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Future fisheries
Status, trends and future perspectives concerning the energy transition of fisheries with focus on Nordic countries

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Abstract

The energy transition of the fishing sector has gained increasing attention in recent years. With focus on Nordic countries, status, trends, opportunities and challenges are summarized to provide recommendations for how to effectively enable an energy transition towards carbon-neutral fisheries. Key challenges include inadequate data collection and reporting of greenhouse gas emissions, low uptake of available technologies, reversed financial incentives fostering use of fossil fuels, and obstructing fishing regulations. Further, emissions are increasing in some countries, and even with decreasing trends in fuel use intensity (litre of fuel per kg landing), rising fuel costs are still affecting profitability. To foster an effective energy transition, short term actions (before 2030) include improved data collection and analysis, improved fishery governance with possibly a revised fleet policy to avoid maladaptation with climate targets, support of availability and innovations in alternative technologies, upskilling fishers, and revision of current financial conditions to enable a just transition. Long-term actions (before 2040) call for creating the required conditions in society, such as decreasing costs for and availability of alternative energy sources compared to marine diesel – calling for major investments by different actors. Overall, co-developing effective roadmaps for the energy transition of a highly diverse sector will be essential.

Keywords: fisheries, Nordic, decarbonization, fuel, greenhouse gas emissions, alternative fuels

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Introduction

Facilitating an effective energy transition of fisheries is urgent. Firstly, the fishing sector is still almost fully dependent on fossil fuels, with increasing fuel costs (e.g., STECF 24-07). Secondly, global fisheries emissions may be increasing (Parker et al. 2018). Thirdly, although fisheries are not a key sector to reduce global emissions (estimated at 0.1–0.5% of global carbon emissions; UN 2024), many uncertainties exist from lack of data – and the sector may be important to specific countries in reaching their climate targets, including many Nordic countries (e.g., Faroe Islands, Iceland). The energy transition, also referred to as decarbonization, of the fishing sector has thus gained increasing attention in Europe, seen in an acceleration in studies and initiatives concerning the energy transition of fisheries in the European Union (EU) in recent years (European Commission 2023a; European Commission 2023b; Ziegler and Hornborg 2023; COM 2023; Alma-Maris 2023; De Vet et al. 2023; Scholaert 2023; Hornborg and Ziegler 2024).

In terms of overall climate ambitions, all EU member states and non-EU Nordic countries (Norway and Iceland) share the common goals to achieve at least 55% emission reductions (compared to 1990) by 2030 and net zero emissions by 2050 through e.g., the EU Climate Law (https://climate.ec.europa.eu/eu-action/european-climate-law_en). The targets for both 2030 and 2050 are net targets, including all potential CO_2 removals by forests and other carbon sinks. Following the legally binding Paris agreement, global greenhouse gas (GHG) emissions must peak before 2025 (https://unfccc.int/process-and-meetings/the-paris-agreement). However, many policies aiming at reducing GHG emissions currently exclude fisheries, such as carbon taxes and emission trading schemes (ETS). Further, fishery management may be maladapted to foster energy efficiencies and use of alternative fuels, where instead eliminating remaining overcapacity, halt overfishing and change in fishing gears offers opportunities (Ziegler and Hornborg 2023). A question also concerns how a 'just' energy transition of fisheries can effectively be achieved, i.e. considering the current different financial conditions for a diverse sector (e.g., small-scale vs large-scale fleets) and availability of alternative technologies.

With a Nordic perspective (i.e., the countries Denmark, Finland, Sweden, Norway, Iceland and the autonomous territories of the Faroe Islands and Greenland), the aim of this paper is to summarize insights gained from years of research on energy use of fisheries, available data and Nordic cross-sectoral perspectives shared on a conference and workshop on the energy transition of fisheries, held during November 19-20, 2024, in Gothenburg, Sweden. The goal is to provide recommendations for effectively enabling an energy transition of fisheries, in Nordic countries and beyond (particularly EU), based on present challenges and potential solutions.

Nordic baselines for the energy transition of fisheries

Current emission levels and climate targets

Short-term targets (2023-2030) and measures highlighted as needed for the energy transition of fisheries include, amongst others, robust data collection and research to describe the state-of-play against which the progress towards decarbonisation targets are measured, calling for a proper monitoring of the GHG emissions of fisheries (Alma-Maris 2023; Ziegler and Hornborg 2023).

For Nordic countries, available statistics on GHG emissions vary in how they are collected and reported and accordingly accuracy (Table 1). Sweden reports GHG emissions for fisheries and aquaculture combined in Statistics Sweden (2024), but the Swedish Energy Agency also provide separate statistics on fisheries on fossil fuel use, but this is not done annually (The Swedish Energy Agency 2023). In Norway, different sources can be used for estimating GHG emissions of fisheries, with different absolute values – for 2021, ranging between 774 000–1 073 000 tonnes CO_2e (Jafarzadeh et al. 2023a). GHG emission data for fisheries also exists for Iceland (Statistics Iceland 2024), but when studied, it is apparent that the data is erroneous, reporting for a non-realistic level of nitrous oxide (N_2O) emissions. However, in the Icelandic national inventory report (Iceland 2024), fisheries are reported separately and with more realistic numbers. Overall, based on current practices in the EU and Nordic countries, arguably representing countries with relatively high-quality statistics available, improved data collection including data quality checks are needed to establish robust baselines for which progress may be measured against and enabling comprehensive understanding of key drivers over time.

Table 1 Indicative baselines on current greenhouse gas (GHG) emissions of Nordic fishing fleets, their contribution to national GHG emissions and data collection. EU DCF= EU Data Collection Framework.

Country	**Source**	**Estimated total GHG emissions from fisheries (t CO_2e)**	**Indicative share of national GHG emissions (%)**	**Mandatory reporting of fuel use?**
Denmark	Statistics Denmark (2024). Data for 2022.	406 000	<0.6	Yes (EU DCF)
Greenland	Statistic of Greenland (2023). Data for 2023.	151 170[1]	<24	Yes (every second year)
Iceland	UST (2023); Iceland (2024). Data for 2022.	503 000	17	No
Faroe Islands	US (2024). Data for 2023.	271 600	21	No
Norway	Statistics Norway (2024). Data for 2023.	863 000	1.3	No
Sweden	Statistics Sweden (2024). Data for 2021.	<89 000[2]	<0.2	Yes (EU DCF)
Finland	Statistics Finland (2024). Data for 2022.	>98 000[3]	~0.2	Yes (EU DCF)

[1]Includes agriculture (marginal but undefined). [2]Includes both fisheries and aquaculture. [3]Includes CO_2, an additional 1 000 tonnes N_2O is also reported.

In terms of climate targets for fisheries, there is now a proposed EU target of net zero emissions of the fisheries sector by 2050, and a partial goal to reduce energy use intensity by 15% by 2030 (COM 2023). Although energy use is not an explicit goal of fishery management today, parts of the EU CFP (see CFP Art. 17) could be used to favour energy efficient fisheries. However, this is in practice still rarely mentioned as one of the criteria for allocating the fishing opportunities (e.g., analysis of allocation of fishing opportunities as per Art 17 and reported in STECF 23-17 for EU countries only mention Belgium using fuel use as a criteria). Some Nordic countries have fishery-specific climate targets. In Iceland, at least 10% of new, small vessels should be partially or entirely electric by 2026, and a 55% reduction in CO_2e should be achieved by 2030 for the total fishing sector. In the Faroese Islands, a 50% reduction of emissions from the fishing sector by 2050 compared to 2010 is sought for. In Norway, emissions may be included in sustainability considerations from 2024, representing a new task type for the Directorate of Fisheries mandated by the Ministry of Trade, Industry and Fisheries. The purpose is to provide assessment of the climate footprint of fisheries and include climate measures in the advice that support the regulatory work of the ministry. Further, although Norwegian fisheries are not included in the EU ETS, there is an Action plan by the Norwegian Government stating that all non-ETS emissions should be reduced by 45% between 2005 and 2030.

For Denmark, Greenland, Sweden and Finland, no specific climate targets for fisheries exist to our knowledge. When energy efficiency is not integrated as a goal of fishery management, risks for maladaptation exist in the form of management actions negatively affecting fuel use efficiency, as seen for e.g., effects from Brexit on Norwegian mackerel fisheries (Scherrer er al. 2024), different fleet policies for the Danish, Swedish and Norwegian fishery for *Pandalus borealis* (Ziegler et al. 2016) and enforcement of species-selective trawls in Sweden (Ziegler and Hornborg 2014). Combined, the energy transition of fisheries would be facilitated if either existing fishing policy (e.g. CFP Art. 17) would become operational, or that more countries define reduction targets – both strategies requiring robust baseline data. Furthermore, there is still a lack of roadmaps listing concrete action plans on how to achieve existing climate targets – i.e., what needs to be done by when and whom to meet set targets and consider cost-effectiveness.

Fleet structure including latest estimates of fuel use

Fisheries represent a highly diverse sector, with different financial conditions, starting points and opportunities for the energy transition (STECF 24-07; Ziegler and Hornborg 2023). The EU and Nordic fishing fleets are large in vessel numbers and heterogenous in terms of fishing patterns, vessel characteristics and fuel use intensity (Table 2); the largest vessels, however, harvest the largest share of the fish resources. Overall, Norway has the largest fleet by all parameters, while Finland has the smallest in terms of gross tonnage and catches but second largest in terms of number of vessels. At a more detailed level, the average age of fishing vessels in Iceland is 31 years but the mean age of trawlers is 22 years, other larger vessels 29 years and small open boats 34 years (majority of vessels). In Norway, average age decreases with larger vessels, e.g. vessels over 28 m have a mean age of 22 years. In the STECF 24-07 report, fishing vessels in Sweden are reported to range from newly built vessels to almost 100 years old, the older ones most likely being more inactive vessels. To this end, the size of fleet and vessels, as well as fishing patterns and fishing economy, all affect opportunities for the energy transition.

Fisheries in the EU are subjected to mandatory data collection on fuel use following the EU Data Collection Framework (EU DCF). How this collection is done (and response rate) varies between countries, but as an example, Swedish data comes since 2012 from logbooks, journals, surveys with a census sample with high response rate (87%) and tax declarations. Fuel use reporting is, however, grouped per fleet segments, often combining vessels using different fishing gears with different fuel use intensity (measured in litres of fuel used per kg of catch landed), complicating interpretation of trends and robust comparisons. Further, unreliable and missing data have been identified (STECF 24-07; Bastardie et al. 2022a), calling for data quality checks. This may be due to, for example, confidentiality issues for fleets with few vessels, lower response rates in national surveys or unharmonized fuel data sampling and treatment. The data collection is also limited to use of fossil fuel, not use of alternative energy sources.

In Iceland, the Faroe Islands and Norway, there is no mandatory reporting of fuel use for fisheries (Table 1) but estimates on fuel use are still available for all Nordic countries (Table 2). However, different coverage and data collection procedure is applied. In Norway, fuel use reporting is conducted both by the Norwegian Fisheries Directorate and Statistics Norway (SSB). The Directorate of Fisheries collects data with an annual profitability survey, and although not mandatory, covers a large percentage of the largest fuel usage. The sampling method used is developed by Statistics Norway (2024), who provides the official GHG emission numbers, but the data here is based on sales data from fuel suppliers and tax reimbursements to attribute fuel use to different industries. In the Faroe Islands, fuel use for the fishing sector is based on data from fuel suppliers for different user groups, similar method as for Norway, reported to Official Statistics authorities that calculate GHG emissions. However, only total fuel consumption is reported in official statistics, and the data only cover larger vessels (in 2022, 293 small coastal vessels also landed catches and at least double the amount that have fishing license). Greenland has very detailed accounting of energy use in fisheries covering a mix of sources (gas oil, gasoline, kerosene, LPG, etc.) at Statistics Greenland (2014); however, information on GT, kW and mean age of vessels is not easily located. Overall, based on current practices in the EU and the Nordics, arguably representing countries with relatively high-quality statistics available, improved data collection including data quality checks are needed to establish robust baselines for which progress may be measured against and enabling comprehensive understanding of key drivers over time.

Table 2 Indicative characteristics of fishing fleets in the Nordics in 2022 (unless stated differently). Data is based on STECF 24-07 for EU countries (Denmark, Finland and Sweden); Statistics Iceland (2024) for Iceland; the Faroese Register of Shipping (2023) and Sjókovin (2024) for the Faroese Islands; the Norwegian directorate of fisheries (2024) and Statistics Norway (2024) for Norway; and Statistics Greenland (2014) for Greenland. Note that numbers are indicative and not fully comparative.

Country	Total tonnage (GT)	Total kW	Total number of vessels	Mean age of vessels	Landings (t)	Estimated energy consumption (l)
Denmark	75 929	236 208	1 989	29	458 203	74 283 472
Finland	14 888	174 223	3 281	36	86 387	8 743 361
Sweden	28 222	145 642	1 060	37	137 889	45 712 754
Iceland	162 919	452 773	1 540	31	1 414 823	165 680 000
Norway	488 530[2]	1 457 902[2]	5 295	30	2 618 101	320 000 000
Greenland	-	-	288[1]	-	304 312	58 486 000[1]
Faroe Islands	95 255[3]	188 801	155[3]	29	582 948	101 409 467

[1]Data for 2023 for number of fishing vessels (there are also 1 755 small boats (dinghies)). Energy use covers gas oil and gasoline (small amounts of kerosene, LPG an electricity is also reported).

[2]GT excludes smaller vessels (46% in number, estimated to increase GT with 5%), kW is converted from HP (multiplying with 0.7457), covers all but five vessels.

[3]GT, kW and number of fishing vessels from 2025 and exclude small coastal vessels. The mean age is only calculated for active vessels.

Trends

The overall trend for EU fisheries (EU-27; STECF 24-07) indicates a fluctuating, but in the most recent years, decrease in fuel use intensity (liter per kg landing). Still, the total energy cost has shown a stark increase between 2021 and 2022 for many EU Member state fisheries – in Sweden an increase by 32%, in Denmark by 38%. In Sweden, the fuel use intensity has decreased since 2013 – while it is reported that due to e.g. increasing fuel prices, the Swedish fleet is facing more economic difficulties than before. In Finland, the fuel use intensity decreased in 2016 and has since remained lower than previous years. The Icelandic fleet used 34% less fuel in 2022 than it did in 1990, whilst the total catches were almost the same, i.e. resulting in decreased fuel use intensity over time. Likewise, fuel use in Faroese fisheries has decreased by 17% over the last 20 years, whilst catches have increased. As a result, the fuel use intensity was 0.13 l/kg for Faroese fishing vessels in 2023 compared to 0.25 l/kg in 2003 (Sjókovin 2024).

In contrary, although total GHG emissions decreased between 2005-2014 in Norway, emissions are increasing in recent years. Suggested drivers behind the development over time are smaller quotas (particularly of cod), fewer vessels but increasing engine power and differences between fleet segments and gears. Major changes have occurred in the Norwegian fishing fleet from the year 2000 to 2023, where the total number of vessels reduced from around 13 000 to 5 500 while the total installed main engine power slightly increased.

Facilitating an energy transition of fisheries

Data collection, sharing and analysis needed

While data for fisheries management supporting stock assessments and monitoring of fishing capacity (e.g., vessel sizes, effort, fishing position, catches) are generally well established and available in official records for EU and the Nordic (although some data is still missing as seen in Table 2), parameters of relevance for understanding energy use requirements are poorly documented. Reporting of the main engine power is usually made mandatory and documented, however, with uncertain data quality (Berkow et al. 2018) and even fraud (European Commission 2019). Potential use and power of auxiliary engines are however very sparsely documented in fleet registers and likely unreliable. Understanding the basics, such as total engine power, would facilitate disentangling of other factors affecting fuel use – such as drivers of fuel use intensity (l/kg) for different fleets based on e.g., age of vessels, fishing ground, storage capacity of vessels, gears used, stock status, overcapacity and operational profile (Hilmasdottir et al. 2024; Ziegler and Hornborg 2023; Bastardie et al. 2022b; Jafarzadeh et al. 2016). The more detailed data available, the better opportunities to identify effective action plans with tailor-made solutions for different fleets.

Some data that is needed to better understand variations in fuel use in fisheries are today lacking or treated as confidential, effectively hindering research. In Norway, non-open data on fuel use, such as reported data for profitability surveys and carbon tax reimbursement numbers (NOK per litre of fuel) for individual vessels from "Garantikassen", may be used for research but is aggregated yearly and not connected to catch reports. There is also a data quality issue, as the different data sources show large variations, particularly for larger vessels (Jafarzadeh et al. 2023a; Winther et al. 2020). For EU fisheries, the fuel use data reported per vessel following EU DCF should be shared for research purposes, but this is currently not the case. Based on experiences from several research projects over the years, this data has not been shared on a vessel basis, but only pre-treated by the responsible authority and provided on fleet basis with unknown potential bias. Further, availability and access to spatial and effort data from Electronic-Reporting-From-Sea (ERS) and Vessel-Monitoring-Systems (VMS) varies for different vessel sizes, where smaller vessels have less detailed data. Some countries publish this data openly for public use, while others maintain it closed and available for regulatory functions; this data is however available for research upon request.

For large fishing vessels and seafood companies based on fisheries, fuel use of fishing vessels is highly important to monitor not the least for economic purposes and is available at high level of detail. An example discussed at the workshop is that a company such as Royal Greenland A/S follows the fuel consumption of its vessels monthly. From this, important insights may be gained, such as the importance of vessel speed and the potential for energy optimization onboard. Further, larger vessels allow for more storage capacity of catches onboard, and use of several trawl nets simultaneously may improve catch efficiency, both favouring fuel use efficiency of fishing activities. However, even if energy efficiency is specifically sought for, the GHG emissions per landing may vary between years due to e.g. fishing conditions (such as ice cover). A study looking at fuel use data on a trip basis for another seafood company found vast differences between species targeted and caught in different fishing trips (Ziegler et al. 2018). When only annual data is collected by authorities, and only for a fleet sample, this variability and associated improvement potentials are not identified. Looking beyond the needs for the energy transition, market demand is increasing for improved transparency in the form of sustainability reporting requirements, such as the Corporate Sustainability Reporting Directive (CSRD) and the EU Product Environmental Footprint (PEF). Here it would be useful to align various data collection efforts to become standardised, simple and easy reporting of fuel use that is quality checked.

Improving energy efficiencies

To initiate the energy transition process in fisheries, improving energy efficiency is the first move and an important enabler by reducing and optimizing use of energy. The magnitude of reductions depends on starting point and strategy, and different opportunities exist for a single fisher compare changes in fishing regulations (Ziegler and Hornborg 2023; Bastardie et al. 2022b; Alma Maris 2023). Measures requiring changes at fishery management level encompass elimination of overcapacity, rebuilding of stocks and allocating quotas to the most fuel use efficient fishing technology. There is however still a need for investigation on under which circumstances (e.g., different gear types) and to which extent stock status correlates with fuel use efficiencies – calling for improved data collection and analysis (see 3.1). At fishers' level, changes in the fishing gear (modification to reduce drag) and changes in the vessel or fishing operation (e.g., reduce speed) can be made.

Elements of energy efficiency at the fisher level include getting the crew engaged – motivated from a general lack of operational insights by the crew – and measure and visualize the total energy profile of vessel operations, evaluate the operational profile of the specific vessel, act to lower fuel use and continuously evaluate and improve over time. Cases have been reported where crews got engaged to the extent that they competed against each other in fuel-saving. Here, digitalization offers many opportunities, i.e. data analysis and user-friendly visualization may enable reductions in energy consumption by influencing skipper´s choices. Intelligent decision support may also include digital twins of vessels, allowing improved understanding of energy optimization, predictive maintenance, redesigning opportunities, use of alternative energy, and route planning. Further, digital twins of engines may offer virtual fuel use measurement with high accuracy.

Overall, targeting decarbonising of the entire fishing operation, not only the vessel, is key. Here opportunities exist from developing standardized approaches for monitoring fuel use both by authorities and individual fishers, including alternative energy sources used, engine characteristics and other energy consuming systems onboard for fishing vessels to improve monitoring of emissions and understand how the energy transition may most effectively be achieved.

Availability of alternatives to marine diesel

Full decarbonisation opportunities are linked to techno-economic perspectives to both energy efficiency measures to take and alternative fuels – what is available on the market, at what cost and GHG emission reduction potential? The energy density of alternative fuels is generally lower compared to diesel, i.e. larger volumes will likely be needed, why size of vessels and storage capacity will be important to factor in when determining suitable solutions. A recent techno-economic analysis concluded that the largest emission reductions opportunities are seen for the large-scale fleet (based on total use and intensity), and that decarbonization requires further innovation, targeted investments and incentives to make the solutions attractive to fishers – particularly for the small-scale coastal fleet (De Vet et al. 2024). Some current technologies are already viable, others not without significant reductions in costs, increases in fuel prices – or both.

The pathways that larger maritime sectors will take will determine conditions and opportunities for the fisheries sector in terms of use of alternative energy sources. Uptake of alternative energy is currently low for the maritime sector – 93.5% of ships in operation globally run on conventional fuel and the alternative fuels used mainly comprise of LNG which is still a fossil fuel. Overall, the maritime sector is highly diverse in their use pattern and vessel construction (numerous designs built in small series), contributing to different operational profiles, huge differences in energy demand and space onboard. Available alternative technologies include batteries, hydrogen and fuel cells, ammonia, biofuels, biogas and wind-assisted propulsion (Table 3) – each with advantages and challenges for fisheries, where a decarbonization strategy specifically for fisheries is lacking (Our Fish and ClientEarth 2022). Although many alternatives to diesel exist, major uptake will require upscaled production, suitable supply chains and major investments in port infrastructure to different extents depending on technology.

Extremely few fishing vessels are operating on alternative fuels globally, where Norway and Iceland may be seen as being in the forefront (Table 3). Fishing vessels have a long-life span and new vessels entering today will run for many years – at least 20 years from now. When this is the case, utilizing biodiesel or batteries within the current vessels will be essential for the energy transition, before alternatives such as methanol, ammonia and hydrogen is more readily available and could justify engine or vessel replacement. In parallel, it is imperative to enable fuel use efficiencies. Retrofit of engines may however be done within the vessels' life span, where e.g. in Norway, 40% of the registered vessels have newer engines – the mean difference between vessel and engine age is 18 years. Further, lessons learnt from Iceland, when one of the largest seafood companies was supported with public funding to test methanol, include that the energy transition will need to factor in supply (both quantity and service locations), pricing (fluctuations, correlation with other energy prices) and potential carbon taxation.

Table 3 Available technologies and indicative number of fishing vessels that have or are in the process of converting to alternative energy sources (based on Ziegler and Hornborg 2023), estimated greenhouse gas (GHG) emission reduction potentials and future perspectives.

Energy source	**Number of fishing vessels (globally)**	**GHG reduction opportunities today**	**Opportunities and needs**
Electricity (full or hybrid)	25 battery-run coastal fishing vessels operating globally, Norway in lead.	Depends on electricity production mix available (fossil or renewable).	Hybrids provide more flexibility. Investments in onshore infrastructure availability essential. Viable predominantly for coastal fisheries, but space/weight for batteries may limit uptake. Ocean going vessels may also benefit to some extent from optimize engine operations through batteries/storage systems.
Compressed methane (fossil- or biobased)	Four fishing vessels use fossil methane and more three ordered, Norway in lead.	Around 25-30% (when fossil based, 100% when fully renewable).	Need to transition away from fossil gas to biogas, but the same systems onboard may be used.
Liquid biofuels (drop-in fuels or 100% biofuel)	Not known. In Norway, 6% is mandated to be blended in already except for fisheries operating 250 nautical miles from the coast.	Depends on feedstock and LCA-modelling choices but estimated at 65-98%.	A solution that may be used for existing engines.
Hydrogen	No commercial. Two vessels in planning stage in Norway, including a 70 m longliner and one demersal trawler, but projects put on hold in 2024.	Not in place today.	Improve technical maturity, establish carbon-neutral supply chains.
Methanol	One vessel in Iceland is being converted to diesel-methanol dual fuel operation.	Under evaluation but reductions depend on methanol production method.	Large-scale potential, have technical maturity but need to transition away from dependence on carbon source By 2024, eMethanol may reduce emissions by 90%. Bio-methanol with some innovation may reduce emissions by 65% in the coming years.
Ammonia	None in commercial operation, but on innovation project funded in Iceland on conversion of trawler.	Not in place today.	Large research projects ongoing in e.g., Norway. By 2040, eAmmonia may reduce emissions by 96%, but various ammonia production methods exist. Improve technical maturity, safety protocols.
Sail-assisted propulsion, use of solar and wave energy	<10 vessels in Europe under test and development.	Under evaluation.	Lowers operating costs permanently, investment payback time 2.5 years for longliner in Panama.

The need for cross-sectoral collaborations to facilitate the energy transition of fisheries cannot be overstated. Engine manufacturing companies may today provide many solutions such as use of electricity (e.g. hybridisation) – but this also requires available infrastructure on land. Further, use of e.g. methanol, hydrogen and fuel cells in the future will besides new infrastructure need more innovations, including considerations of storage needs and safety. From a supplier perspective but also the vessel operator, important factors to consider are costs of storage, service logistics and cost, and cost of operations. Here, alternatives such as biofuels may use existing logistics and vessels, while others (e.g., hydrogen) will demand more changes to current structures and costs. Lastly, besides the need for more innovation and investment, including staff training in the fisheries sector (COM 2023; UN 2024), there is also much technology available that needs implementation, such as energy-efficient gears and ship designs (Bastardie et al 2022b). There is therefore a need for close industry-research collaboration projects focusing on implementation, cross-learnings including social acceptability of solutions. Cross-sectoral consultations can help identify other drivers e.g. innovation uptake and investments will most likely continue to be low as long as availability of fish resources are associated profitability is uncertain, and younger fishers cannot easily or are not attracted to enter the fisheries (e.g. Bastardie et al 2024). An example is a Norwegian project where several stakeholders and research and industrial entities collaborated to investigate the possibilities for using hydrogen and ammonia-fed fuel cells for powering a coastal fishing vessel (Jafarzadeh et al. 2023b). The findings showed high potential for reducing emissions for long trips using ammonia; however, technical, economic and safety challenges with using ammonia were identified. The study found hydrogen-driven fishing vessels feasible, but the Norwegian fish quota system, which among other aspects is based on vessel length, creates limitations for fuel storage and thus also limits range of the fishing operation.

Short- and long-term economy

The European Commission has identified the economics of the energy transition as one of the four main areas of action (COM 2023). A report by Our Fish and ClientEarth (2022) highlights that removal of fossil fuel subsidies would not only favour energy efficiency, a finding supported by scientific literature (e.g., Ziegler and Hornborg 2014), but also that fossil fuel taxes could be redirected to financing new technologies. In Norway, the NOx fund currently redirects taxes on NOx emissions from propulsion engines >750 kW to support NOx reduction measures. Many international commitments exist for phasing out or reduction of fossil fuel subsidies, it is e.g., one of the Sustainable Development Goals (SDGs) that should be reached by 2030, and part of the Glascow Climate Pact (COP26). Several analyses however indicate that development goes in the opposite direction, e.g., the degree of change in fossil fuel subsidies per capita between 2019-2021 has increased, including for many Nordic (Our World in Data 2024); for 2022, an all-time-high has been observed with a doubling compared to 2021 (IEA 2022). It is repeatedly stated that the fishing industry may not cover the costs due to poor profit margins, however, many fisheries in Nordic countries are very profitable (Nielsen et al. 2018); all are also negatively affected by rising fossil fuel prices. So far, emergency measures are often implemented by national governments to address abrupt rising fuel prices caused by e.g. geopolitical events, such as financial support for sudden increase in fuel cost. As long as use of fossil fuels is cheaper than alternatives with lower GHG emissions, and short-term economy is prioritized over long-term investments, there is little incentive for the industry to initiate the transition.

Some changes are now seen related to market incentives and carbon emissions from the fishing sector. As part of the European Green Deal, a carbon pricing scheme has been proposed in the EU to include the fishing sector in the Emissions Trading System (ETS). This proposal accompanies the revision of the Energy Taxation Directive, which is currently on hold. The aim of this revision of the directive is to lower taxes on alternative, greener fuels while increasing taxes on fossil fuels. However, revising tax policies presents a challenge at the EU level, as it requires the endorsement of a qualified majority of member states. In this context, Norway has a carbon tax on fuel for fisheries, but with a refund, designed to increase linearly from reduced rate to full rate in 2030. Denmark introduces a carbon tax for the fishing sector in 2025, with plans for a gradual increase until 2030.

Overall, balancing short-term costs against long-term gains will be important for the energy transition, but currently comes with many uncertainties and challenges (Ziegler and Hornborg 2023). Some energy efficiency measures go hand in hand with instant improvement of financial conditions, such as optimising vessel speed and decrease fuel use and associated costs, while others come with substantial investments, such as major changes in vessel design, engines or even building of new vessel. For a commercial fisher, income is highly related to annual quotas, when getting approval from the bank to loan money for long-term investments may be challenging depending on the timespan of fishing opportunities. Many small-scale fisheries comprise of very old vessels (STECF 24-07), and simply cannot afford to invest to favour energy efficiencies. The heterogeneity of fishing fleets also calls for tailored solutions, were e.g. in the Faroese Islands, demersal factory trawlers comprise of new and large vessels (four in 2023, average age ~15 years) and whereas small, long-liners comprise of more vessels and are the oldest (22 in 2023, average age ~45 years). On top of this, the fishing patterns vary. Aligned with this, it is imperative that the energy transition of fisheries is designed to favour a just process (Metta et al 2022), acknowledging the different conditions of fleets. When aiming for full decarbonisation – which overall is costly today compared to current practice – uncertainties in what to invest in is prevailing; development of energy costs and infrastructure availability over time is difficult to predict. This calls for identifying and applying flexible solutions today, that can be adaptive to future development.

Governance for long-term sustainable fisheries

Improving the governance framework and coordination and cooperation between stakeholders was one area of action identified by the European Commission (COM 2023). The discussions so far have been held in different fora, hampering e.g., development of common strategy and exchange best practises. One key issue pertinent to fisheries is fishery management regulations and how current metrics for monitoring fleet capacity may pose hinders for the energy transition, given the larger storage volumes needed while vessels are restricted by fishing regulations that intent to preventing increase in length, GT and kW (Hornborg and Ziegler 2024). This is also why minimising energy use before shifting over to alternative fuels would be necessary to minimize need for increased storage space. A key question in designing new fishing vessels and promoting energy efficiency and the use of alternative fuels is therefore how to align with, or transform, fishing regulations intending to manage fleet capacity with revised, maybe more suitable indicators fulfilling both purposes. In e.g., EU, Norway and Iceland, vessel length, GT and kW is used for fishery management purposes such as monitoring of fleet capacity and access to quotas and fishing grounds. This leads to vessel designs that may compromise energy efficiency while still having similar or even increased catch capacity (i.e., short but tall and wide vessels). In the EU, GT and kW of vessels are used to monitor fishing capacity – but are in practice not the most suitable to use due to failure to acknowledge e.g. technological creep that represents unaccounted increase in catch efficiency (Eigaard et al. 2014). Thus, current metrics used to monitor fleet capacity in the EU are failing the intentions to decrease overcapacity and overfishing of stocks while also challenging the energy transition (Hornborg and Ziegler 2024). Identifying how to align potential needs related to vessel characteristics to facilitate the energy transition with more efficient monitoring of fishing capacity and eliminating any remaining overcapacity will arguably be a crucial endeavour over the coming years.

Another important component related to improved governance of fisheries is the potentially high influence of fuel use intensity (l/kg) from effective elimination of overcapacity, ensuring sustainable exploitation levels and promotion of energy-efficient gears (e.g., Ziegler and Hornborg 2023, Ziegler et al. 2016; Ziegler and Hornborg 2014). It is unclear to which extent this may improve energy efficiencies for different fleets, but increasing abundances and decrease of overcapacity has proved successful for fuel use intensity of many fleets in Nordic countries and beyond (Ziegler et al. 2016; Kristofferson et al. 2021; Jafarzadeh et al. 2016; Parker et al. 2015) and different gear types used to target the same species show large variability in fuel use intensity (Parker and Tyedmers 2015; Bastardie et al. 2022c). Opportunities thus likely exists at fishery management level to promote energy efficiencies that would also be in line with sustainable use of fisheries resources (e.g., rebuilt stocks).

Conclusions

- Urgent actions are needed for an effective energy transition of fisheries, with pressing challenges related to current financial incentives and fishery regulations. One impediment is that few energy transition targets exist specifically for fisheries today, as illustrated for Nordic countries, and action plans on how to get there are missing. Further, improved fishery governance – including both elimination of overcapacity and overfishing and use of indicators that are effective in monitoring catch capacity without impeding the energy transition – would foster long-term sustainable fisheries.
- Diverse fishing operations and conditions require tailored solutions. As illustrated for the Nordics, fishing fleets are diverse in terms of size, age, number of vessels, and landings – a common finding for fisheries that contribute to different opportunities and challenges for an effective energy transition.
- Identification of opportunities needs improved data collection and analysis. Data on annual fuel use or fuel costs are collected per vessel by most European countries, but with varying quality and coverage– but is today not easily available on a vessel basis for research.
- The energy transition builds on enabling energy efficiencies and flexible solutions for alternative energy systems – fleets with e.g., many new vessels will likely run for the coming decades, why use of fuels that require no or minor adjustments and improving energy efficiency of operations are more likely than switching to alternative fuels that requires new vessels. Further, to improve incentives for an energy transition, current fossil fuel subsidies in fisheries should be redirected towards instead supporting uptake of new technologies and lowering the cost of alternative fuels.
- Collaborations across a broad set of societal actors and researchers are essential to enable the energy transition of fisheries, e.g., develop strategies and exchange best practises.

Recommendations

Short-term actions (before 2030) include:

- **Improve future data collection and analysis of new and existing data.** There is a need for improved understanding of the basics of energy efficiency in highly heterogenous fisheries, including analysis of both available data that is unexplored and collection of more detailed data. This would underpin effective action plans for the energy transition through being able to disentangle different drivers and identify improvement potentials for different fleets. Action:
  - Standardize data collection on fuel use of vessels and make it mandatory to report.
  - Allow high-detail data on fuel use to be shared for research.
  - Investigate feasibility using models and tools for various implementation paths including existing or yet-to-come energy transition solutions.
  - Incentivise monitoring of operational profile of vessels by fishers to improve understanding of current fuel use and fit-for-purpose alternative solutions.
- **Improve governance of fisheries to facilitate the energy transition.** It is increasingly urgent to avoid risks for maladaptation between energy efficiency and current fishery management. Actions:
  - Scrutinize potential hindering fishery regulations, including identification and use of indicators and strategies for monitoring fishing capacity that are more effective in eliminating overfishing and without conflicting the energy transition.
  - Implement more effective fishery management measures to remove remaining overcapacity and rebuild stocks, and where relevant and data can support, allocate quotas to fleets with highest fuel use efficiency based on e.g., gear type.
  - Set milestones for achieving the energy transition of fisheries – a detailed timeline on what needs to be done to reach the targets including evaluation of cost-effectiveness of different actions.
- **Support availability and innovations in technology, including training of fishers.** There is both need for more research and innovation including staff training in the fisheries sector, but also implementation of technology available. Actions:
  - Progress innovations on alternative energy sources (including safety and storage need) and apply effective funding for enabling the transition including investments in onshore infrastructure.
  - Engage in close industry-research collaboration projects focusing on implementation, cross-learnings including social acceptability of solutions.
- **Enable a just transition acknowledging short- versus long-term economy.** The need for phasing out fossil fuel subsidies is repeatedly highlighted while the costs of the energy transition can be substantial, motivating a thorough cost-benefit analysis (short-term vs long-term) to identify both overall changes

needed (e.g., fishery regulations and financial incentives) and tailored solutions for specific fleets in terms of effective energy transition measures. Actions:

- Scrutinize fishing regulations and current financial incentives that may hinder the energy transition.
- Investigate current conditions (e.g. profitability and private investment capacity) and funding opportunities for specific fleets.

In the longer-term (before 2040), it is vital to create the required conditions in society, such as decreasing costs for and availability of alternative energy sources compared to marine diesel, to enable a just energy transition for the diverse fishing sector. This calls for major investments in port infrastructure allowing for use of green energy to ensure a production of sustainable and nutritious foods from the ocean also in the future.

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