels, gears and use of antifouling.
>
> Assessments of ecological pressures (impacts on target species, by-catch, habitats and ecosystem) are not part of the LCA methodology and are therefore either not included, or included through parallel assessment of other indicators. When included, trade-offs with fuel use intensity may occur, such as in species-selective trawling (where the reduction in catch leads to high fuel use per unit landed). There is also support for correlations; fuel use intensive practices in the form of beam trawling also imply e.g. higher habitat pressure.
>
> Source: Ziegler et al. 2016a

Fuel taxation is also problematic in fisheries. Because the fuel on fishing vessels is often used on international waters, it cannot be taxed in the same manner as fuel used within a country (as e.g. in agriculture, transports, industry) and is hence cheaper than fuel used in these other sectors. This results in that some highly fuel use intensive fisheries can stay profitable – which they would not be if the same conditions as for example for the agricultural sector applied (Ziegler and Hornborg 2014). The tax exemption also makes fisheries even more vulnerable to increases in world market prices for oil, since increases translate directly into the same proportional increase in price, as many fishers have experienced during 2022. The current world energy crisis has led to 2-3 times higher fuel prices for EU fishers in 2022 compared to 2020 (data from EUMOFA presented by N. Carvalho in October 2022). For a company for which fuel cost is the second most important variable cost after labour costs, this is a very challenging situation. At the same time, while labour costs have increased, the proportion of costs constituted by fuel actually decreased between 2008 and 2019 (N. Carvalho, October 2022), although there are large differences between different segments. From the necessity to curb greenhouse gas emissions, and the most likely continued increase in costs of fossil fuels, proactive efforts to reduce fisheries dependency of fossil fuels are vital.

From a food system perspective, the agriculture sector is ahead of fisheries in terms of reducing its fossil dependency, which may be related to the higher fuel prices paid. Lagnelöv et al. (2022) conclude in a simulation study for the Swedish agricultural sector that the greenhouse gas emissions of agricultural vehicles could be reduced by 50-70% by shifting to battery-electric or hydrogen power. This large reduction potential is both due to lower emission fuels, and to the increased transmission efficiency of electric vehicles, which reduces the energy need by 50-65% (Lagnelöv et al. 2022). If fisheries do not follow, their current relative advantage of producing low-climate, high-nutrition, food may disappear.

The upside for fisheries is that reducing greenhouse gas emissions of fisheries may be easier to target than in agriculture. In agriculture, a large part of greenhouse gas emissions are of biogenic origin such as methane and nitrous oxide from animals, manure and soil management. These emission sources may be more challenging to reduce that those from the use of fossil fuels since they originate in biological processes. In fisheries, greenhouse gas emissions mainly originate from use of fossil fuels and synthetic refrigerants, and thus, focusing on reducing these two inputs based on current knowledge and technology would give major emission reductions. This will however pose a wide set of challenges: from requiring new investments and changes in regulations to implementing new technology and changing fisher behaviour. Emerging research shows that there are also potentially underestimated effects on the carbon cycle of fisheries which may change this view (see chapter 5).

To this end, due to the major importance of fuel use in fisheries both for emissions and economy, reducing the dependency on fossil fuels is key for the future development and even existence of the sector. Overall, there are two different pathways to reduce the dependency on fossil fuels:

1. Reduce fuel use (volume of fuel used per unit of catch landed)
2. Shift to alternative fuels

This report will explore these two options in regard to current status and evaluate measures that could be implemented in fisheries, their emission reduction potential and associated costs, feasibility, challenges and policy options that would facilitate their implementation. First, a synthesis of the current status on use of fossil fuels and alternative energy sources in fisheries is provided, including important drivers of fuel use intensity (volume of fuel used per unit of catch landed) and data availability (Chapter 3). This is followed by an overview of potential measures that may be taken to reduce the fuel use intensity and shifting to alternative fuels, including reduction potentials, costs, enablers and barriers as well as policy options (Chapter 4). In the following Chapter 5, a brief summary of current knowledge on non-fossil fuel based greenhouse gas emissions of fisheries is provided. Chapter 6 presents policy strategies or packages of the options presented earlier and Chapter 7 presents the conclusions from the work. The report is based on scientific and grey literature, project database searches and expert consultations, described more in detail in a method chapter (Chapter 2).

1.2. Aim

This study aims to i) provide an overview over potential measures that may be taken to reduce the fuel use and greenhouse gas emissions of fisheries; ii) estimate their fuel and greenhouse gas emission reduction potential and economic feasibility, and iii) describe policy options that would facilitate their implementation.

2. Method used

2.1. Literature searches

A restricted search for peer-reviewed literature related to fuel use intensity, reduction opportunities and greenhouse gas emissions was performed in Scopus on October 20th and November 16th, 2022. Titles, abstracts and keywords were first screened for the search terms fuel AND fish* (using '*' returns all hits with fish as a base, i.e. fishery, fishing, fisheries, etc.) which resulted in 4 147 papers. Not all papers were found to be relevant for the purpose of this study, and a second search restricted papers through searching within the search results specifically for intensity (57 hits), gear (34 hits), reduction (186 hits), cost (171 hits) and LNG (4 hits). Furthermore, since two global compilations on knowledge gaps already exist (Parker and Tyedmers 2015; Parker et al. 2018), the search result was restricted to cover papers published from 2015 and onwards to see if any new information was available. No relevant hits were found for other search terms tested (such as hydrogen, electri*); this information will be complemented through other sources (reports, expert consultations, references in literature found). Furthermore, a separate search was done on October 20th, 2022, on fish* AND refrigerant (32 hits), finding one recent review published in 2022 on the topic which was used for chapter 5 on other important aspects.

Search results were screened for recent and relevant papers, excluding papers not referring specifically to fisheries (i.e., not maritime operations such as transport). These papers were used as starting point for the chapters on fuel use intensity, opportunities to reduce fuel use and alternative fuels in fisheries.

2.2. Project database searches

Three searches were undertaken in the EU project database CORDIS in November 2022 to identify ongoing or finalised projects of relevance for the topic decarbonising the fishing sector. The search terms fish* AND fuel AND reduction AND measure, resulted in 101 hits. Search terms fish* AND electric* gave 33 hits and fish* AND energy AND battery 160 hits. Scrolling through the resulting lists of projects lead to the identification of 11 projects that from title and abstract sounded interesting to take a closer look at. The Norwegian Seafood Research Fund (FHF) project database was also searched for projects (2016-) with search term 'drivstoff' (fuel in Norwegian) which resulted in 18 projects, 13 of which interesting to take a closer look at (Table 1). In addition, six projects had already been identified while participating in the conference/fair Nor-fishing (https://nor-fishing.no/en/about-the-nor-fishing-foundation/ in Trondheim in August 2022. All projects identified are listed in Appendix 1.

2.3. Expert consultations

Eight consultations were held during December 2022 and January 2023 with a total of 12 experts with complementing relevant expertise for the project. A set of questions was prepared which guided the conversation, complemented with specific questions depending on each person's field of research and experience. The opportunity was also taken to screen for additional references, projects and ideas of measures that had not come up earlier, these are integrated into the analysis and referred to either to these additional publications or websites or, when this was not possible, as personal references.

Table 1: Experts consulted.

Name of expert	Organisation	Expertise
Antonello Sala	National Research Council (NRC) and Institute of Marine Biological Resources and Biotechnologies (IRBIM), Italy	Energy audits of fishing vessels and technological innovation e.g. related to gears
Peter Tyedmers and Robert Parker	Dalhousie University, Canada	Fisheries fuel use intensity data
Maria Grahn and Selma Brynolf	Chalmers University of Technology, Sweden	Expertise in maritime transport including technological perspectives on vessels, energy efficiency and assessments of alternative fuels (from the perspectives cost and environmental)
Sepideh Jafarzadeh	SINTEF Ocean, Norway	Fuel efficiency of Norwegian fisheries and LNG as alternative fuel
Staffan Waldo	AgriFood Economics Centre at the Swedish University of Agricultural Sciences and Lund University, Sweden	Fisheries economics including taxation
Ole Ritzau Eigaard and Francois Bastardie	National Institute of Aquatic Resources is an institute at the Technical University of Denmark (DTU Aqua)	Fuel use in fisheries (including gear development) and fisheries management
Andreas Bach and Fredrik von Elern	Swedish Maritime Technology Forum (SMTF) at RISE Research Institutes of Sweden, Sweden	Maritime technology and alternative fuels
Jordi Guillen	Joint Research Centre (JRC), Italy	EU data collection on fuel use and costs in fisheries

Based on the review of projects, literature and consultations, a spreadsheet was prepared listing all suggested measures, documenting their emission reduction potential and a qualitative estimated costs on short- and long-term associated to both investment and operating costs. This information was then summarized in Table 2 as the main outcome and result in this report.

All experts that were consulted were given the opportunity to comment on the conclusions made regarding the feasibility of all measures proposed.

2.4. Other information sources

On October 26, 2022 a hearing was held in the European Parliaments Committee of Fisheries (PECH) on the Impact of the energy price crisis on the fisheries sector and the future of fuels. Presentation and discussions from this hearing were used to start identifying actors and improvement measures (PECH 2022). In this hearing, the European Commission presented an initiative that encompasses four areas for the energy transition of fisheries. Two meetings were held with the DG Mare group working on this initiative to exchange approaches and findings and the initiative was launched February 21, 2023 (EC 2023a,b).

The contractors were during the project period independently contacted by various NGOs active in the field energy use and transition of fisheries (Oceana, Our Fish and ClientEarth). These organisations provided some insight to their previous work on the topics, including a workshop held in June 2022 by ClientEarth/Our Fish, of which a recording was available and could be accessed, including the presentations used at the workshop (ClientEarth 2022). A report was published in April 2023 by these two groups together (Our Fish & ClientEarth 2023).

Ongoing project collaborations were furthermore used to obtain information, including a meeting with pelagic fisheries Producer Organisations (POs) in Sweden and Denmark and with a fisher association of ocean-going fishing vessels in Norway (fiskebat.no).

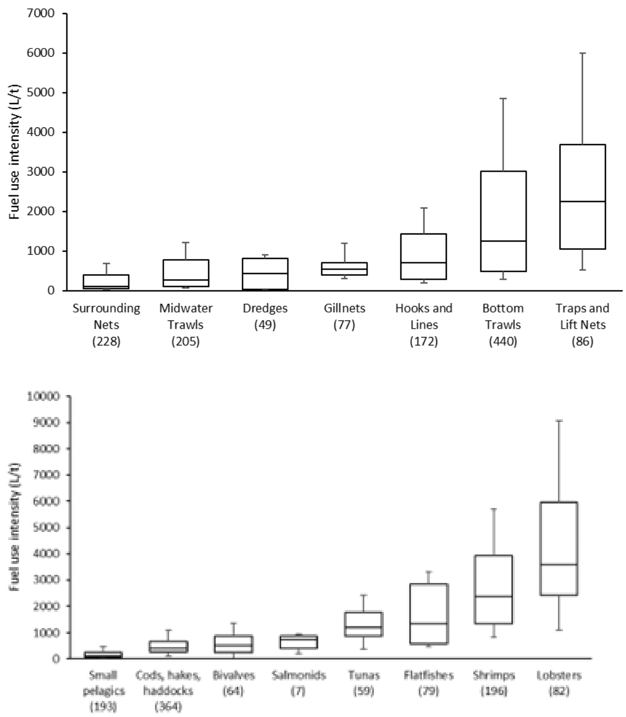
Grey literature of high relevance for the study was identified both from these initial contacts and the expert consultations held, in particular Bastardie et al. (2022a,c), Engelhard et al. (2022), Thompson & Thompson (2021) and Gabrielii and Jafarzadeh (2020).

3. Synthesis and findings

3.1. Current fuel use intensity in fisheries

The fuel use intensity (FUI) in l/kg landed of different fisheries is highly variable (Parker and Tyedmers 2015). At the extremes, small and shoaling pelagic fish can be fished extremely efficiently (often below 0.1 l/kg) whereas crustaceans, depending on species and gear type, are often found at the highest end of fuel use intensity (sometimes over 10 l/kg) (Fig.1). Depending on the level of detail studied and methodology used, several insights have been gained on the drivers, development and variability of FUI at different scales. Below, these are presented, starting on a global scale and going down to the fishing vessel level.

Figure 1: Fuel use intensity by gear classes and and by groups of target species.



Source: Prepared for this report by Robert Parker based on data from the Fisheries Energy Use Database (FEUD) Numbers in parentheses are count of records. Records truncated to exclude <1990 fishing year. Boxes are 25th to 75th percentiles, middle line is median, and whiskers are 10th to 90th percentiles. Groups names have been shortened for: Small pelagics (herrings, sardines, anchovies), Salmonids (salmons, trouts, smelts), Tunas (tunas, bonitos, billfishes), Flatfishes (flounders, halibuts, soles), Shrimps (shrimps, prawns), Lobsters (lobsters, spiny-rock lobsters), definitions following ISSCAAP.

For **global fisheries**, a fuel use intensity database has been built on collated records from different studies and industry, the Fisheries Energy Use Database (FEUD; Parker and Tyedmers 2015). The median FUI of global fisheries from the available records in FEUD since 1990 is 0.64 l/kg (Parker and Tyedmers 2015). Based on the differences in FUI between species groups and gear types, greenhouse gas emissions per tonne have increased with 21% between 1990 and 2011, driven by changed catch composition towards increased contribution from fuel use intensive crustacean fisheries (Parker et al. 2018). However, the FEUD database is not complete, so extrapolations and assumptions are needed when studying trends at global scale, and all factors with potential influence on fuel use intensity in a certain fishery cannot be considered (e.g., fleet structure, stock status). Other studies have used other approaches for global fisheries, such as using the engine power of fishing vessels and assume fishing effort (in hours) per fishing day for different fleet segments and fisheries (Greer et al. 2019). They suggest that greenhouse gas emissions (based on fuel use intensity) of global fisheries have increased, are considerably higher than previous estimates, and that small-scale fisheries are associated with significantly lower emissions per catch than large-scale, industrialized fisheries. This model, however, was not based on actual fuel use data, but on weakly grounded assumptions that were predestined to give that specific outcome (Ziegler et al. 2019). To conclude, there are large data gaps related to FUI of global fisheries, available records are not evenly distributed across the globe and robust methods or data collection strategies are needed to fill these data gaps.

On a **country or regional basis**, officially collected data often exists to inform on trends. This data is collected for economic purposes and is affected by collection strategy and extrapolation. One example is the fuel use data collection through the Data Collection Framework (DCF) that underpin the STECF Annual Economic Reports (AER) in the EU (STECF 2022). Other countries/regions have similar data collection, such as the annual Norwegian Profitability study where analyses have found reductions in fuel use intensity for Norwegian fisheries from 2003-2012 (Jafarzadeh et al. 2016), and from 2001-2015 (Skontorp Hognes and Jensen 2017). Similar data records have been studied for Icelandic fisheries, were reductions have been found for demersal species but not for pelagic fisheries from 2002-2017 (Byrne et al. 2021), and for some Australian fisheries during the 1990s and 2000s (Parker et al. 2015). Based on DCF data for the EU fleet, total fuel consumption of the EU fleet has continuously decreased since 2008, while landings have fluctuated; combined, the whole EU fishing fleet has today an average FUI of 0.5 l/kg, slightly fluctuating between 2008 and 2018 (STECF 2022). However, it has been found that this data is not suitable for analysis of FUI in different fisheries in the current data collection format and presentation, and calls have been made for appropriate level of data resolution (Bastardie et al. 2022a,c). The data collection is not complete and coverage varies between Member States, which have defined different methods of sampling their fleet. In addition, some collect fuel use data, other fuel cost. In the latter case, data needs to be translated to fuel volumes which, given the volatility of fuel prices, adds uncertainty to the estimations and makes comparisons difficult. As an alternative to use data collected for economic purposes to study trends at country or regional basis, Bastardie et al. (2022b) instead used an effort-based model to study fuel use intensity for Danish fisheries for the period 2015-2019. It was found that although effort declined, no significant drop in FUI could be seen, and that the variability observed between fleets and stocks may indicate opportunities for decreasing FUI; this includes promoting best-available gear types for the species in terms of fuel use intensity and rebuilding overfished stocks. Furthermore, it was found that target species with high value can sustain fisheries with high FUI; the high landing value will keep the fishery profitable, further supported by the tax exemption of fuel used in capture fisheries.

On a **fleet or fishery basis**, different analyses have been done to study potential effects from size of vessel or fleet structure on fuel use intensity, using different underpinning data. Cheilari et al. (2013) studied records underpinning the AER covering a fourth of the fishing vessels of the EU over 2002-2008. They found that overall, most energy efficiency indicators improved after 2004, coinciding with a fuel price increase, but that there was a variability across fleet segments. Furthermore, records indicate slightly fluctuating or improved FUI for the time period studied, with active and passive segments ending up around the same FUI at the end of the time series (up to ~1.5 l/kg) except for beam trawls at ~2.5 l/kg. This FUI is considerably higher than the average of the most recent STECF AER report, indicating improvements since 2008. There are also other more detailed studies using DCF-data, where as an example Ziegler and Hornborg (2014) found that the Swedish demersal trawl fisheries overall decreased their fuel use intensity during 2002-2010. Furthermore, no major difference in fuel use intensity between different sizes of vessels was found for the Swedish demersal fisheries; one exception is species-selective trawling for northern prawn (*Pandalus borealis*) with large vessels, where larger vessels become more fuel use intensive. However, from applying effort-based modelling of the northern prawn fishery in the Skagerrak, a fishery that was included in Ziegler and Hornborg (2014), different management strategies affecting fleet structure and quota share between countries was found to influence FUI for three countries fishing on the same stock (Ziegler et al. 2016b). In this fishery, the larger vessels had a higher FUI compared to smaller vessels in the Swedish and Norwegian fleets (where quota was limited and many vessels were engaged), while the opposite pattern was found for Denmark (where a few vessels were engaged to catch a large share of the quota). Other studies at fishery or fleet basis include:

1. Kristofersson et al. (2021) studied FUI of demersal fisheries in Iceland based on economic data collected and found that the greenhouse gas emissions decreased

with 40% between 1997-2018, with the most important driver being higher overall catches and abundance of stocks.

2. Bastardie et al. (2022a) studied trends in fuel use intensity for the North Sea beam trawl flatfish fishery based on STECF AER data. They found that FUI varied slightly between member states' fleets but were overall cut by half from year 2008 to around 2014 when it stabilized and slightly increased again in the most recent years. The decrease in FUI was primarily driven by higher catch efficiency, where besides influence of technological development, stock status was correlated with catch rates.
3. Chassot et al. (2021) developed a model based on different data inputs to study FUI of large-scale purse seine tuna fisheries in the western Indian Ocean between 1981-2019. They found considerable inter-annual variability, driven by tuna abundance, catchability and fishing strategies.
4. Sandison et al. (2021) studied own collected data on the Scottish pelagic fishing fleet and found inter-annual variability in fuel use to be small, assumed to be the result of opportunities for internal trading of quotas.
5. Ziegler et al. (2021) studied economic data collected for Norwegian fisheries and found that the FUI of shrimp fisheries is in general higher than those targeting fish and fluctuate considerably between years. Furthermore, the FUI of shrimp fisheries had increased by over 50% between 2007-2017, whereas it decreased by 20% for demersal fish and 5-10% for pelagic fish respectively.

Small-scale fisheries compared to large-scale fisheries deserves further attention, since these are often promoted as low-impact and fuel efficient (Greer et al. 2019), especially those using passive gears (Suuronen et al. 2012). Fuel use data from small scale fisheries is less available in global records, especially from developing countries, but when looking at differences between gear types, surrounding nets (such as purse seines) have an extremely low FUI with low variability whereas demersal trawls but also many passive gears (hook and lines, pots and traps) have a highly variable FUI (Parker and Tyedmers 2015). Thus, the FUI of small-scale fisheries arguably depends more on the fishing technology than the actual size of the vessel. A few recent examples where specific data have been collected include:

1. Ceballos-Santos et al. (2023) studied fisheries in Cantabria (northern Spain) targeting a mix of pelagic species with purse seines and longlines. They found that the small-scale fleet using longlines had a lower fuel use intensity compared to the purse seine fishery, 0.07 l/kg compared to 0.25 l/kg. This highlights the importance of data collection and use of appropriate data when discussing FUI of different fisheries, since the outcome of this study is the opposite to the general pattern seen in Parker and Tyedmers (2015).
2. Almeida et al. (2022) studied small-scale fishing for octopus in Algarve (Portugal). They found that this fishery had different FUI depending on passive gear type; on average 1.21 l/kg for traps and 0.5 l/kg when using pots to target the same species. Variability also differed, which may indicate differences in fishing behaviour or fishing grounds. Overall, the large difference in FUI illustrates the heterogeneity of the sector, even within a gear segment (pots and traps) and the same target species.
3. Ferrer et al. (2022) studied small-scale fisheries around Baja California (Mexico) and found that FUI increases sharply in fisheries where the target species has a $B/BMSY < 1$. This relationship highlights the importance of keeping healthy stocks also for small-scale fisheries.

On a **fishing vessel** basis, several factors interplay for FUI. For a demersal freeze trawler, it has been found that FUI may vary between trips depending on target species, where targeting of shrimps is generally associated with a higher FUI compared to fish due to lower catch rates (Ziegler et al. 2018). Furthermore, it was found that FUI could be more variable within a year than between years, driven by a combination of targeted species, fishing pattern and fishery regulations. Sandison et al. (2020) studied greenhouse gas emissions of the Scottish pelagic fleet (61 to 78.9 meters in length), of which over 96% of emissions were driven by the use of fossil fuels. They found variability between the eleven vessels supplying primary data, ranging between 0.28-0.74 CO_2e/kg landed round fish under the studied time period (2015-2017). The study suggests this variability is likely influenced by a skipper effect, a phenomenon also described in other fisheries (Ruttan and Tyedmers 2007). Chassot et al. (2021) also found differences in annual FUI of different tuna purse seiners, ranging from less than 0.5 l/kg to over 0.8 l/kg. On a fishing vessel basis, it can thus be said that FUI is driven both by the fuel consumption of the fishing operation (a combination of vessel, fishing behaviour and fishing technology including hourly fuel use) and the catchability of the targeted species. Several technological improvements can be made to reduce overall fuel consumption of fishing operations, both related to the vessel and the gear (Bastardie et al. 2022a); this will be further detailed in Chapter 4.

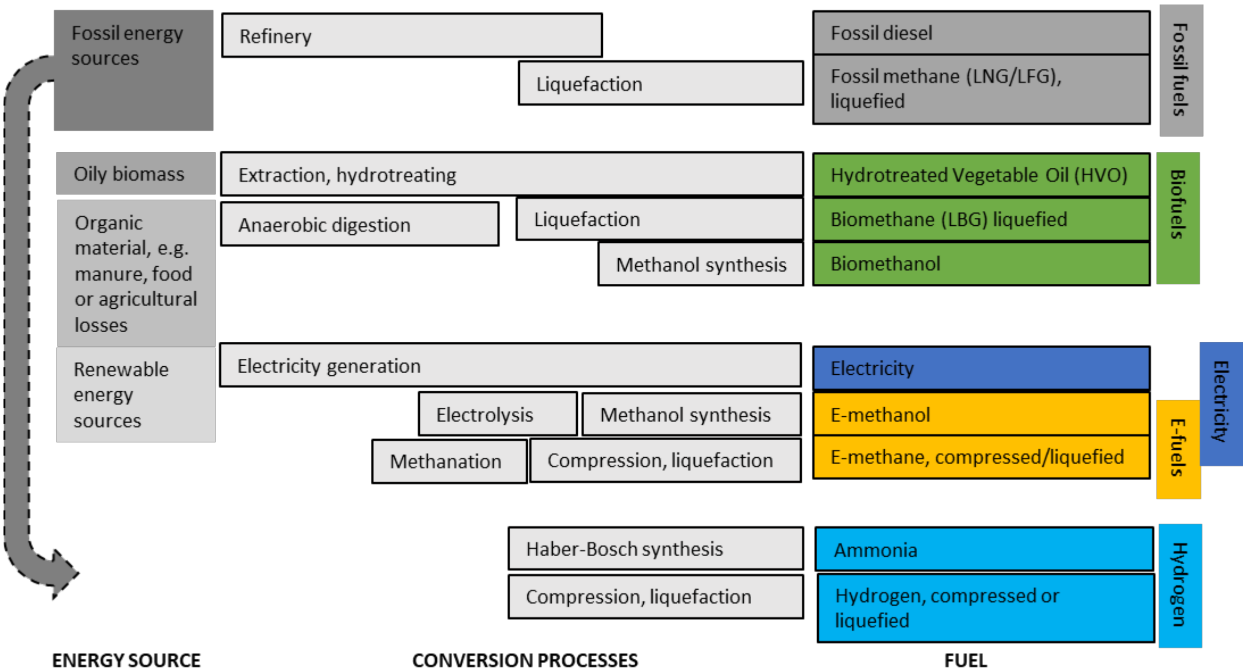
3.2. The status of alternative fuels in fisheries

As mentioned in the introduction, fossil fuels dominate as the energy source used in current fisheries and there are few available alternatives. There is a 'hen and egg' situation regarding the infrastructure available to supply new fuels to the maritime sector, including fisheries, where investment in infrastructure will not take place without sufficient demand – and vessels can not be operated on an alternative fuel that is not readily available in steady supply. The so called FuelEU Maritime regulation (part of the Fit for 55 package launched in 2021) aims to address this problem by stimulating the decarbonisation of the maritime sector by limiting the carbon intensity of fuels used and requiring use of electricity in port. In parallel to the present report, and EU initiative compiled examples of alternative fuels used or under development to be used in fisheries which is now available (EC 2023b).

In 2018, 0.3% of the world shipping fleet was using alternative fuels, while 6% of the vessels ordered in the same year had some kind of alternative propulsion system (Gabrielii and Jafarzadeh 2020). The decisions made in the shipping sector on how to decarbonise strongly influences the fishing sector due to the much larger volumes of fuel used in shipping; the fishing sector will thus benefit from infrastructure built by the shipping sector. Iceland is one of few countries where fisheries dominate the maritime sector (DNV 2021).

The recent increases in fuel prices – to levels higher than the price of taxed diesel in 2019 – combined with the need to phase out tax exemption, reducing the dependency on fossil fuels resulting in greenhouse gas emissions have speeded up the interest to transition to alternative fuels. This chapter will briefly introduce the main options for alternative fuels that are being discussed today, their characteristics and at what technological readiness level they are in in terms of introduction to the shipping and or fishing sectors. An overview over maritime fuels and their sources is given in Fig. 2 (modified from Brynolf et al. 2022).

Figure 2: Main current and future energy sources and pathways to possible future marine fuels, categorised into main fuel types.



Source : Modified from Brynolf et al. 2022, Fig. 9.3. The arrow indicates that fossil energy can be used to produce alternative fuels (with or without carbon capture technologies), including e-fuels and hydrogen, which strongly influences the emission profile of the fuel. L= Liquid, C= Compressed, LNG/LFG = Liquid Natural/Fossil Gas, LBG= Liquid Biogas, HVO= Hydrotreated Vegetable Oil.

3.2.1. Liquefied natural/fossil gas (LNG/LFG)

Liquefied natural/fossil gas (LNG/LFG) is cooled fossil methane which is still a fossil fuel, but one that decreases greenhouse gas emissions by around 25% compared to oil-based fuels when combusted. Liquefying the gas requires energy (about 10% of the energy contained in the fuel) but reduces the volume needed to store the fuel and leads to a low temperature (-162°C) which can be used on vessels where onboard refrigeration is needed to reduce the energy use for cold storage onboard (Jafarzadeh 2016). The maritime sector has long experience of transporting and handling LNG and this makes it easier to introduce as a fuel, although there are differences between transporting a substance and using it as a fuel. The price development of natural/fossil gas has however followed that of oil, making it problematic from a cost recovery perspective. Furthermore, there is a problem with methane slipping (uncombusted methane leaking out), which represents a loss of fuel and causes climate impact. The revised Energy Taxation Directive (EC 2021) proposed that fuels should be taxed per energy content and environmental impact, while low-carbon fuels are suggested to be exempt from tax during 10 years. Due to these challanges, neither the literature nor the experts consulted for this project foresee a large-scale use of LNG/LFG in future fisheries (Jafarzadeh et al. 2012, 2017). However, the infrastructure currently being built both in port and onboard for LNG can pave the way for biogas (see 3.2.3) and even ammonia (see 3.2.7). Although LNG/LFG today supplies a minor share of the fuel to the fishing sector and does not represent a major solution to decarbonising fisheries, it will likely be used by the sector at least in the short-term. LNG/LFG has additional advantages over conventional fuels such as lower emissions of particles, NO_x and improved working conditions on ships compared to conventional diesel. Compared to the zero emission fuels hydrogen and ammonia, LNG/LFG has the advantage that there is more experience and better infrastructure in place (Jafarzadeh, pers. comm), as well as the already mentioned potential to use the cold fuel to reduce the energy needed for refrigeration. Four fishing vessels operating on LNG/LFG are in use today worldwide and three are ordered (DNV 2022).

3.2.2. Electrification

Electrification can be done fully or partially (hybrid operation with diesel). The sustainability and climate outcome of using batteries onboard depends on how the electricity used to charge the batteries was produced. Also, the production of the batteries themselves can have other sustainability challenges than greenhouse gas emissions, such as requirement of limited rare earth elements. Norway is leading the electrification development both in the shipping and fishing sectors, where hybrid or fully electrified vessels are starting to be operated mainly in nearshore conditions due to the weight and space requirements of batteries (see e.g. projects listed in Table A1 in Annex 1). It is more energy-efficient to use electricity directly, rather than using it to produce e-fuels (see below), but the weight, size and cost of batteries at present prevents their wider use in offshore applications. Currently, 25 battery-run fishing vessels are operating in the world (DNV 2022). When multiple fuels are used in hybrid-solutions, it is important to stimulate use of the most low-impact fuel and minimise the time the engine is run on diesel. Based on the expert consultation with Sepideh Jafarzadeh, there are indications that some of the hybrid vessels use electricity mainly during fishing (a minor part of the energy use for passive gear fisheries), but often diesel when steaming. An additional advantage of hybrid operation is that batteries can be used to enable operation of the engine closer to its optimum, which reduces the fuel use. This was e.g. the case with new tuna purse seiners (Chassot et al. 2021). However, the need for ultra-freezing actually led to increased fuel use, as the storage was run by diesel. In such cases, it could be worthwhile to consider renewable methane or other compressed or liquefied fuels (see below).

3.2.3. Biofuels and e-fuels: Methane

Methane from renewable sources of biomass (biogas) can be used in the same way as LNG/LFG and has the same properties – and some challenges. It can be produced through anaerobic digestion or direct gasification, in the latter case the methane is cleaner in the sense that it is not mixed with propane and ethane. It can also be produced through the electrofuel route, i.e. using electricity, combining renewable carbon dioxide and hydrogen in a methanation reactor (Fig. 2). Methane slipping is still an issue for biogas and there seems to be a tradeoff between NO_x emissions and methane slip for different engine technologies (Brynolf et al. 2022). Biogas is, to our knowledge, currently not used as a fuel in any fishing vessel. Biogas can also be liquefied to Liquefied Biogas (LBG). This fuel requires the same infrastructure in port and onboard as LNG/LFG and the uptake of LNG/LFG in the shipping sector can therefore pave the way for future wider use of LBG in both shipping and fisheries. In 2018, the first maritime bunkering of LBG took place in Sweden, but this was not for fishing vessels.

3.2.4. Biofuels and e-fuels: Biodiesel/HVO

Biodiesel generated from different forms of biomass is a liquid fuel that can be mixed with or replace fossil diesel straight away using existing vessels and fuel infrastructure. It was therefore seen as the most promising alternative fuel today by the Swedish and Danish Pelagic Producer Organisations contacted. Despite its name, Hydrotreated Vegetable Oil (HVO), it is often produced from animal-sourced by-products from the meat processing industry, but it can also be produced from basically any type of biological raw oil from agriculture or the pulp and paper industry. The main challenge for scaling up is the availability of these raw oils. It is also important to carefully consider whether these by-products should be seen as raw material free from any impact generated during the upstream industry; this is an important methodological decision in Life Cycle Assessments which can lead to large differences when quantifying their greenhouse gas emissions. If livestock-based by-products from a greenhouse gas intensive sector are sold to biodiesel producers, it is difficult to argue that they are not part of the economics of the livestock industry and contribute to its profitability, especially when demand for biodiesel increases. Regardless, as with methane, the type of biomass or energy source used to produce the biodiesel is therefore key to the greenhouse gas emission profile. Biodiesel is, to our knowledge, currently not used as a fuel on fishing vessels.

3.2.5. Biofuels and e-fuels: Methanol

Alcohols are liquid fuels just like the conventional fossil fuels and the main alcohol discussed as a future maritime fuel is methanol. It can be used in dual-fuel concepts together with diesel or replace diesel oil. While the main production pathway for methanol is fossil today (using LNG/LFG), it can be produced from renewable sources as an e-fuel (using a similar production pathway as e-methane, Fig. 2). One important aspect that needs control due to toxicity and health hazard is that formaldehyde can be formed in the combustion process, but it has the advantage that it is one of the fuels that need the least modification of tanks when shifting from diesel oil (besides biodiesel). In case of leakage, methanol mixes with water and is biodegradable and is not classified as a marine pollutant. This makes it possible to place tanks on or even in ship hulls, which reduces the problem of lost space from using less energy-dense fuels. Methanol bunkering is also less complex than that of gaseous fuels, but the energy density is only about half of that of diesel oil (Fig. 3). An Icelandic trawler is currently being converted to diesel-methanol dual fuel operation (urseafood.is) and development in this area is intense (EC 2023b).

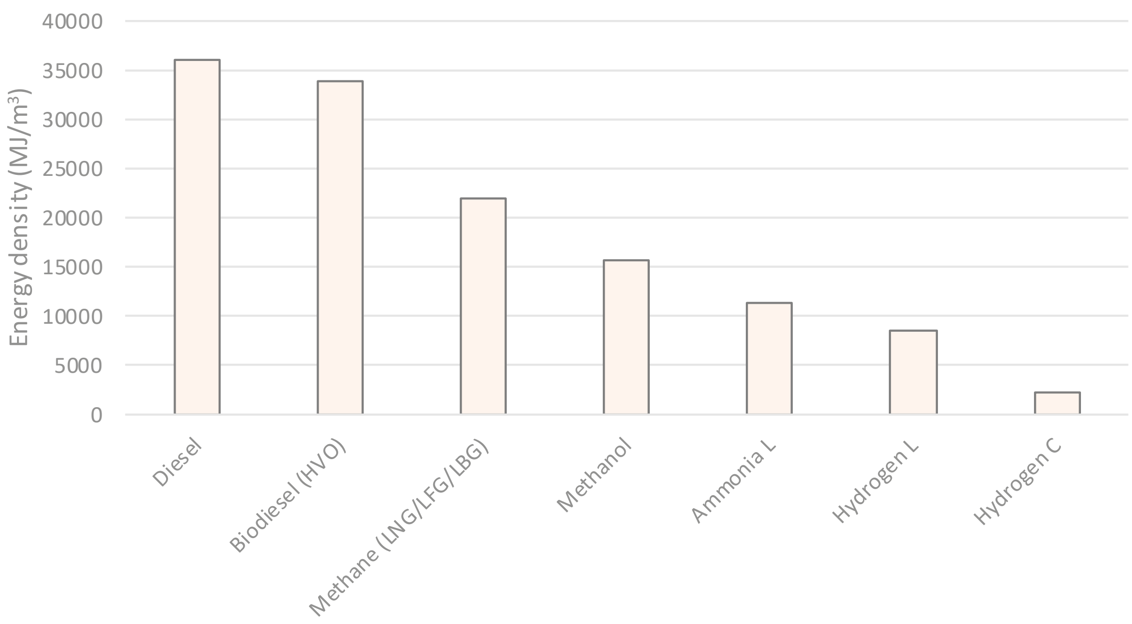
3.2.6. Hydrogen

Hydrogen is classified as a zero emission fuel, but just as for other fuels, its life cycle-based emissions depend on how the hydrogen has been produced. Hydrogen in compressed or liquefied form can be combusted, but this leads to large NO_x emissions. If hydrogen is liquefied, this process requires around 30% of the energy content of the fuel, which leads to high capital costs, also due to the need for insulated cryogenic (very low temperature) tanks. Hydrogen can also be used in fuel cells and it has been estimated that 1l of diesel can be replaced by 0.2 kg of hydrogen, which, with current average hydrogen production emissions, leads to a 75% reduction of greenhouse gas emissions. Applications using hydrogen are being developed both for shipping (Brynolf et al. 2022) and fish farming (Gabrielii and Jafarzadeh 2020). Hydrogen applications for fishing vessels are in a very early stage and development is intense (EC 2023b).

3.2.7. Ammonia

Recently, ammonia has come into focus in discussions about future maritime fuels. It is a fas that is already widely used as a climate-neutral refrigerant replacing older types of so called hard or soft freons, which both have a very high global warming potential ('soft' freons having a lower ozone depletion potential). Ammonia can be seen as another way to store hydrogen and can be liquefied at a much higher temperature than hydrogen (-33 instead of -253°C) or at room temperature to a pressure of 7.5 bar. It is more energy dense than hydrogen and thus gives more energy per volume used and therefore demands less space onboard which is preferable on longer trips. Compared to LNG/LFG or methanol, the need for insulated pressurized tanks for ammonia gives rise to increased volume need. However, there is no need for cryogenic tanks, as for LNG/LFG and liquefied hydrogen. The tanks used for LNG/LFG seem to be possible to use also for ammonia, a reason why investing in such technology today still could be worthwhile also when shifting away from LNG/LFG. Historically, there were safety risks involved when using ammonia onboard, as it is explosive. These risks have been mitigated to the extent that ammonia is the most frequent refrigerant used in new vessels today (Sandison et al. 2020; Skontorp Hognes & Jensen 2017; Söylemez et al. 2022). The experience of using ammonia onboard as refrigerant, and of transporting it, gives some experience of handling it that makes it easier to start using it also as a fuel. Leakages or spills would still pose a risk both for fishers and the marine environment and add to the volume of reactive nitrogen circulating with potential impacts such as eutrophication. To our knowledge, ammonia is currently not used as a fuel on fishing vessels.

Figure 3: Energy density of current and future maritime fuels



Source: Data from Brynolf et al. 2022, Table 9.2. L= Liquid, C= Compressed, LNG/LFG = Liquid Natural/Fossil Gas, LBG= Liquid Biogas, HVO= Hydrotreated Vegetable Oil.

3.3. Summary of projects

The search for projects related to decarbonising the fishing sector resulted in identification of 45 ongoing or finalised projects with various approaches in relation to the topic (Table A1). While a large proportion of the projects are performed through practical application such as development and testing of new technology (66 %), there is also a group of projects that rather concern management and social aspects such as decision-making tools, policy instruments and/or competence building (30%). Among the projects that are performed at national level, there is a predominant representation of Scandinavian countries – of the total number of projects identified, 36% and 16% are based in Norway and Sweden, respectively. Denmark, Iceland and Italy are represented as well. The searches were undertaken in one European and one Norwegian project database, which of course influences which projects are found, as do the experts consulted who pointed us to additional literature and projects in their vicinity.

Thematically, a majority of the practically characterised projects explicitly concern reduction of fuel use and promotion of energy efficiency through concrete measures related to gear development, infrastructure and/or introduction of alternative fuels. However, even measures that are not directly aimed at reducing the use of fuel, such as autonomous vessel technology to detect fish, can be assumed to ultimately have beneficial side effects by making fishing operations more efficient. Gear development within the projects target trawlers or coastal fishing vessels, and otherwise fishing vessels in general, and include improvements such as digitalisation, electrification and hybrid solutions for batteries and propulsion systems. Alternative sources of energy that are being tested in the projects include ammonia, biofuels, hydrogen, lithium batteries and methanol, and a recurrent topic is infrastructure and technology that makes alternative fuels more accessible to the fishing sector, such as on-board extraction of energy and sea-based platforms for on-site conversion of wind and wave power into hydrogen. Another theme is development of technology related to artificial intelligence and automatisation. Examples include trawl equipment with ability to diagnose operational efficiency by processing data, and optimisation of sailing routes and time schedules through self-learning ship performance.

Projects related to management include development of assessment frameworks and decision-making tools that integrates environmental sustainability, and development of knowledge to improve catch regulations regarding, for instance, quotas. Only one project explicitly aims at educating crew, however several projects focus on competence building and knowledge development through collaboration and creation of networks and platforms in which fishers can constitute one of the actors included.

4. Measures to decarbonise fisheries

Through a combination of review of scientific and grey literature, project searches leading to more grey literature, expert consultations and additional publications and projects provided by the experts, a number of measures to decarbonise fisheries were identified. Measures are actions that can be taken by different actors to reduce fuel use and/or emissions. Findings were compiled into a table which was sent to the consulted experts who were invited to provide input before finalization (Table 2). In the table, the measures are grouped into different areas depending on which societal actor or mechanism that requires change, such as fishery management, fishing technology; or outside the fishing sector. Fishery management measures have been separated into those that require a major policy change (such as a change in objectives), merely implementation of existing policy (such as article 17 of the current CFP) or require minor adjustements in policy to provide incentives. For all areas, a brief summary of current 'feasibility' (main barriers and challenges today) and 'enablers' in the form of policy options that facilitate and enable these measures that are in the remit of the fishery sector are provided. Furthermore, an indicative cost estimation for the fishing industry on the short- and longer-term, and the potential range of emission reduction opportunities was quantified, based on available information, and categorized as described below. Needless to say is that the uncertainty around greenhouse gas emission reduction potential and costs is high, and that these estimations are highly context-dependent, depending on e.g., the starting point for a vessel and fishery, and should be seen as merely indicative.

Interpretation of Table 2:

(green)	Aligns with economic objectives (for the fishers remaining in the fishery).
(yellow)	May increase costs to the fishing industry (e.g. initial or smaller investments), if possible, qualitative assessment of scale inserted in the form of high-medium-low costs.
*	Small reduction (≤10%)
**	Medium reduction (≤50%)
***	Large reduction (>50%)

Reduction potentials should be seen as indicative since these are very context dependent and cannot easily be compared across measures.

Abbreviations: fuel use intensity (FUI, in l/kg), maximum economic yield (MEY), maximum sustainable yield (MSY), Common Fisheries Policy (CFP), Marine Strategy Framework Directive (MSFD), European Maritime, Fisheries and Aquaculture Fund (EMFAF), Data Collection Framework (DCF), International Convention for the Prevention of Pollution from Ships (MARPOL), International Maritime Organization (IMO), European Union Emissions Trading System (EU-ETS), hydrochlorofluorocarbons/hydrofluorocarbons (HCFC/HFC), greenhouse gas (GHG).

Table 2: Potential measures that could be taken towards decarbonisation of fisheries involving both energy efficiency and alternative fuels.

Area	Measure	GHG emission reduction potential	Cost (5 ys)	Cost (≥5 ys)	Motivation and feasibility (barriers and challenges)	Policy options (to enable measure)	Example references
Fishery management	Change in policy – **Include low GHG emissions as objective**	***	low-high[1]		Reductions through management measures will only be prioritized if stated as an objective. The reduction potential is seen as high but is dependent on effective policy instruments. If prioritized over other goals, it may conflict social objectives and introduce short-term costs to industry (investments). Making data from energy audits or standardized surveys available on a suitable level of aggregation is vital for this measure.	See section 6.1 and 6.2	Ziegler et al. 2016a; Ziegler & Hornborg 2014; Sala et al. 2021; Epstein et al. 2022; expert consultations (Bastardie & Eigaard; Sepideh Jafarzadeh; Antonello Sala; Jordi Guillen)
	Change in policy- **Allocate allowable emissions to fisheries**	**	medium		Instead of including the overall sector in the EU-ETS, emission quotas could be allocated to the fishing sector by fishery. This increased predictability and transparency incentivise fuel saving, and emission-reducing investments. Designing the initial allocation method could be challenging. Requires monitoring of fuel purchases and quota trade. If tradeable, one benefit may be that it could be a cost-effective policy instrument when fishers with opportunities for having low costs to reduce emissions may sell their emission quotas.	See section 6.1	Byrne et al. 2021
	Change in policy –**Set target at MEY instead of MSY**	***			Generally, allows for higher fish abundance and catch efficiency, and thus improved profits. MEY however requires more data and analysis, may not be applicable for all fisheries, and will introduce short-term loss in catch volume. Implies further fleet and effort cuts.	See section 6.1 and 6.2	Hornborg & Smith 2020; Farmery et al. 2014

Area	Measure	GHG emission reduction potential	Cost (5 ys)	Cost (≥5 ys)	Motivation and feasibility (barriers and challenges)	Policy options (to enable measure)	Example references
	CFP implementation – **Eliminate overcapacity and rebuild stocks**	***			No linear correlation and requires additional regulations (e.g. not increase the quota when abundance increase), social implications from fleet cuts. Requires effective cooperation with neighbouring countries that exploit the same stocks.	See section 6.1 and 6.2	Waldo et al. 2016; Kristofersson et al. 2021; Ferrer et al. 2022; Parker et al. 2015, Byrne et al. 2021, Malmström et al. 2023, Bastardie et al. (2022b); expert consultation (Peter Tyedmers & Rob Parker)
	CFP implementation – **Apply article 17 in CFP and align with MSFD**	***	medium		Most direct reduction potential since change in gear can be done immediately, but may require large restructure of some fleets, initial investments and have social implications. Path dependency hinder (management and fishing traditions). Aligns with the EU Biodiversity Strategy for 2030 and progress towards achieving Good Environmental Status (MSFD).	See section 6.1 and 6.2	Bastardie et al. 2022c including Annex; expert consultation (Peter Tyedmers, Rob Parker, Jordi Guillen)
	Incentivising – **More gear flexibility allowing for fuel use efficiency**	***	low		Need robust decision-support at regulating agencies for this to be efficient and to make sure trade-offs don't occur (by-catch, effect on fishing mortality). The estimated low cost is due to potential costs for changing gears.	See section 6.1 and 6.2	Bastardie et al. 2022c, including Annex
	Incentivising – **Design catch shares and a fleet structure allowing for fuel use efficiency**	**			With catch shares, fishers may plan their activities better and may allow improved fuel use efficiency through less competition. Well-designed systems are however needed to not conflict social objectives.	See section 6.1 and 6.2	Thompson & Thompson (2021); Sandison et al. (2021); pelagic fisheries PO in Sweden; expert consultation (Jordi Guillen)
Fishi ng Tech	Optimise vessels- **Fuel optimised hull design**	***	low-high		Feasibility high when vessels are to be replaced (at low additional cost when designing a new vessel), low feasibility due	Define the operational profile of the vessel and let it guide vessel design	Expert consultation (Antonello Sala)

Area	Measure	GHG emission reduction potential	Cost (5 ys)	Cost (≥5 ys)	Motivation and feasibility (barriers and challenges)	Policy options (to enable measure)	Example references
					to increasing cost of replacing a vessel before it is needed due to e.g., vessel lifetime.	Relax vessel length restrictions so that vessels can be designed to be most fuel efficient	
	Optimise vessels – **Drag force reduction including hull cleaning and treatment**	**	low		Requires investments and change in behaviour (fouling treatment)	Define the operational profile of the vessel and let it guide optimisation Introduce regulations and cost models incentivising fuel use efficiency Allocate well-designed structural funds (EMFAF), e.g. per degree of reduction enabled. Require frequent hull cleaning	Bastardie et al. 2022c including Annex, (Table 12); Thompson & Thompson (2021); Norwegian Government (2019)
	Optimise vessels – **Optimise operations**	*	low		Crucial with solutions tailored for operation needs, but requires training of crew for optimised fishing, system thinking on how to target energy consuming, installations, and installations (e.g. autonomous operations, positioning) Resistance to change, absence of strong leadership/collaboration, lack of vision and strategy, lack of communication. Short term wins are not celebrated	Define the operational profile of the vessel and let it guide optimisation Allocate funds for installing flow meters (EMFAF) Allocate funds for training crew in fuel-saving vessel operation Introduce regulations and cost models incentivising fuel use efficiency	Expert consultation (Andreas Bach & Fredrik von Elern) Bastardie et al. (2022c); SEAOPS (Appendix 1), Gabrielli (presentation at ClientEarth/OurFish workshop); Expert consultation (Antonello Sala)
	Optimise vessels – **Improved engine (propulsion and auxiliary engines)**	**	low		Many technological innovations exist to promote energy efficiency.	Define the operational profile of the vessel and let it guide optimisation Allocate well-designed structural funds (EMFAF)	Bastardie et al. (2022c); Thorion (Appendix 1); Wang et al. 2022
	Optimise gear – **Drag force reduction and**	**	low		Poor uptake of gears developed, easier for fishers to modify existing gears than change to other gear types. Gear modification has the largest effect in demersal fisheries.	Allocate well-designed structural funds (EMFAF) to gear development	Bastardie et al. (2022c); Sala et al. (2008)

Area	Measure	GHG emission reduction potential	Cost (5 ys)	Cost (≥5 ys)	Motivation and feasibility (barriers and challenges)	Policy options (to enable measure)	Example references
	improved catchability						
	Use cleanest diesel	*	low	low	Black carbon has an albedo effect and with no incentive to buy diesel with the lowest emissions, price and availability will determine which fuel that is used.	Lower tax/fee for cleanest diesel	Zhang et al. (2019)
Fishing behaviour	**Planning of fishing activities (when and where to fish)**	**			Feasible (already done when fuel prices go up, through AIS fishers may already choose fishing location easier and spend less time searching) but care must be taken to avoid tradeoffs regarding e.g. by-catch	Minimise competition between fishers through e.g., catch shares Allow more flexibility in fishing patterns to minimise fuel use	Bastardie et al. (2022c); Abernethy et al. (2010); FishGuider (Appendix 1); Swedish pelagic fisheries PO
	Reduce or optimise speed	**			Direct effect that doesn't require investments and may outperform reductions from e.g., vessel design. Increases time spent fishing (and potential cost of labour) and are affected by personal motivation and fuel prices.	Redirect current tax exemption of fuel to instead support funding for fishers that take reduction measures, or support of extra cost for labor.	Bastardie et al. (2022c); Sala et al. (2011)
	Energy audits and crew training	**	low		Vital first step for energy efficiency and proper choice and use of alternative energy solutions. Baselines enables establishment of measures against defined benchmarks, and monitoring effects from measures and new technology. Other environmental issues may be addressed simultaneously.	Allocate funds fisheries on installing flow meters (EMFAF) Incentivise for other actors to develop and perform energy audits and crew training Revive the website (EC 2023c) with training materials, tips, application forms for fuel reducing measures etc.	Sala et al. (2022); Bastardie et al. (2022c); expert consultation (Antonello Sala)
Alternative energy	**Liquefied Natural/Fossil Gas (LNG/LFG)**	**	high	low	Number of LNG ships are increasing but is little motivated today due to costs and low availability of bunkering options in some regions, uncertainties related to methane slip and upcoming regulations, requirement of larger tanks on vessels and safety issues.	Not specific policies needed for its promotion as it is a fossil fuel that is already being implemented, but can be part of future fuel flexible solutions and can in particular pave the way for renewable methane.	Brynolf et al. (2022); Gabrielii & Jafarzadeh (2020); Jafarzadeh (2016); expert consultation (Sepideh Jafarzadeh, Andreas Bach & Fredrik von Elern)

<table>
<tr><th>Area</th><th>Measure</th><th>GHG emission reduction potential</th><th>Cost (5 ys)</th><th>Cost (≥5 ys)</th><th>Motivation and feasibility (barriers and challenges)</th><th>Policy options (to enable measure)</th><th>Example references</th></tr>
<tr><td></td><td>Hybrid (fossil/electric)</td><td>**2</td><td>medium</td><td></td><td>Battery mainly used when fishing today, fuel when steaming. Optimises diesel engine operation. Feasible in nearshore settings</td><td rowspan="5">The same policy options are enablers for incentivizing use of the different alternative fuels:

Ban use of fossil fuels by 2050

Aim for fuel flexibility when incentivizing energy transition

Define the operational profile of the vessel and let it guide optimization

Allocate well-designed structural funds (EMFAF)

Relax vessel length and kW restrictions

Support land infrastructure (e.g., redirection of taxes)

Compensate for green investments</td><td>Van Leeuwen & Monios (2022); Gabrielii and Jafarzadeh (2020), pers comm with Norwegian fisher organisation Fiskebåt; Brynolf et al. (2022); expert consultation (Sepideh Jafarzadeh)</td></tr>
<tr><td></td><td>Sail assisted propulsion and wave energy</td><td>***</td><td>high</td><td></td><td>High investment cost but lowers operating costs permanently, payback time 2.5 years for longliner in Panama. No production, storage, distribution cost or infrastructure needed for energy provider. In IPCC, seen as having the largest potential (reductions and at lower costs), although associated with large uncertainties.</td><td>Van Leeuwen & Monios (2022); Ayro WingSail (EP hearing); Bound4Blue eSAIL (ClientEarth /OurFish WS); Wavefoil (Annex 1)</td></tr>
<tr><td></td><td>Full electrification</td><td>***2</td><td>high</td><td></td><td>Batteries are expensive, heavy and can affect vessel stability, take up a lot of space on or under deck. Lack of infrastructure on land. Not feasible for offshore fleets. May be feasible for nearshore, but flexibility is preferable.</td><td>Van Leeuwen & Monios (2022); Brynolf et al. (2022); Gabrielii & Jafarzadeh (2020), expert consultation (Sepideh Jafarzadeh), Icelandic proposal (Fiskerforum 2022, IGOV 2022)</td></tr>
<tr><td></td><td>Methanol</td><td>***2</td><td>high</td><td>medium</td><td>Promising but requires twice the storage capacity of diesel. GHGs and competition with food/feed production depends on biofuel production pathway.</td><td>Brynolf et al. (2022); Gabrielii & Jafarzadeh (2020)</td></tr>
<tr><td></td><td>Biofuels (biogas, biodiesel)</td><td>** 2</td><td>high</td><td>low</td><td>Low investment but higher operation costs. GHGs and competition with food/feed production depends on biofuel production</td><td>Brynolf et al. (2022); Gabrielii & Jafarzadeh (2020); Byrne et al.</td></tr>
</table>

Area	Measure	GHG emission reduction potential	Cost (5 ys)	Cost (≥5 ys)	Motivation and feasibility (barriers and challenges)	Policy options (to enable measure)	Example references
					pathway. Might reduce incentives to apply other more cost-effective measures.		(2021); IPCC (AR6 WGIII, Figure SPM7)
	Hydrogen	***2	high	medium	Hydrogen-fed fuel cells are promising in the long-term but not ready yet. Storage onboard, infrastructure, cost, and safety issues are main challenges because it requires cooling for liquid form and gaseous takes space.		Zerokyst; expert consultations (Sepideh Jafarzadeh, Andreas Bach & Fredrik von Elern); Brynolf et al. (2022); Gabrielii & Jafarzadeh (2020)
	Ammonia	***2	high	medium	Promising due to less space required onboard, already used in refrigeration, and existing LNG bunkering infrastructure may be used. Main challenges include currently available bunkering infrastructure, safety, end use and existing value chains.		Gabrielli (presentation at ClientEarth/OurFish workshop); Brynolf et al. (2022); Gabrielii & Jafarzadeh (2020)
Catch use	**Full utilization of catch and trimmings**	*	low		Reduces fuel use/emissions per kg of the product and goes hand in hand with reducing product losses and may give more income to the fishery, although requires more processing time, but it does not reduce fuel use/emissions of the fishery	Incentive full catch utilization	Norwegian regulation to allocate additional quota to vessels producing silage onboard form processing side streams
Societal	**Phase out climate-forcing refrigerants**	**	medium		Replacing synthetic by natural refrigerants has a large potential, where these are still used. Conversion costs are high, but refrigerant costs are thereafter lower.	Support (through e.g., EMFAF) for full conversion from synthetic (HCFC or HFC) to natural refrigerants such as ammonia.	CoolFish (Annex 1); Söylemez et al. (2022); IPCC report (AR6 WGIII Figure SPM7)
	Green infrastructure in ports	*			Providing green infrastructure on land is a large societal cost but of no cost to the fishing industry and essential for energy transition. Many challenges, including lack of energy/effect, different frequency of energy, and no real business opportunity for ports but many ports are working with this.	Include fisheries in Fit for 55 (set of proposals for EU Green Transition) Allocate structural funds to support installation costs	pelagic fisher in DK; expert consultation (Andreas Bach & Fredrik von Elern)

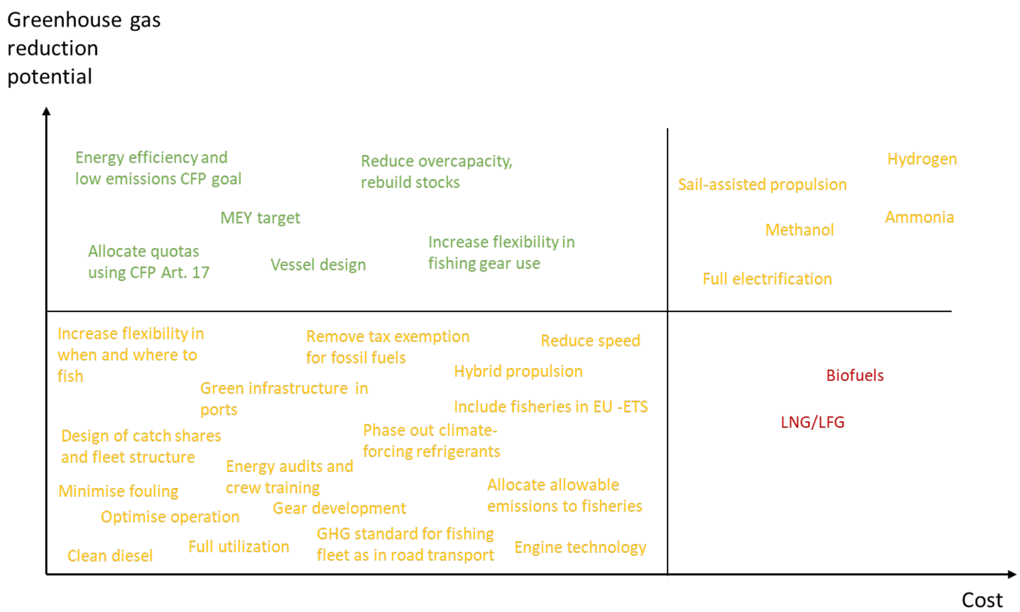
Area	Measure	GHG emission reduction potential	Cost (5 ys)	Cost (≥5 ys)	Motivation and feasibility (barriers and challenges)	Policy options (to enable measure)	Example references
	Incentivising – **GHG standard for fishing fleet**	**	low	low	Creates incentives and has worked for electrification of transports, but unclear on what level this could be implemented for fisheries (company, fleet or country?).	Set greenhouse gas emission standard for 'average fleet' under what is achievable by conventional fuels to trigger investments, which are smaller on a fleet than on a vessel level	Comment made at ClientEarth/OurFish workshop in June 2022
Economy	**Introduce GHG emission fee through including fisheries in EU-ETS scheme**	**	medium		A green transition is challenging without incentives to decrease emissions/improve fuel use efficiency and the EU commission has suggested that the fishing sector should be included in the EU-ETS scheme; ensuring optimum management (rebuild stocks, reduce overcapacity) may however have larger effect.	See section 6.3	Waldo et al. (2016); expert consultations (Selma Brynolf & Maria Grahn, Sepideh Jafarzadeh); Norwegian Government (2019)
	Remove general tax exemption	**	low-high	low-high	Eliminating the current tax exemption is a cost-effective economic policy instrument to favour energy efficiency. However, increased fuel cost will hit fleets differently, with strongest effect on inefficient fisheries with low catch value. This could be mitigated through well-designed compensation, such as redirecting support for green investments. If aiming for reduced emissions, removing the exemption could be counter-productive if exemptions remain in place for emissions from higher impact protein sources such as beef.	See section 6.3	Waldo et al. (2016); Carvalho & Guillen (2021); EC (2021); Bastardie et al. (2022b)

[1]depending on if only improving fuel use efficiency (low cost) or installing alternative energy solutions (high cost)

[2]assumes only renewable energy is used in the production

Table 2 shows that six of the identified measures are assessed to have both high greenhouse gas emissions reduction potential and low or medium costs, indicated by green text in the summarizing Figure 4. These measures are all related to energy efficiency (rather than to alternative fuels) and represent the most low-hanging fruits to pick. At the other end, LNG/LFG and biofuels are found marked red, because they are rated as having a medium emission reduction potential and high costs. Figure 4 is only intended to illustrate the outcome of Table 2 and should not be seen as a recommendation not to go for LNG/LFG or biofuels, in particular because the uncertainties in these estimations must be considered to be large. It is important to keep in mind that the costs are the short-term costs incurred for the industry remaining in the industry after the measure has been introduced. Most measures fall into the lower left square where the reduction potential is lower than for the green ones, low or medium, and costs are also estimated to be low or medium. Most alternative fuels are also marked in yellow, because they are assessed to have a high reduction potential (if produced using renewable energy), but also high costs on the short-term, therefore representing more 'high-hanging fruits'.

Figure 4: Summary of findings in table 3 in terms of greenhouse gas reduction potential and cost.



Source: Table 2. Measures grouped according to Measures shown in green if they have a high GHG reduction potential (***) and low or medium costs (see Table 2), as red if they either have a low reduction potential (*) and medium or high costs or medium reduction potential (**) and high costs. Measures in yellow are either lower potential (lower left square) than the green-marked ones - or higher cost (upper right square). The measures are not scaled/ranked within each square. The cost estimate represents a best estimation of short-term costs (<5 years) for the fishing industry remaining after introducing the measure based on the information available, and is connected to considerable uncertainty and variability. The reduction potentials do not have a timescale, some can be immediate, others take longer time.

Available opportunities to reduce fuel use and emissions span from no added cost to industry to major investments required– and highlights the importance of a systems perspective. As a first step, a green transition in fisheries is challenging without political will and incentives to decrease emissions/improve fuel use efficiency. Following this, it is vital to acknowledge the necessity of taking actions towards ensuring an optimally managed fishery (e.g., rebuild stocks and reduce overcapacity); relative to these measures, the potential further reductions enabled through technological measures or introducing costs for emissions or fuel costs may be small (e.g., Waldo et al. 2016; Parker et al. 2018). For the individual fisher, in the short term, operational changes such as slowing down during steaming are quicker and more effective, and come with no extra cost (except the extra time). In comparison, technological innovations such as implementing minor changes to vessel and gears, typically individually result in smaller reductions, although combined, they can lead to substantial reductions, and they require some investment. Furthermore, to facilitate energy efficiency and the green transition, providing the right incentives in fishery management is important, especially since use of alternative fuels today comes at higher costs and inefficient fisheries are maintained and supported by current practice (fishing pattern, overcapacity, gear allocations, tax exemption, etc.). Optimizing fisheries for low emissions per unit caught instead of overall catch volume would be a good starting point; this form of larger changes such as allowing for higher stock abundance by changing fishing policy from MSY to MEY would improve fishing economy, fuel use efficiency – as well as be a more risk-adverse fishing strategy in a broader perspective, including ecosystem considerations (Hornborg and Smith 2020).

4.1. Energy efficiency

This report has identified several pathways to reduced fuel use intensity at different scales. An array of potential drivers behind fuel use intensity can be identified, and opportunities for reduction are within the remit of a range of different actors (Table 2). For further details on the potential reduction from specific measures, a few recent reports provide useful overviews of a large and complex area (Bastardie et al. 2022c, Thompson & Thompson 2021, Gabrielii & Jafarzadeh 2020). Some measures are more difficult to implement than others; there are differences in what may be achieved by a single fisher relative to what must be done at a higher level such fishery management (national) and policy objectives (regional). It is also a matter of costs for the fishing industry, in the short term compared to longer perspectives.

'If low fuel use intensity was stated as an explicit goal of fisheries management, this would improve data and monitoring, which is the first step towards reduction.'

Source: Expert consultation with Jordi Guillen, fisheries economist

In a study on Nordic fisheries, it has been found that managing fisheries for optimised economy (fleet size and rebuilt stock) has the potential to reduce fuel consumption by 29% and improve economic performance by 100% - outweighing any additional benefits foreseen from other measures such as including fisheries in emission trading systems, impose CO_2-taxes or taxing fuels as is done for private citizens (Waldo et al. 2016).

Maintaining healthy stocks which allows for higher abundance in the sea and thereby improved catch efficiency may thus decrease FUI, although the correlation is not always straightforward. At management level, a theoretical investigation has found that changing target reference points from the current EU Common Fisheries Policy objective of Maximum Sustainable Yield (MSY) to instead Maximum Economic Yield (MEY) may allow for larger reductions in FUI compared to losses in landings (Hornborg and Smith 2020). An Australian case study found a potential, theoretical reduction in emissions by 80% from fishing at MEY (Farmery et al. 2014). In terms of empirical evidence, there is support for a correlation between FUI and stock abundance, but there may also be regulatory constraints and compensatory effects. As an example, although stock abundances were found to be important to FUI of Icelandic fisheries, the effects differed between fishing sectors (Byrne et al. 2021). A potential explanation put forward by the authors could be choke effects introduced when some stocks increase more in abundance compared to others in mixed fisheries, and the most quota-restrained species may trigger avoidance behaviour. Bastardie et al. (2022a) also investigated this correlation and that found that it can occur suggest but also that it also may be prone to compensatory or rebound effects; if overall fuel costs are reduced from higher catch efficiency it may allow for more fishing effort and by this preventing overall fuel savings. This highlights the importance of having a combined perspective of fuel cost and fishing policy and regulations.

To allow for recovery of overfished stocks in the EU, various species-selective practices are today enforced. Depending on strategy, these **measures may come with a trade-off** in higher FUI. In Swedish demersal trawl fisheries, as an example, species-selecive demersal trawling are mandatory to continue to selectively target crustaceans (*Nephrops norvegicus, Pandalus borealis*) while avoilding by-catch of quota restrained species such as several gadoids and elasmobranchs. Decreasing catch efficiency makes this fishing gear even more energy demanding per catch volume (Ziegler and Hornborg 2014). For some species, such as *Nephrops norvegicus*, alternative fishing methods exist that have both a high selectivity for the target species, low seafloor pressure and lower energy demand, such as creeling (Hornborg et al. 2017; Ziegler and Valentinsson 2008). With current legislation, fishers may be locked into energy-demanding practices – when instead, a quota allocation favouring creeling over trawling would have the potential to reduce the overall FUI of the fishery while promoting benefits to depleted stocks and habitats.

To improve FUI it is also **important to see which incentives are created under the current management framework.** During the expert consultation with DTU Aqua, it was put forward that there may be benefits to FUI from changing from an effort regime to quota regime in some fisheries. In an effort regime, it is important for the fisher to maximise the fishing time spent in the form of having a larger vessel and engine, steam fast, leading to more energy demanding practices. As an example, in the Mediterranean, there are no quotas but fishing days are limited. To make most use of each fishing day, fishers will fish spend as much time as possible at sea during a day, which may lead to both more steaming and continued fishing despite low catches, than what would have been sensible under a different regulation. This makes a fishery more inefficent compared to introducing fishing quotas and/or cutting down the fleet to better match available fishing resources. If a suitable quota regime could be enforced such as catch shares, without e.g. incentivising discards such as high-grading, the fisher could better plan fishing activities to minimise FUI.

> *'Measuring fuel consumption on fishing vessels is the first step toward understanding and improving energy efficiency.'*
>
> Source: Expert consultation with Antonello Sala, Senior fisheries scientist

In efforts to reduce fuel consumption and installing alternative energy sources in fisheries it was repeatedly stressed in literature and expert consultations that **it is vital that measures taken are tailored for the operational needs of individual vessels and fisheries** – there is no one-fits-all solution, and estimates on costs and reduction potential are highly context dependent. For individual vessels, energy audits are seen as crucial to understand the use profile and identify reduction opportunities (e.g. Basurko et al. 2013, Thomas et al. 2010, Chassot et al. 2021; Sala et al. 2022) and standardised reporting of data is a prerequisite for FUI to be used for monitoring of fuel efficiency over time, across fisheries, in particular if it should form the basis for allocation of fishing opportunities. Depending on gear used, different focus and scope may be needed for improving energy efficiency (Bastardie et al. 2022a). As an example, passive gear segements may come a long way on focussing on vessel improvement while demersal trawlers also need to pay more attention to the gear in their efforts.

4.2. Alternative fuels

The wider use of each alternative fuel that has *lower GHG emissions than the currently used fossil-based diesel oils* (definition of low-carbon fuels from Brynolf et al. 2022) is considered to be an essential measure for decarbonisation. The development of the shipping sector as a whole limits and determines what will be feasible for the fishing sector both on the short and long term, because of the dominating volumes of energy source they stand for.

Except for the measures for increased energy efficiency presented and discussed in 4.1, the fastest and most cost-effective options to decarbonise through alternative fuels is to drop in or blend in liquid fuels like biodiesel, biomethanol or liquid e-fuels into current fuels. Three possible short-term pathways towards decarbonisation of maritime activities on the short term has been identified for the shipping sector (Brynolf et al. 2022), and due to the strong interdependency of the two sectors, these pathways are likely relevant also for the fishing sector:

1. The **methanol pathway**: Methanol is only used in small scale today, and is most often produced using fossil energy. Replacing it with bio- or e-methanol will reduce GHG emissions significantly, while having the advantage of being a fuel in liquid form at room temperature, therefore not requiring advanced technology for storage.
2. The **LNG/LFG pathway**: LNG/LFG is perhaps the most established alternative fuel today and its uptake in the fishing sector can pave the way for lower carbon forms of methane, like liquid biogas (LBG) or e-methane, while utilizing similar infrastructure as for LNG/LFG both in port and onboard the vessel. Despite current high cost for LNG/LFGs, converting to LNG/LFG today can facilitate future full conversion to zero-carbon fuels in gaseous form.
3. The **diesel pathway**: Fossil diesel is replaced by biodiesel or e-diesel, but keeping the same form of fuel and using a similar type of engine.

Neither of these pathways are fully carbon neutral, even if non-fossil energy sources are used, and therefore require use of carbon capture technology to become fully carbon neutral. On the long term, it seems that either the methanol or a more long-term hydrogen pathway (see below) that requires more technological innovation are the most feasible ways forward.

The **hydrogen pathway**: When hydrogen is produced without emissions, using renewable energy sources, it is a fully carbon neutral fuel. Its liquefaction requires substantial amounts of energy and therefore is is suggested to use hydrogen to produce ammonia which can be stored more easily at a higher temperature and using less space onboard

Most fuels can either be combusted and used directly or to generate electricity or other fuels. Some alternatives (including hydrogen, ammonia, methane (LBG) and methanol) can also be used in fuel cells, electrochemical cells in which the energy contained in the fuel is converted in an electrochemical reaction, much like in a battery, but requiring a continuous flow of fuel and an oxidizer (often oxygen). **Fuel cells enable more efficient transformation of energy carriers than combustion processes**, but the technology is still under development.

'Regulations on fish quota and vessel length can limit the possibilities for using alternative fuels: fuels with low energy density (e.g., hydrogen) take a lot of space, which may require relaxed vessel length to fit them onboard without reducing the catch storage and space needed for fishing operations. Fishers' "green investments" can be costly and need to be accompanied by some form of compensation, such as additional allocation of fishing opportunities'.

Source: Expert consultation with Sepideh Jafarzadeh, naval architect.

While **how the fuel was produced is key for resulting emissions**, starting to use a 'future fuel' can be a step in the transition even if it initially is produced from fossil sources – by facilitiating investment in infrastructure, and training crew in how to use it – but it must be accompanied by a concrete plan for how to source the fuel from low- or no-carbon sources (or carbon capture techniques) for achieving a full decarbonisation.

To decide which fuel is most suitable for which vessel, understanding the operational profile of the vessel is a crucial first step to finding the most suitable alternatives to fossil fuels. The operational profile includes proportion of time used for steaming, searching and active fishing, the time spent at sea per trip, shore-based facilities available in home port (e.g. for charging batteries), but also the need for onboard cooling of products or heating of spaces used by the crew. In cases where onboard refrigeration is required, energy required to liquefy the fuel can be reutilised for cooling onboard (e.g. LNG/LFG). Recovery of excess heat can replace costly and inefficient heating based on fossil fuels. Optimising the choice of fuel and technology for the actual operational profile of the vessel is critical to obtain a long-term fuel efficient operation. This may involve using batteries to enable operation of engines closer to its optimum and recovery of energy from various equipment used onboard. Overall, planning for '**fuel flexibility**', i.e. avoid being dependent on one single fuel, is very valuable to be able to optimise based on factors like vessel activity, fuel supply and price.

Sail-assisted propulsion is also starting to be implemented in the shipping and fishing sectors and would, while requiring a substantial investment and crew training, lead to direct and lasting emission reductions as the direct use of wind energy represents a no-cost form of energy both in terms of economics and emissions once the equipment has been installed. Sail-assisted propulsion can be implemented together with any of the pathways above and has the additional benefit of increasing safety, since it in case of engine breakdown, still allows some level of navigation of the vessel.

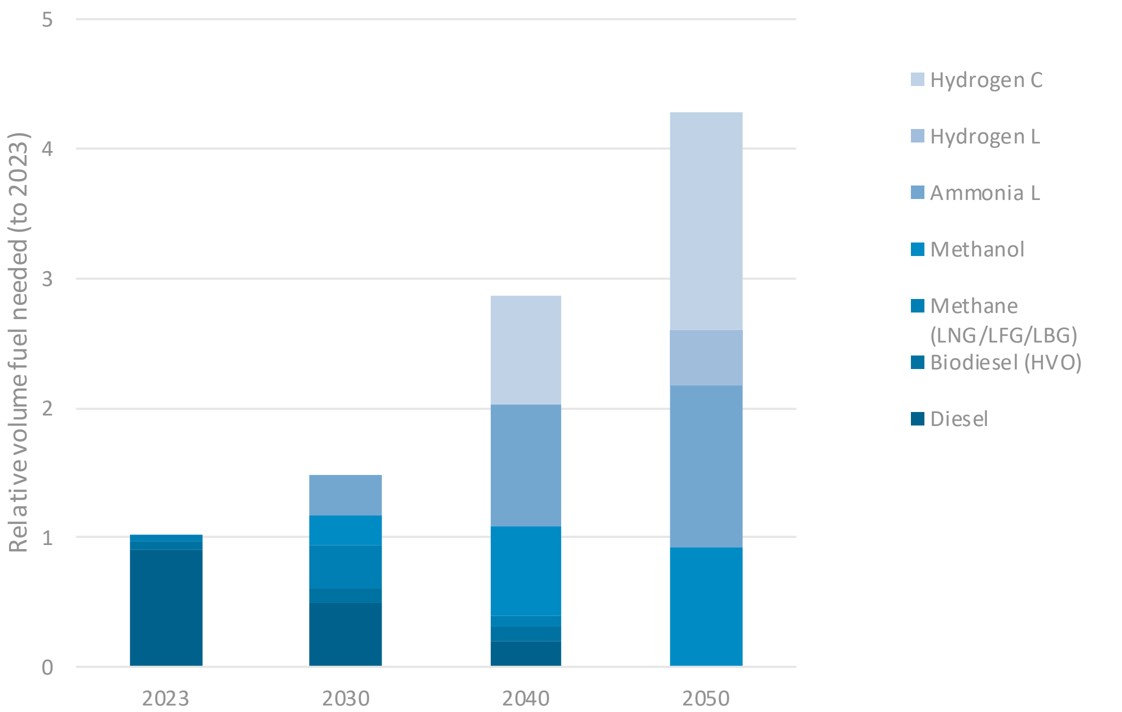
Overall, promising alternatives exist but require substantial initial investment (Korberg et al. 2021) that may be challenging depending on current profitability of the sector – but once installed, will offer cost reductions. As an example, based on some innovations identified from projects (Table A1, Annex 1), in terms of utilizing renewable energy, sail assisted propulsion may decrease emissions between 5-15% (Bound4Blue), 20-35% (Ayro) or even 100% (Client Earth workshop), depending on fishing type and technology, and investing in retractable bow foils that may use wave energy may decrease by 5-15% (Wavefoil).

Regardless of pathway, in the transition away from fossil fuels, costs will initially increase compared to present in the short term (2030), and a system perspective and considering long-term benefits is again crucial. Based on the latest IPCC report (AR6 WGIII; Figure SPM7), it is important to acknowledge that both reduction potentials and costs relative to reference situation as estimated today may change in longer term perspectives.

4.3. Future scenarios

The stepwise transition from fossil to renewable fuels to achieve negligible emissions from the fishing sector would increase the volume of fuel needed around four times (Fig. 5). Underlying assumptions are that by 2030 10% of the energy use in the fishing sector comes from biodiesel, 20% from methane (LNG/LFG/LBG), and 10% each from methanol and liquid ammonia. In 2040 it was assumed that fossil diesel only represents 20%, biodiesel 10%, methane 5%, methanol and ammonia each 30% and compressed hydrogen 5%. In 2050 the mix was assumed to be composed by methanol and liquid ammonia (each 40%) and liquid and compressed hydrogen (each 10%). If these are produced using renewable energy sources only, the fishing sector would be fully decarbonised. It was also assumed that the energy use stays the same, and this may actually not be true. In the electrification of tractors, it has been observed that the energy use was reduced significantly due to increased transmission efficiency of electric vehicles (50-65%) (Lagnelöv et al. 2022). The specific requirements of each fuel are important to take into account in the future regulations of design of fishing vessels.

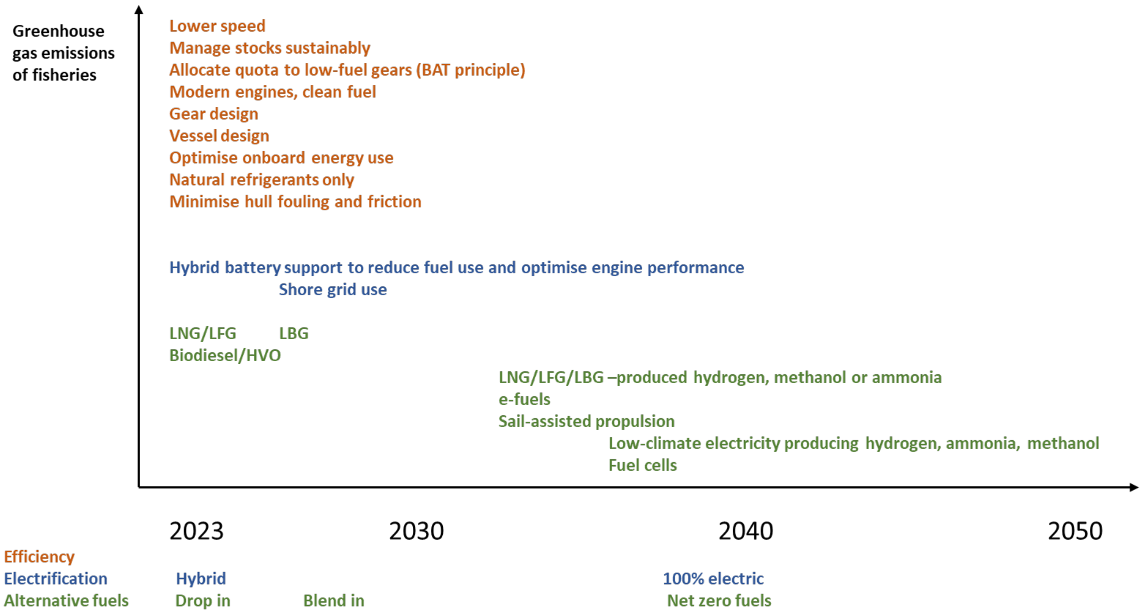
Figure 5: Hypothetical transition scenario from fossil to fully renewable fuels showing the relative increase in fuel volume needed.



Source: Based on data from Brynolf et al. (2022). Assuming energy use stays the same and alternative fuels are produced using renewable energy only. L=Liquid, C= Compressed.

Keys to successful transition are that the infrastructure on land (production and distribution) is established together with prototypes (which can be small-scale and mobile) and that partners from the whole value chain collaborate (presentation by C. Gabrielii at ClientEarth/Our Fish workshop). Based on the literature, projects and expert consultations undertaken for this report, the various decarbonisation measures identified, both for energy efficiency and alternative fuels, may be placed on a timeline based on how close they appear to be to implementation (Fig. 6).

Figure 6: Schematic timeline showing how close the identified measures are to implementation



Source: Prepared for this report based on the literature and project review and expert consultations. Measures in orange are related to energy efficiency, blue measures to electrification and green measures to alternative fuels and the energy sources used to produce them.

4.4. Enablers and barriers

'Before submitting the fuel use and landing data to the EU, a quality check by experts with technical and biological competence is required at the national level.'

Source: Expert consultation with Antonello Sala, Senior fisheries scientist.

The variability in FUI presented in chapter 3 and reduction opportunities for different actors summarised in **Error! Reference source not found.** are associated with different enablers and barriers, as well as with different costs and reduction potentials. In agreement with the findings of Bastardie et al. (2022a), there is more consensus on factors influencing fuel use intensity compared to clearly disentangling which aspects should be prioritized to improve efficiency; this needs to be tailored for the specific fishery depending on current status and local conditions. As an example, passive and active gear segments have very different inherent characteristics related to their fishing operations – and all fisheries benefit from healthy stocks and an optimised fleet structure, while the extent of benefits depends on fishing area, country and targeted species.

> *'In hindsight, fisheries have typically looked for technological solutions to high fuel use, like new net designs or more efficient engines. However, managerial factors like stock status and fishing capacity and behavioural factors like vessel speed can have a much greater effect on fuel consumption at a fishery level'.*
>
> Source: Expert consultation with Peter Tyedmers and Rob Parker, experts in energy use of fisheries.

The current energy crisis is not the first one. Energy price shocks have put energy efficiency in fisheries in focus before – driven by the need to reduce costs, rather than emissions. In times of low fuel prices, in part due to subsidies, there is less motivation to focus on energy efficiency, despite the fact that fuel still represents one of the main costs of fishing companies. One example is the tradeoff between fuel and labour costs when reducing the steaming speed. In times of high fuel costs, it is worth to spend the extra time, while the costs for additional labour rise with lower fuel prices- resulting in fast steaming being the most profitable option. Since the last energy crises, the focus of fisheries management has been on other topics and this has led to fishing fleets that are far from optimised in terms of fuel use. To tackle the increasingly urgent endevour to adapt to and mitigate climate change, it is important to acknowledge the limitations of technological measures (e.g. gear, hulll and bow design) compared to policy changes (changd gear use, stock status) – and carefully navigate between long-term needs relative to short-term actions, which arguably should both be aligned.

4.4.1. Legislation

Many of the measures identified to enable decarbonisation of the EU fishing sector have support in existing fisheries regulations, or require smaller amendments of existing barriers. Four overarching changes to the current CFP regulation (EU 1380/2013) are seen as important enablers to decarbonise fisheries:

1. Low energy use and greenhouse gas emissions of fisheries needs to be explicitly stated as goals of the CFP for these to become prioritied and monitored.
2. A ban to use fossil fuels by 2050 would provide clear incentives and conditions for the fishing sector to start the process of decarbonising now, this would need to be accompanied by funding opportunities and compensatory measures to overcome financial and other thresholds and ensure fisheries can stay viable during the transition
3. A vital change for installing alternative energy sources is to evaluate how fishing capacity may be addressed without regulations on allowed kW or size of the vessel. Fossil fuels require less space for storage, while many alternative fuels such as LNG require heavier engines or larger vessels to be able to keep the catch holding capacity while also accomodating for storage and use of the less-energy dense new fuels. Even if the extra kW or size is only used for the alternative energy source, current regulation related to defining fishing capacity stands in conflict with the needs for with installing alternative energy sources (Bastardie et al. 2022a), and is thus a barrier for transition. This change would better align fisheries with the stated intention for the CFP to '*contribute to the Europe 2020 Strategy for smart, sustainable and inclusive growth, and should help to achieve the objectives set out therein*.'
4. A larger change but an important enabler for energy efficiency is to set objectives related to population abundance well above current target of maximum sustainable yield, such at maximum economic yield. This implementation would offer improved contribution to Article 2 objective 1 that advocates for long-term sustainability.

Based on findings by Byrne et al. (2021) related to Icelandic fisheries, it is important that policies aiming to reduce GHG emissions are flexible regarding how fishers participate due to the high variability in fuel use pattern even within a single fishing fleet. As an example, the relationship between stock status and fuel use intensity varies between fleet segments due to e.g. fishing behaviour.

For change in gears, there is ample support in the current CFP (e.g. Article 17) and changes only need to be done in regulations which defines the technical measures on catches and landings of marine biological resources, operation of the fishing gear and interaction of fishing activities with marine ecosystems (EU 2019/1241).

The regulation related to data collection of EU fisheries (2017/1004) would benefit from calling for mandatory fuel use monitoring of EU fishing vessels as a first step towards understanding current fuel use patterns for different fleets and underpin support for which alternative energy sources are most applicable for different fleets. This is motivated by the high relevance of fuel use in fisheries for their greenhouse gas emissions and costs, but also for the links between fuel use and wider environmental impacts (Ziegler et al. 2016a). Reduced fuel use would lead to lower-impact and more profitable fisheries.

4.4.2. Economy and equitable transition

> *'Tax exemption of fuel is a strong disincentive for innovations to improve fuel efficiency in fisheries'.*
>
> Source: Expert consultation with Antonello Sala, Senior fisheries scientist.

Careful navigation between current versus long-term economy is one key component for improved energy efficiency and transition towards decarbonisation of fisheries. As an immediate action, increase in fuel price have been shown to influence fisher behaviour, where e.g. in the UK, change in fishing strategies was found to compensate for decreasing profitability as seafood prices may be more fixed compared to fuel prices (Abernethy et al. 2010). Strategies include fishing closer to shore or targeting species with higher market prices. Furthermore, the same study found that fisheries with the most energy intensive fishing methods are most severely hit by increasing costs, while those that have invested in fuel efficiency may have higher resilience. With current rise in fuel prices, it has also been seen that some vessels decide not to leave port due to high costs.

In the short-term, the current tax exemption may allow for energy intensive practices to remain profitable, illustrated in a case study of Swedish demersal trawl fisheries (Ziegler and Hornborg 2014), and thus allow for continuation of fisheries with high FUI that would be unprofitable if the fuel was taxed as it is for other sectors. This is particulary the case for when landing value of the targeted species is high, such as for many crustaceans. A recent review however found that although introducing a fuel tax hits demersal trawl fisheries more than small-scale fisheries with passive gears due to different fuel use efficiencies, fisheries with poor profit margin (including small-scale fisheries with passive gears) may also become unprofitable if the fuel is taxed due to low landing value (Malmström et al. 2023). Furthermore, it was found that fuel use decreases to some extent when prices go up, but it is difficult to fully compensate the increased cost by fuel use reduction measures. The proposal for a revised Energy Taxation Directive (EC 2021) suggests to include fisheries in the sectors to which fossil energy is taxed, even though at a lower rate than in other sectors; while renewable energy use should be exempt from tax during 10 years. If this is adopted, it will represent a strong incentive to reduce and shift out fossil fuels.

> *'In an optimally managed fishery, when stocks are healthy and no overcapacity of fleets, introducing a carbon tax has a small effect compared to the effect from optimised management.'*
>
> Source: Expert consultation with Staffan Waldo, fisheries economist.

Increasing the cost of fuel through adding costs for emissions or removing the tax exemption will inflict fuel saving operations to the extent possible, which may thus be seen as an enabler. However, Roll et al. (2022) conclude that the gradual removal of tax exemption and introduction of a carbon tax in Norway (Norwegian Government 2019) may only have a limited effect on fuel use and associated emissions. Its introduction is connected to the removal of other fees as a compensatory measure to not increase overall costs in the fishery. In the first year, when introduced (2012) the increase in carbon dioxide fee and the reduction in a 'control fee' roughly corresponded to each other, but since then the carbon dioxide fee has increased and will contrinue to increase, but is still less than what other maritime sectors pay (Norwegian Government 2019). Based on the expert consultation with Staffan Waldo, a fisheries economist, there are elements of cost elasticity, that have been observed when fuel costs increase- this provides an opportunity to reduce speed to consume less fuel but will in turn require more time spent fishing with higher costs for crew – and the opposite can be observed when fuel price decrease. However, since the economic resilience differs between sectors, where higher fuel costs hits fleets at smaller profit margins harder, the opportunities to invest in new technologies likewise differ. Increasing costs experienced by the whole fishing sector is today also a barrier to afford the energy transition towards alternative energy sources. It will be more expensive to invest and utilize alternative energy sources, such as installation and possibly also running costs, as well as future projections are more uncertain (availability, changing policy instruments). Combined, targeted actions to enable restructuring and investments before decreased profitability is further progressed are therefore urgent, while acknowleding the different conditions for different fleets.

> *'If fisheries are to be included in emission trading schemes, compensatory support measures will be needed to not increase overall costs'.*
>
> Source: Expert consultation with Jordi Guillen, fisheries economist.

4.4.3. Technological changes

For technological changes, barriers are found in both implementation of available technology (gears with reduced drag) and technological readiness level of alternative energy sources such as hydrogen. More research are also needed on energy efficiency measures for vessels and gears, that are designed for specific fisheries.

Based on the expert consultation with researchers at DTU Aqua, Ole Ritzau Eigaard and Francois Bastardie, the curve for fuel use reduction enabled through technological development of vessels and gears has not flattened out yet – there is still progress and further opportunities for reduction. However, as identified in Bastardie et al 2022a, there is a lack of implementation of existing measures that may improve energy efficiency. This may be due to a range of barriers, some more difficult to overcome than others. One is that it may be difficult to transfer technological development made for one fishery to another, since gear innovations are often specific to the targeted species and gear type. There may also be structural barriers, such as lack of collaboration, limited knowledge transfer, different priorities and ineligibility of obtaining structural funds for investment. A barrier to uptake of innovations can sometimes be the use of technical definitions of technologies (such as fishing gear) in legislation and permitting processes, when development goes beyond these definitions of categorizations.

> *'The technology exists, even if it needs to be further developed, it is mainly a matter of economy and uncertainties related to markets. What is the most promising alternative energy source to invest in, now and in the long run, and what does the availability look like? And it must cost more to emit for a change to take place.'*
>
> Source: Expert consultation with Selma Brynolf and Maria Grahn, researchers in energy systems analysis.

Based on the consultation with Selma Brynolf and Maria Grahn, researchers in energy systsems analysis, there is a large potential for energy efficiencies (such as hull design, speed, maintenance) but the development is not linear towards improved energy efficiency over time since it is also influenced by fuel costs (if low, speed may increase to save time). Fisheries have similar challenges and prerequisites as the rest of the maritime sector, but may have very different travel pattern compared to marine transport, and the most promising alternative energy source will depend on fishing pattern.

In terms of enabling use of alternative energy sources, there are different barriers today that have to be overcome. Based on the interview with maritime technology experts Andreas Bach and Fredrik von Elern, the choice of alternative energy source for fisheries will depend on energy availability, targeting pattern, such as how predictable/planned the fishery is, and vessel capacity to accommodate for storage of energy sources with lower energy density – it is important to consider the operational needs.

Based on the consultation with Selma Brynolf and Maria Grahn, researchers in energy systems analysis, it is important to look at total costs of production, storage needs, available infrastructure on land, distribution, potential loss of income from reduced load capacity.

4.4.4. Fishing behaviour

Based on the expert consultation with Staffan Waldo, fisheries economist, change in behaviour is already an important enabler in improving energy efficiency. When fuel prices go up, fishers adapt by targeting species of higher value, fish closer to ports or reduce speed during steaming to and from fishing locations (Abernethy et al. 2010, Malmström et al. 2023). Behaviour is more difficult to regulate and may overshadow improvements in other areas, such as technological improvements made, and is also multidimensional if motivated from cost (e.g. cost of fuel versus extra time needed at sea).

'The first step towards energy efficiency and investment in alternative energy solutions is to find out the energy profile of the vessel's operational pattern. This knowledge is in turn the basis for deciding on what type of fuel and drivetrain that is suitable for the specific vessel – a relatively small investment that soon pays back through improved efficiency.'

Source: Expert consultation with Andreas Bach and Fredrik von Elern, maritime technology experts.

Knowing the details of the fishing behaviour during fishing operations and energy profile of the vessel are regardless essential enablers for targeted actions on how to optimise current use of machinery, reduce fuel use and provides vital input to which alternative energy sources are feasible – as well as optimizing their installation and operation. Furthermore, fishers often report that they only fish during good weather when fuel price is high (Malmström et al. 2023). With climate change projections of increased storm frequencies, this may exacerbate the vulnerability of weather-dependent fleet segments – thus providing a barrier to traditional behavioural adjustments. Furthermore, since fuel costs will most likely continue to, this will inevitable continue to affect fishing behaviour. This calls for proactive management to mitigate potential consequences from rising fuel costs for the local ecosystem from increased fishing intensity in certain areas or high interest in the most profitable species.

Bastardie et al. (2022a) find that further reductions in fuel use intensity through technological innovations not neccessarily lead to decreased fuel use due to compensatory behaviour – improved fuel use efficiency may incentivise trips to more distant fishing grounds which balances out the savings in fuel use enabled.

4.4.5. Knowledge capacity

Regarding the state of knowledge, current knowledge capacity is to some extent sufficient. For example, it is rather a matter of using fuel-efficient fishing gears more widely than further developing fishing gear. Other areas are less mature and in great need of knowledge and innovation, such as the use of alternative fuels in the fishing sector.

In terms of knowledge in the industry, during the consultations, the resistance to collaborate and change in the fishing industry was mentioned (e.g. Antonello Sala, Senior fisheries scientist), despite availability of e.g. energy auditing of vessels as a basis for improving their energy efficiency using exisiting technological solutions. This so called 'innovation gap' (lack of uptake of exisiting solutions) becomes even larger when novel technologies, e.g. fuels, are to be introduced. Crew and skipper training programmes are therefore central to the successful transition, focusing on the changes that will be experienced by the crew in terms of working environment, safety etc., but also on the importance of these measures to make fisheries long-term sustainable and competitive also in the future. A sense of pride to collaborate within the crew, or even within the fleet, to reach these ambitious goals would be a desired outcome of such training efforts.

5. Additional potentially important non-fuel sources of greenhouse gas emissions of fisheries

Although greenhouse gas emissions of fisheries are dominated by the use of fossil fuels, there are additional sources that in some cases may be substantial and it is important not to forget them in the ambition to decarbonise fisheries. First, there are still **some uncertainties related to the full climate forcing effect** caused by combustion of fishing vessels. A recent study found that old and small fishing vessels may be associated with high emissions of methane – a greenhouse gas with more powerful radiative forcing (Wang et al. 2022). Also, black carbon particles are released from the combustion of heavy fuel oil which reduces snow albedo, particulary important for fisheries in Arctic regions representing a large part of the maritime sector in Arctic regions (McKuin and Campbell 2016; Zhang et al. 2019). Even though carbon dioxide emissions between different types of oil are similar and directly related to the carbon content, the climate forcing effect of soot particles and other combustion emissions can potentially give important contributions to the climate impact of fisheries and are in need of further study. Therefore, changing to cleaner diesel fuels (giving rise to less soot particles) and improving engines are thus also important, regardless of the FUI.

Secondly, recent years have seen increased scientific attention to the role of fish and fisheries for the carbon flux in the ocean where marine sediments offer crucial storage capacity (e.g., Mariani et al. 2020; Sala et al. 2021; Saba et al.). **Biogenic emissions** of especially fisheries in contact with the seafloor are poorly understood and that more knowledge about the fate of carbon resuspended into the watercolumn by benthic fishing gear might change our view on greenhouse gas emissions from such fisheries. Although Sala et al. (2021) suggests that the current extent of disturbance by demersal trawling has the potential to contribute with carbon losses at the same magnitude as from soils from farming, these estimates are still associated with large uncertainties; a recent review suggests mixed results for different conditions (Epstein et al. 2022). Following estimates in the latest IPCC report (AR6 WGIII figure SPM7), major reduction potentials, although highly uncertain, is overall found in various measures to improve carbon sequestration and restoration of ecosystems; all however estimated at higher costs compared to present.

Finally, previous studies have found onboard **refrigeration** to, under certain conditions, be an important contributor to greenhouse gas emissions in fisheries (Winther et al. 2009; Iribarren et al. 2011; Skontorp Hognes & Jensen 2017). Refrigeration consumes additional energy, but more importantly, requires a refrigerant, which to some extent often leaks from the refrigeration system to the atmosphere and needs to be refilled at regular intervals. Globally, most fishing vessels with onboard refrigeration still use the so called 'hard freons' or hydrochlorofluorocarbons (HCFCs), very often R22 which both has a high global warming and ozone-depleting potential (Söylemez et al. 2022). This refrigerant is being phased out worldwide, including in the EU (EC 2000, 2009) Reg. 2037/2000; Reg. 1005/2009) for its ozone-depleting potential under the Montreal Protocol, and is often being replaced by ammonia (R717) or increasingly also by carbon dioxide (R744) in new vessels (Sandison et al. 2020; Skontorp Hognes & Jensen 2017; Söylemez et al. 2022), both grouped as natural refrigerants without ozone or climate impact. In colder climate countries, around 50 new vessels have had R744 installed as the only refrigerant since 2016 (Söylemez et al. 2022). On old vessels, however, it is very costly to change the refrigeration system and often, other refrigerants that can be used with the exisiting system are used, so called 'drop in' refrigerants, often of hydrofluorocarbons (HFCs) also called 'soft freons'. These have the advantage that they do not deplete the ozone layer, but when it comes to climate, their impact is actually even higher than the substance being replaced, HFCs have climate forcing indexes of 2-4000 kg CO_2eq/kg compared to R22 which has 1800 kg CO_2eq/kg. This is a classic tradeoff situation resulting from focusing on solving one environmental problem at a time. Full replacement and shifting to natural refrigerants should be incentivised and supported.

6. Assessment of policy options

The measures identified in Table 2 that are sorted under the areas Fishing technology, Fishing behaviour, Alternative energy, Catch use and Societal, all refer to important steps that can be taken to facilitate the decrease in energy use and transition towards use of alternative energy sources – all representing enablers for making policy changes, which is seen as the most important incentive to initiate change. This section therefore focuses on the areas Fishery Management and Economy, representing the most crucial areas to target in the first place to initiate change. Policy options are here discussed as different packages, one with the goal to either i) enforce a strict decarbonisation of the fishing sector, ii) focus on energy efficiency as a first step and iii) only comprising of economic policy instruments without changing current fishery management. The first option (indicated by i) above and 6.1 below) focuses on implementing and improving the CFP and avoids adding direct costs for fishers through e.g. taxes. The third option (indicated by iii) above and 6.3 below) focuses only on that type of economic instruments, while option ii) above (6.2 below) represents a middle way between these two.

6.1. Full decarbonisation

A strict top-down policy package that integrates the necessary societal transition towards decarbonisation into fishery management.

This policy package requires first of all that promoting energy efficiency and reducing greenhouse gas emissions is either i) stated as an explicit policy objective in the Common Fisheries Policy (CFP), or ii) requires the political will to enforce or interpret the current CFP stricter concerning that it should enable alignment with societal objectives regarding climate change mitigation through, e.g., using Article 17 to enforce management actions. For the second option, it would be beneficial to explicitly specify that the definition of low impact fishing indeed includes fuel-related emissions when initiating management actions. As an example, the current definition of 'low impact fishing' in the CFP includes fuel emissions but only refers to impacts on the marine ecosystem and fish resources in the subsequent text in the regulation.

There are several existing ambitions – globally, within the EU and nationally – that support this policy package. These include, besides individual member state ambitions, the legally binding international treaty the Paris Agreement that was adopted at the COP-21 (UN 2015), the current revision of the EU Energy Taxation Directive (EC 2021), the EU Green Deal with the ambition to have no net-emissions by 2050 (EC 2019), the OECD commitment to phase out inefficient fossil fuel subsidies (OECD 2021), and support achievement of e.g. goals 12 and 14 in the United Nation's Sustainable Development Goals (UN SDGs; UN 2023). It calls however for substantial additional, societal investments to enable the transition, such as green investments in ports and further innovations for the possibility to use alternative energy sources in fisheries, the latter requires more funds for technological research.

Essential for this policy package is to make robust emission data for fisheries available through e.g., improving and/or extending the current EU Data Collection Framework (DCF) requirements (EC 2017) (EU Regulation 2017/1004), and implementation of fuel use data collection through e.g., clear method instructions and ensure technical, biological and economic expertise (possibly working across countries) have a look at national data before being submitted to the EU. This important action for enabling this policy package, in combination with other enablers within the remit of fisheries management, data collection and structural funds, include several larger or smaller changes in policy at different levels (Table 3).

Trade-offs exist mainly in the short-term perspective (5 years), where substantial increased costs are foreseen. However, it is also a vital transition for more resilient and long-term economy and competitiveness of the fishing sector. Social trade-offs may occur due to different profit margins fleets across the EU; it is important with well-designed incentives such as thoughtful use of structural funds that enable an equitable transition, as well as support for those leaving fisheries as a result of fleet cuts. Gear restriction such as a ban of demersal trawling in protected areas and further restrictions where viable gear alternatives exist may improve fuel use efficiency – but it is important that additional actions are taken to minimise risk that trawl effort is displaced to other fishing grounds and, if domestic supply is decreased, may also lead to increased imports, both with potentially increased net-effect on emissions.

Benefits include, besides enabling the necessary transition towards decarbonisation of the fisheries sector, a systems perspective over quick-fixes and continued opportunities for highly nutritious food production, improved long-term competitiveness of fisheries among food sectors and alignment with long-term economic objectives. Other benefits include that shifting away from in particular demersal trawls targeting species with high fuel use intensity aligns with current discussions related to the EU Biodiversity Strategy for 2030 (EURACTIV 2023) to ban demersal trawling in protected areas. Restoration of fish stock, allowing higher abundance which may also allow for more healthy size structure and decrease demersal trawling effort also aligns with achieving descriptions for Good Environmental Status of the EU Marine Strategy Framework Directive (MSFD; EU Directive 2008/56/EC). From a global perspective, measures in this policy package also align with the goals and targets adopted in the COP 15 Kunming-Montreal Global Biodiversity Framework (CBD 2022).

6.2. Improved energy efficiency

A top-down implementation of existing fishing policy to incentivise fuel use efficiency without adding extra costs while allowing for more bottom-up actions by the fishing industry.

This policy package pays careful attention to how to operationalize the stated policy objectives in the EU CFP to favour improved fuel use efficiency while allowing the industry to adjust through bottom-up actions by e.g., changing gears and investing in new technology. As an example, current EU CFP legislation refers to that it should ensure populations to be '*above levels that can produce the maximum sustainable yield*' – this mandates elimination of overcapacity and rebuilding of stocks, but also allows for applying maximum economic yield (MEY); regardless of degree of restoration of fish abundance, it would allow for both improved fuel use efficiency and economy for the fishing sector. The current EU CFP legislation also refers to that it should ensure '*long-term environmental, economic, and social sustainability*'; which cannot be achieved without the necessary energy transition.

Besides a general necessity to break the trend in expansion of fisheries with high fuel use intensity for improved long-term resilience of the sector (Parker et al. 2018), several existing ambitions also support this policy package. These include all the ambitions stated in the policy option above but focuses more on enabling improved energy efficiency rather than full decarbonisation. For many of the technological measures to reduce fuel use (such as change in vessel and gear), the knowledge already exists, it is more a matter of implementation in the fishing sector (Bastardie et al. 2022c).

Essential also for this policy package is to make robust fuel use data for fisheries available through e.g., improving and/or extending the current DCF requirements, and many other enablers under the policy package of full decarbonisation also applies for this policy package, although less focussed on emissions (Table 3).

Trade-offs mainly occur in the form of short-term social implications from fleet cuts. However, if overcapacity exists, economy is poor and long-term sustainable exploitation of marine resources is at risk, why priorities are arguably needed. Social implications need to be taken into account in this transition and support to e.g. develop alternative business in coastal communities will be needed to avoid negative trends. A challenge with this policy package is that only focusing on energy efficiencies may on the one hand be less costly for the fishing sector compared to initiate full decarbonisation (the first policy package above) and avoid poor decisions taken based on current maturity/availability of alternative energy sources, but on the other hand, there is a risk that the fishing sector falls behind in the necessary societal transitions required in the long-term perspective.

Benefits include most of those mentioned for the policy package on full decarbonisation but contributes less to energy transition and thus the Paris Agreement (UN 2015). Improved fuel use efficiency aligns with economic objectives, in particular if aiming for maximum economic yield.

6.3. Economic policy instruments

Enforcing fuel use efficiency and energy transition through applying economic policy instruments incentivising the fishing industry to adjust.

This policy package is limited to the introduction of economic policy instruments to incentivise fuel use efficiency and decarbonisation of the fishing sector, not introducing changes in fishing policy such as favouring gear types and improving stock status. Here, the different policy options in Table 3 may not to the same extent be seen as a package as for the other two alternatives; instead, careful navigation between them is needed when identifying the most suitable alternative, while only some options may benefit from being combined into a policy package. The economic incentives may be used to decrease emissions through various bottom-up actions made by the fishing industry, such as investing in new technology.

In support of pure economic instruments as policy options is that a higher cost to emit greenhouse gas emissions would incentivise a green transition, and that fuel cost has been seen to be one determinant of fuel use in fisheries – fuel saving operations are observed when prices increase. Several existing policies support change in current economic policy instruments for fisheries, including the adoption of the EU Green Deal, the revision of the Energy Taxation Directive and the ongoing World Trade Organization (WTO) negotiation to prohibit harmful fisheries subsidies. Important enablers include different forms of taxations and incentives to invest in technology that decreases emissions, which can have both different design and be enforced at different levels (Table 3).

Trade-offs exist if purely adding further costs without compensation to an industry in an already delicate economic situation. Carvalho and Guillen (2021) find that a removal of the fuel tax exemption may risk turning the overall profit margin from positive to negative, noting that the small-scale fleet (under 12 m deploying passive gears) would be less impacted than the large-scale and distant-water fleets. Higher economic costs may also favour fisheries targeting more high-value species such as crustaceans. It is thus extremely important to design a potential tax/fee in a clever way, which creates the incentives for transition, without increasing total costs or even shifting demand from one type of food to another with higher emissions. If, for example, only greenhouse gas emissions of fossil origin are taxed, this will favour food systems that potentially have much higher overall greenhouse gas emissions, but of biogenic origin (e.g., livestock production with emissions of methane and nitrous oxide). The introduction of carbon taxes thus calls for a system perspective, to identify how to reduce emissions most effectively without providing unfair costs. All extra costs added to the fishing industry may influence the price for consumers for seafood products originating from EU capture fisheries. Guillotreau et al. (2022) conclude that a oil price increase of 10% transmits into a 3% landing price increase in a tuna fishery. High energy prices will also influence the post-harvest supply chain with higher costs for processing and transportation and the longer the food chain, the weaker the price transmission signal (Persson 2011). The landing price increase found by Guillotreau et al. (2022) was lower than in the decade preceeding and it seems that other factors, including market situation and competition, are more important for consumer prices and the possibilities to compensate for increasing prices of an important input in this way is limited.

Benefits includes same taxation as the agricultural sector and thus fair competition in terms of fossil fuel costs. However, without considering the importance of recovery of fish stocks, pure economic policy instruments may be less effective to reduce emissions.

Table 3: Summary of the three policy packages further assessed.

Option	Targeted document	Policy option			Comment
		6.1	6.2	6.3	
Reform CFP sustainable exploitation targets beyond eliminating overcapacity relative to MSY (aim for MEY)	EU CFP (EU Regulation 1380/2013)	X	X		Revision of CFP may not be needed since it states that it should be **above** MSY
Enforce further fleet and effort cuts to eliminate existing overcapacity	Yearly setting of quotas, plans for effort cuts	X	X		Will have social implications but follows the objective of current CFP
Implement well-designed catch shares to favour fuel use efficiency	Member State national regulations	X	X		Supported by regionalisation objective in the current EU CFP (Article 18)
Allocate quota based on environmental performance within and between fleet segments	Member State national regulations	X	X		Supported by the EU CFP (Article 17) and may align with ambitions related to biodiversity (e.g., EU Biodiversity Strategy for 2030)
Change from effort to quota regime to favour fuel use efficiency	Member State national regulations; EU CFP (EU Regulation 1380/2013)	X	X		Varying need across fleets/regions
Implement mandatory measuring of fuel use on vessels and suitable reporting	EU DCF (EU Regulation 2017/1004)	X	X		Vital for decision-support, both for fishers and policy
Compensate fishers investing in energy efficiency or other emission reduction measures (e.g., through additional quota shares)	EU CFP (EU Regulation 1380/2013)	X	X		May affect relative stability between member states or require that adjustments are done within member state's shares
Promote use of fuel use saving and green technology through structural funds	Regulation 508/2014 on the European Maritime Fisheries and Aquaculture Fund (EMFAF)	X	X	X	Current use of funds varies between member states, may require more clear directions from the EU
Allow more free choice of gear on vessels to favour the most fuel-efficient fishery	EU Regulation 2019/1241	X	X		Needs to make sure trade-offs don't occur, such as negative effects on fishing mortality and biodiversity
Phase out tax exemption and subsidies for fuel use	EU Energy Taxation Directive (EC 2021); Council			X	Full exemption affects fleets differently due to varying profitability (depends both on fuel use efficiency and landing value of species) and may hinder

	Directive 2003/96/EC; Member State national taxation				affordability to invest in green technology.
Define 'total allowable harvesting emissions' per fishery, and allocate emissions to individual vessels, possibly tradeable, as part of a national emissions reduction plan.	Member State national regulations	X			Will favour use of best available technology. Emission rights can also be auctioned.
Apply a resource tax, i.e., a fee for utilizing the resource dedicated to fund research and green investments	EU Regulation 1303/2013	X	X	X	A general resource tax would impact all fishers regardless of energy efficiency while e.g., a tax on effort or fuel may be more suitable.
Include fisheries in the EU-ETS	Directive 2003/87/EC			X	Offers a cost-effective measure for fisheries to pay for emissions
Change the current taxation to fully account for externalities (Pigou tax)	EU Energy Taxation Directive (EC 2021)			X	Guillen et al. (2016)
Create a specific system with emission quotas for fishing fleets	Member State national regulations			X	Has been implemented in Norway
Design subsidies to favour fishers who decrease emissions the most per financial support	EU Energy Taxation Directive (EC 2021); Member State national taxation			X	Offers cost-effectiveness to reduce emissions
Introduce national GHG fees related to fuel use	Member State national regulations			X	To not increase costs for fishers and keep the incentive to reduce fuel use, compensate by reducing other taxes or fees that is related to the landing value, not the fuel use.

6.4. Summary

Ideally, these policy packages could be combined, or undertaken in parallel (as opposed to only selecting one) to achieve larger emission reductions faster. For Iceland, where the maritime sector, as opposed to most other countries, is dominated by fisheries, scenarios for decarbonisation have been modelled (DNV 2021) and concluded that strong policy measures including support for onboard investments, a carbon tax and a gradually increased required share of carbon-neutral fuels will be required to reach carbon neutrality by 2050. Goals are set even higher (caron neutrality by 2040) and regulations have been proposed to facilitate this development (Fiskerforum 2022, IGOV 2022). For all packages identified here, robust decision support through improved fuel use data collection and required targeted actions at both EU and member state level are essential. It is also essential to always base such actions on the specific characteristics and requirements of the specific fisheries, to ensure efficient uptake and emission reduction. The packages also have different effects on greenhouse gas emissions and at different costs (Table 4). The prospect of a fully decarbonised competitive EU fishing sector by 2050, if the right steps are taken today, is overall not beyond reach.

Table 4: Summary of the overall outcomes for the different policy packages.

Policy package	GHG effect	Cost effect	Trade-offs
Full decarbonisation	Eliminates	Low for society but high for the fishing industry in the short-term (but aligns with economic objectives in the longer term) and needs to be accompanied by proper incentives for investment opportunities.	If prioritised above other goals, there could be trade-offs with biodiversity or socioeconomic goals.
Promotion of energy efficiency	Large reduction	Aligns with economic objectives but may come with investment costs in the shorter time perspective and may not incentivise energy transition for improved long-term economy.	Social implications from fleet cuts and allocation of fishing opportunities for fuel use efficient segments. May induce long-term vulnerability compared to other sectors if not including targeted actions to decarbonise.
Economic policy instruments	Medium (?) reduction	Low for society but adds costs to the fishing industry in short- and long-term and needs to be accompanied by proper incentives for green investment opportunities.	May favour species with high economic value but lower food value such as crustaceans, may introduce unfair competition with food production with high biogenic emissions (beef), introduces effect on equity due to sectors being highly different in profitability today and are hit differently.

7. Conclusions

This review, and the identification of emission reduction opportunities and policy options to support them, has shown that there are multiple parallel ways forward towards a decarbonised European fishing sector.

1. First of all, emission reduction needs to be stated as an explicit goal of fisheries management for this to become a priority. Robust baseline and performance data needs to be collected and made available continuously on a suitable level to be able to follow up on performance and e.g. allocate fishing opportunities based on performance.
2. We find that many measures to increase the fuel efficiency of fisheries could be taken right away, by simply implementing existing regulations to rebuild fisheries and reduce overcapacity. Applying 'best available technology' principles in the allocation of fishing opportunities for gears and fleets would also lead in this direction.
3. New economic policy instruments like emission fees or quotas – or or simply reduced fuel tax exemption – would make investments for improved energy-efficiency or alternative fuels more competitive. However, it is important that such changes are accompanied by compensatory measures to mitigate increased costs, and consider how an equitable transition may be supported, while keeping the incentives to decarbonise intact; a larger reduction potential is foreseen from combining economic policy instruments with changes in fishing policy to decrease overcapacity and rebuild stocks.
4. Flexibility is important because it allows optimisation towards certain goals, such as minimising fuel use. Flexibility related to both type of gear and type of fuel used onboard allows fisheries to adjust to the future development of target species distribution and abundance and volatile prices of conventional and alternative fuels.
5. Financial, technical and behavioural hurdles need to be overcome before a wider uptake of alternative fuels will happen in the fishing sector, but once these hurdles are overcome, a fully carbon neutral fishing sector may be possible. The shipping sector will determine what alternative fuels will be most accessible also for the fishing sector and a ban on the use of fossil fuels in marine sectors by 2050 would create clear incentives and conditions for taking the necessary steps.

Overall, taking a systems perspective to the transition to a decarbonised fishing sector is critical to avoid taking dead-ends, quick-fixes and transfer from one problem for another. Fisheries should be managed as part of the food system AND a natural ecosystem, providing valuable contributions to human nutrition in the form of animal-source foods at relatively low emissions already today. If an energy transition is implemented, and fisheries become better aligned with biodiversity objectives, their long-term contribution to supplying sustainable and nutritious foods produced in the EU- and to providing livelihoods- would improve.

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ANNEX

Table A1: Projects of relevance for decarbonisation of the fishing sector

Project	Short project description and reduction measures mentioned	Source	Website to project or project publications
Fuel saving in Portuguese trawlers	Testing of fuel consumption during different fishing phases and construction of new trawl gear models for fuel savings and optimisation of energy use on board Portuguese trawlers.	CORDIS	https://cordis.europa.eu/project/id/TE.2.408/es https://www.researchgate.net/publication/223235017_Strategies_for_improving_fuel_efficiency_in_the_Portuguese_trawl_fishery
FOUL-X-SPEL	Development of environmentally friendly antifouling coating that prevents leaking, minimise surface roughness, and improve hydrodynamic properties of hulls.	CORDIS	https://cordis.europa.eu/project/id/285552 https://cordis.europa.eu/docs/results/285/285552/final1-foul-x-spel-final-report.pdf
Development of fuel saving bottom trawls	Testing and development of bottom trawls, saving fuel through use of low drag netting materials and larger meshes in the upper part of the trawl.	CORDIS	https://cordis.europa.eu/project/id/TE.2.444
EcoSail	Launching of the EcoSail technology, which allows end-users to minimise fuel consumption through features such as self-learning ship performance and advanced decision support systems that enables optimisation of sailing routes and time schedules.	CORDIS	https://cordis.europa.eu/project/id/820593
SMART TRAWLING and Icelandic project Optigear	Development of intelligent winch and control systems for fishing vessels (Smart Trawling), and trawl equipment with ability to process data from winch gear, ship maneuvering and outer conditions such as weather, in order to diagnose operational efficiency (Optigear).	CORDIS	https://www.naustmarine.com/marine/r-d-projects
MYFISH	Creation of decision-making tools to facilitate sustainable management and protection of marine ecosystems, by defining variants of MSY that account for redefined meanings of yield and sustainability.	CORDIS	https://www.myfishproject.eu/

BENTHIS	Integration of the role of marine benthic ecosystems in fisheries management, through development and synthesising of knowledge about how trawling can impact the seafloor, which resulted in an assessment framework applicable across European seas.	CORDIS	https://www.benthis.eu/en/benthis.htm
Electric voyage	Introduction of a patented technology for boats, enabling electric propulsion as well as digitalisation and remote management of data and key parameters through a cloud system.	CORDIS	https://cordis.europa.eu/project/id/101010233
H2OCEAN	Development of a multi-use open-sea platform, using energy from multi-trophic aquaculture farms and other applications to harvest wind and wave power, which can be on-site converted to and stored as hydrogen that ships can collect.	CORDIS	https://cordis.europa.eu/project/id/288145
RENShip	Battery vessel innovation project coordinated by Navis EHF, developing a fishing vessel powered by a hybrid propulsion system of methanol and lithium batteries connected to wind turbines and solar powers.	CORDIS	https://cordis.europa.eu/project/id/807237
CoolFish	Development of technologies and concepts for more integrated, energy-efficient and climate friendly cooling, freezing and heating onboard fishing vessels.	Nor-Fishing	https://www.sintef.no/en/projects/2019/coolfish/
ZeroKyst	Development of a new zero-emission vessel, retrofit zero-emission propulsion to 10 vessels, and development of a flexible supply system of electricity and hydrogen.	Gronn Platform project	https://zerokyst.no/en/
Ammonia fuel bunkering network	Development of infrastructure for use of green ammonia as fuel in ships in Norwegian ports, through a network of bunkering terminals and with the aim to have the first terminal ready in 2023.	Gronn Platform project	https://www.sintef.no/en/projects/2021/ammonia-fuel-bunkering-network-for-marine-sector/

ICES Workshop on innovative fishing gear (WKING)	Workshop in response to the EU Commission (EU DG-MARE) seeking advice on progress with innovative fishing gear, to provide information on objective, technical specificities and environmental impact of the gears that are being used.	Expert consultation (Eigaard & Bastardie)	https://ices-library.figshare.com/articles/report/Workshop_on_Innovative_Fishing_Gear_WKING_/18618275 Final report available online
FishGuider	A decision-support tool for the maritime and marine sector to plan fishing activities, developed by fishers, SINTEF and NTNU, and actors within communication solutions such as Wi-Fi and 5G.	Nor-Fishing	https://www.ncmc.no/fishguider_c440621574
SEAOPS etc.	Development of several solutions for energy optimised operations, such as autonomous operations, hybrid propulsion and dynamic positioning of fishing vessels.	Nor-Fishing	https://www.brunvoll.no/news/how-can-autonomous-operations-and-dp-contribute-to-an-even-more-sustainable-business
K-SIM Fishery	State-of-the-art fishery simulator made for training of crew promoting e.g. fuel consumption.	Nor-Fishing	https://kongsbergdigital.com/products/k-sim/fishery/
Wavefoil	Development of retractable bow foils, offering 5-15% fuel savings through using wave energy converted into propulsive energy.	Nor-Fishing	https://wavefoil.com/
Thorion	Implementation of an integrated pump system, replacing traditional AC motor (using alternating current) to DC motor (converts direct current) to reduce energy use.	Nor-Fishing	https://www.ydra.no/en/thorion
Development of hybrid propulsion systems for fishing vessels	Converting a coastal vessel to hybrid propulsion	FHF	FHF project No. 900922 (2013-2014) Original title: Utvikling av hybride fremdriftsssystem for fiskefartøyer Referred to as 'Fremtidens fiskeri er elektrisk' (future fisheries are electric) in Thompson et al. 2017 Klimaveikart 2017 (see below Climate road map for the Norwegian fishing fleet 2017)
Development of a knowledge base for CO2 emission reduction in the fishing fleet on short (2030) and long (2050) term	Development of a model and measures to increase knowledge about energy and fuel use within the fishing sector, in order to help fishers adapt to future regulations and incentivise reporting of emissions.	FHF Ongoing	https://www.fhf.no/prosjekter/prosjektbasen/901773/ Original title: Utarbeidelse av kunnskapsgrunnlag for reduksjon av CO2-utslipp fra fiskeflåten på kort (2030) og lang sikt (2050)

Alternative environmental energy sources for hybrid coastal fishing vessels	Overview of various methods for energy extraction on-board hybrid fishing vessels, to form basis for practical solutions (short-term) and minimise/eliminate the use of internal combustion engines (long-term).	FHF	https://www.fhf.no/prosjekter/prosjektbasen/901194/ Final report: Jensen et al. 2016 Original title: Alternative miljovennlige energikilder for hybrid kystfiskefartoy
Effects of different climate measures and regulations for approval of hydrogen as fuel in the fishing fleet	Development of (so far lacking) regulations for hydrogen fueled fishing vessels for approval of Loran Hydrogen (the world's first hydrogen fishing vessel), to make the technology more accessible and make 'green' fish better paid in the market.	FHF Ongoing	https://www.fhf.no/prosjekter/prosjektbasen/901714/ Original title: Effekt av olika klimatiltak og avklare regler for godkjenning av hydrogen som drivstoff i fiskeflåten
Economic and environmental consequences of regulations and institutional frameworks for fisheries	Documentation of fisheries management and its influence on fuel use and greenhouse gas emissions in the sector. Conclusions include significant potential in quota flexibility to reduce fuel consumption, and that new vessels are more energy efficient due to larger size and use of tools.	FHF	https://www.fhf.no/prosjekter/prosjektbasen/901573/ Final report: Isaksen et al 2021 Original title: Okonomiske og miljomessige konsekvenser av reguleringer og institusjonelle rammer for fiskeriene
Greenhouse gas emissions in the Norwegian fishing fleet in the period 1995-2015	Improving catch regulations and the institutional framework of Norwegian fisheries (1995-2015), through knowledge about minimising fuel consumption, safeguarding the value potential of catches, and improving profitability.	FHF	https://www.fhf.no/prosjekter/prosjektbasen/901248/ Final report: Skontorp Hognes & Jensen 2017 Original title: Klimagassutslipp i norsk fiskeflåte for perioden 1995-2015
Energy-efficient and environmentally friendly trawling systems for the shrimp trawler Arctic Swan	Development of gear technology (new trawl design, gears/clumps and trawl doors) to streamline fishing for ocean-going shrimp trawlers and reduce energy consumption per kg catched shrimp (catch per unit effort).	FHF Ongoing	https://www.fhf.no/prosjekter/prosjektbasen/901752/ Original title: Energieffektive og miljövennlige trålsystemer for reketråleren Arctic Swan
Electrification of the coastal fleet using batteries and fuel cells	Study of concrete measures to remove emissions from coastal fishing vessels, resulting in suggestions of hydrogen and ammonia-based propulsion. According to the results, ammonia has great potential apart from some technical and	FHF	https://www.fhf.no/prosjekter/prosjektbasen/901640/ Final report: Jafarzadeh et al. 2021 Original title: Elektrifiering av kystfiskeflåten ved bruk av batterier og brenselceller

	economic challenges, whereas hydrogen is considered feasible, but that vessel length creates limitations for longer ranges due to the quota system.		
Climate roadmap for the Norwegian fishing fleet: An update of the 2017 report	Update of the climate roadmap to form basis for achievement of national (Norwegian) and international goals and targets related to greenhouse gas emission. Effective measures identified include a shift in climate policy from a carbon tax with a compensation scheme to a requirement of biofuel inclusion with a permanent compensation scheme.	FHF	https://www.fhf.no/prosjekter/prosjektbasen/901716/ Final report: Thompson & Thompson 2021 Original title: Klimaveikart for norsk fiskeflåte: En oppdatering av rapporten fra 2017
Climate road map for the Norwegian fishing fleet	Generation of knowledge about measures and policy instruments to form a national strategy for reducing emissions in the Norwegian fishing fleet. The most effective measures identified are a structural rationalisation of the fishing fleet (smarter fishing), increased efficiency of vessels and equipment, and introducing biofuels and zero-emission solutions.	FHF	https://www.fhf.no/prosjekter/prosjektbasen/901339/ Original title: Klimaveikart for norsk fiskeflåte Final report: Klimaveikart 2017 Thompson 2017
Pre-study: ECO trawl concept-Trawl doors changed to active thrusts where only electric power comes from the vessel	Development of trawling technology that replaces the traction from the propeller with powerful electric propeller units (thrusters) that receive electricity from a generator on the trawler and can be controlled in the water with side and depth rudders, which makes the system more efficient and environmentally friendly.	FHF	https://www.fhf.no/prosjekter/prosjektbasen/901364/ Final report: Bjornenak 2020 Original title: Forstudie: ECO trawl-konsept-Trawldorar bytts ut med aktive thrustere der kun elektrisk kraft kommer fra fartoyet
Fish finding autonomous surface vessels: a pre-study	Pilot study demonstrating 'fish finding' autonomous vessels, that use echo sounders to monitor fishing grounds and detect fish inflows and send this information to land and vessels.	FHF	https://www.fhf.no/prosjekter/prosjektbasen/901202/ Final report: Hauge & Pedersen 2016 Original title: Fiskeletende autonome overflatefarkoster: Forstudie
Hybrid energy systems for small fishing vessels	Documentation of battery hybrid propulsion technology, with electric	FHF	https://www.fhf.no/prosjekter/prosjektbasen/901186/ Final report: Aersaether & Eldby 2018

	drive of propeller, diesel generator and battery, for smaller coastal fishing vessels. Conclusions include that the technology reduces noise and running time on the diesel engine, among other benefits.		Original title: Hybrid energisystem for småfiskefartoyer
H2020 ENOUGH	Addressing and reducing emissions generated from the food systems, by identifying measures for food businesses to achieve climate neutrality, improve integrated sustainability, meet societal goals, and increase awareness among relevant actors.	CORDIS	https://enough-emissions.eu/
RightFish	Reducing emissions and other environmental impact from commercial fisheries, i.e. through design of fishing gears with less impact on seabed.	BlueBio ERA-NET	Information not found.
Nordic roadmap	Knowledge sharing and launching of pilot projects and studies, as part of a Nordic cooperation platform and with the aim to establish 'green' corridors' and enable infrastructure for new fuels in the shipping sector.	Chalmers consultation	https://futurefuelsnordic.com/
Potential and conditions for Swedish shipping's conversion to fossil-free propulsion	Generation of knowledge regarding short- and long-term (2030 and 2045, respectively) implementation of different propulsion technologies, including electricity, biofuels, and fuel cells with new fuels such as hydrogen, ammonia or electrofuels.	Chalmers consultation	https://research.chalmers.se/project/10903 Original title: Potential och förutsättningar för svensk sjöfarts omställning till fossilfri framdrift
Hydrogen, ammonia and Battery-electric propulsion for future ships	Evaluation of hydrogen, ammonia and electricity as carbon-free energy carriers in shipping, including comparison with alternative fuels regarding cost, climate and environmental impact.	Chalmers consultation	https://www.chalmers.se/en/projects/Pages/HydrogenQ-ammonia-and-battery-electric-propulsion-for-future.aspx
Sustainable shipping now	Ten-year (2019-2028) industry program coordinated by the Swedish Transport Administration, aiming at creating an internationally competitive, sustainable and safe Swedish shipping	Chalmers consultation	https://lighthouse.nu/sv/verksamhet/hallbar-sjoefart Original title: Hållbar sjöfart nu

	sector through collaboration between academia and the public and private sector.		
Passenger ferries with all-electric drive systems – dimensioning, technical evaluation and life cycle assessment for operation in Swedish waters	Information not found.	Chalmers consultation	https://www.chalmers.se/sv/projekt/Sidor/PassagerarfQrjor-med-helelektriska-drivsystem---dimensioneringQ.aspx Original title: Passagerarfärjor med helelektriska drivsystem – dimensionering, teknisk utvärdering och livscykelanalys vid drift i svenska farvatten
EXIT – External costs, control instruments and cost-effective measures to achieve sustainable shipping	Evaluation of the external costs generated by or related to shipping through impacts on climate, marine environments and human health, based on case studies in Swedish exclusive economic zone, the Baltic Sea and European marine waters.	Chalmers consultation	https://www.chalmers.se/sv/projekt/Sidor/EXIT---Externa-kostnaderQ.aspx Original title: EXIT– Externa kostnader, styrmedel och kostnadseffektiva åtgärder för att nå en hållbar sjöfart
Electrified ship propulsion – considering efficiency and environmental impact	Information not found.	Chalmers consultation	
The future of hydrogen – societal challenges. TechForH2 competence center.	Knowledge and competence building regarding hydrogen propulsion in heavy transports, through collaboration between different modes of transport.	Chalmers consultation	https://www.chalmers.se/en/departments/m2/news/Pages/TechForH2---for-a-sustainable-hydrogen-economy-of-tomorrow.aspx
Catalysis for sustainable energy: insights from cost and environmental assessments	Information not found.	Chalmers consultation	
Climate change and the CFP: adaptation and building resilience to the effects of climate change on fisheries and reducing emissions of GHGs from fishing	Extensive report exploring the resilience of EU fisheries to climate change and ways to reduce GHG emissions through management and technological measures	European Commission/ CINEA/ EMFF/ DTU consultation	Bastardie et al. 2022: https://cinea.ec.europa.eu/publications/climate-change-and-common-fisheries-policy_en

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The fishing sector is facing major challenges in the accelerating energy crisis, owing to its high dependency on the stable supply of fossil fuels at low prices. This report reviews the literature on drivers of energy use, identifies potential reduction measures and provides an overview of opportunities for using alternative fuels in the fishing sector. Each measure is evaluated in terms of greenhouse gas emission reduction potential and costs, and challenges and policy options that could facilitate implementation. A timeline lists measures that could be implemented in the shorter and longer term, on the basis of scientific and grey literature, projects and expert interviews.

A considerable reduction in fuel use could be achieved by utilising existing EU regulations to the full (for instance, by rebuilding stocks and allocating fishing rights in accordance with Article 17 of the Basic Regulation on the common fisheries policy). It is crucial to use economic policy instruments, such as taxes, fees and emission quotas widely, to incentivise the transition. A ban on fossil fuel use in fisheries by 2050 would give clear long-term incentives and create the conditions needed for the transition. Such a policy must be accompanied by well-designed funding opportunities for green investments and compensatory measures to avoid increasing short-term costs. Overall, a systems perspective is needed to achieve an energy-efficient, decarbonised fishing sector, without causing other environmental impacts.

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