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How to ensure sustainable fisheries while renewing the EU fishing fleet for modernization and energy transition?

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The European Union's (EU) fishing fleet has struggled with overcapacity, which has led to overexploitation of fish stocks. Since the 2013 Common Fishery Policy (CFP) last reform, efforts to promote sustainable fisheries have resulted in healthier fish stocks and a reduction in fleet size. While EU fleets now comply with capacity limits, challenges remain, threatening sustainability and the fishing sector's viability. Despite improvements since the reform, economic disparities and imbalances in fish resources persist. By collating expert knowledge and data analyses, this study examines if facing future challenges, such as energy transition and attracting young fishers, may require extra capacity to accommodate more efficient or alternative engines for greener fuels, and improve working conditions, in the context where country-specific capacity ceilings limiting the fishing capacity are not reached. However, current policies may limit short-term profitability of the current active fleet. At the same time, the EU fleet policy should ensure that fleet renewal, modernization, and profitability improvements, which may require additional capacity or not, alongside improved efficiency over time, do not result in an improved ability to catch fish that would exacerbate fleet imbalances, create overcapacity, or put more pressure on exploited stocks. Our findings indicate that the current EU fleet imbalance will likely worsen whenever capacity is reused, or extra capacity is granted without controlling for the ability to catch fish, and without monitoring for the right metrics beside fleet or vessels kW and GT. It appears optimistic to assume that reactivating unused fishing capacity or granting extra fishing capacity will not be used to catch even more fish. The findings aim to inform recommendations for improvement and to find applicable solutions within the EU framework, while addressing ongoing challenges in EU fisheries without compromising the fleet's capacity to catch fish in ways that do not contribute to overcapacity and imbalance. It appears advisable that fishing capacity would best be managed at the fleet level, not reduced per individual vessel, to ensure balance with fisheries opportunities, support the energy transition, and safeguard socioeconomic resilience under the CFP.

KEYWORDS
decarbonisation, fishing fleet policy, fleet modernisation, overcapacity, safety and wellbeing, seafood, working conditions

1 Introduction

The Common Fishery Policy (CFP) adopts a precautionary approach (CFP Art 2 in EU 2013), with flexibility to maintain sustainable fisheries, economic returns, and resilience to climate-related challenges (e.g., Bastardie et al., 2022b, 2024, OECD, 2025). This flexibility is required because EU waters span several ecoregions characterized with different fleet sizes and fishing practices. In particular, differences between the Northeast Atlantic and the Mediterranean make regulation complex. In the Northeast Atlantic, fisheries management relies on Total Allowable Catch (TAC) and quota systems and technical measures for its large vessels, while in the Mediterranean, fisheries are characterized by more diverse, smaller-scale vessels that require varied management approaches. When catch monitoring is challenging, as in the Mediterranean with numerous landing sites and small operators, regulating fishing technologies may seem more practical (e.g., Pita et al., 2020; Sierra-Castillo et al., 2024). As a result, controlling fishing effort and equipment allowances are sometimes favored over fish quota systems.

Effective fisheries management should focus on setting smart limits on catches, effort, and regulating gear, while avoiding restrictions on upgrades that enhance safety, working conditions, and environmental performance. A fundamental contradiction in limiting the fishing capacity is that a gain in efficiency is essential to rebalance EU fleets on the economic side (e.g., the small-scale fishing sector at the edge of profitability STECF AER, 2025a). At the same time, this gain in catch efficiency was, and may still be, the primary driver of overcapacity and the increased risk for overexploiting EU marine resources. Hence, certain fishing techniques and technologies, like seining in specific areas, are criticized not because they are inherently harmful, but because of their catch efficiency (Bromhall et al., 2026; Sala et al., 2023). The use of advanced fishing equipment is often viewed as unfair, and prompts calls for technological restrictions, even though more efficient fishing techniques could reduce operating costs.

A more effective strategy would be to allow technological advancements while reducing fishing effort to ensure sustainability (Sterner and Coria, 2012). However, monitoring the different harvesting capacity generated by different technologies and fishing gear remains difficult, making it hard to regulate fairly. This challenge is compounded by "technological creep", which often occurs in fisheries development. Technological creep describes the often-unnoticed adoption of increasingly advanced and efficient fishing technologies that boost catch rates and reduce costs. There have always been innovations (e.g., improved fishing gear), and this drive to improve efficiency through technological development is not new. A long story of innovations include power blocks to haul nets during netting or seining operations, stronger net materials, to semi-pelagic doors for trawls, and fish-school-detecting devices (Eigaard et al., 2014; Sala et al., 2023; STOA, 2024), accompanied more recently with AI-based tool helpers developed in recently funded EU projects (e.g., OPTIFISH https://optifish.eu/, INFINIFISH https://infinifish.eu/, EVERYFISH https://everyfish.eu/, MarineGuardian https://marineguardian.eu/). Hence, monitoring the diverse harvesting capacities introduced by various technologies and equipment is challenging, complicating efforts to regulate fisheries fairly.

This raises a fundamental question: what is the most effective way to manage fisheries for enhancing resource extraction efficiency while promoting sustainability, or at least without undermining it? This dilemma is heightened by the trade-off between increased catch efficiency, which typically lowers costs and, for example, unwanted CO2 emissions, versus the potential risks to sustainability and future seafood extraction, which may increase operating costs and fuel use if future opportunities decline (Bastardie et al., 2022b). However, improved efficiency will also improve the economic performance which can support vessel modernisation, enabling fleets to address future challenges such as the energy transition and generational renewal of vessel captains and the crew. Modernisation and catch efficiency is also necessary to make the fishing occupation safer while the highest incident rates occur during operations related to operating the fishing gear (Chauvin et al., 2017). Greater catch efficiency and safety could also increased risk of overexploitation, as well as reduced fairness and equity in income distribution (e.g., Merayo Garcia et al., 2018). These issues reflect conflicting objectives: efficiency, cost-effectiveness, societal welfare, safety, and the need for energy transition.

In these conflicting views, political science often demonstrates that the implementation feasibility within a governance framework is crucial to policy effectiveness (e.g., Ostrom, 1990; Sterner and Coria, 2012). For example, an ideal regulation that is poorly implemented or difficult to implement may be less effective than a more politically feasible measure that achieves broader compliance. Hence, because it is not judged by some stakeholders politically and economically feasible (NAT/895-EESC-2023, STOA, 2023) there are too few EU Member States initiatives in place to optimize fishing capacity due to the EU fishing fleet policy aimed first at limiting capacity (see CFP Articles 22 and 23). This has made it difficult for EU fleets to become more efficient overall. In contrast, the pursuit of the objective of energy transition in EU, as well as promoting more selective fishing, should take into account the possibility of fishing fleet modernisation through the control of the ability to catch fish that go beyond measuring vessel physical characteristics only (such as engine power or gross tonnage), and possibly focus on safe working conditions and navigation, as well as targeted and effective catch.

Encouraging stakeholders to adopt innovations voluntarily and encouraging EU Member States to promote supportive policies can be achieved by demonstrating tangible ecological and operational benefits, as well as economic feasibility and viability. This also involves identifying room for maneuver for adding some extra or renewed capacity within the existing EU fleet. To contribute to this endeavor, this paper first assesses the status of the EU fleet, its current fishing capacity and the degree of balance with their fishing opportunities. Second, it examines the needs for its future management and provides recommendations for resolving conflicting objectives and dilemmas, including how to best promote fleet renewal without impairing future fishing opportunities from overfishing (i.e. a situation where high fishing pressure leads to decreasing catches) and overcapitalization (i.e. where economic inefficiencies arises from excessive financial investment) whenever adding or redirecting new capacity.

2 Materials and methods

A study was tasked by the European Commission (EC) to examine the drivers behind EU fishing capacity evolution with a view to subsequently managing the challenges and the future of the EU fleet. The present investigation prolongs this study. Readers seeking more details are referred to Bastardie et al. (2026).

We used the EU fleet register (Article 24, 2013 CFP), a public database containing information on all EU fishing vessels, including those flying the flag of an EU Member State([1]). Data in the Fleet Register can be classified in three categories: (i) administrative identifications (e.g., vessel name, registration port); (ii) technical characteristics (e.g., length, tonnage, fishing gear, power); and (iii) historical events (e.g., modifications of characteristics, entry into and exit from fleet). The EU Fleet Register is regularly updated ([2]) and serves as a key tool for monitoring the implementation of fleet capacity management by Member States. Member States must inform the EU of any changes to a vessel's status, such as scrapping or modification. Based on these declarations, the total fleet capacity can be calculated per country. Fleet capacity per Member State is then deducted from the register by summing up across all registered vessels. Allocation of the fishing capacity among Member States within the EU fishing fleet is reported in https://webgate.ec.europa.eu/fleet-europa/index_en.

To assess the balance with the fishing opportunities in the EU, Member States are also responsible for sending fleet capacity reports to the EC by 31st May each year (Article 22, 2013 CFP) ([3]). This provides an overview of how well EU fleet segments are balanced with their fishing opportunities for most recent years as reported by the EU Scientific Technical and Economic Committee for Fisheries (STECF) every year.

We continued reviewing reports and published literature identified by our expert knowledge to identify challenges that the EU fleet is currently facing, which often assume that extra fishing capacity requirements are to be granted for ensuring the energy transition and fleet modernisation (e.g., ERGOSPACE, 2007). Hence, to anticipate the risk of inducing further imbalance if extra capacity would be granted to address these future challenges, we continued by analyzing catch rates in order to estimate anticipated landings. Note that this anticipation initially disregarded potential changes or increases in catch efficiency for simplicity. These catch rates and historical landings were deduced from aggregating the EU Fisheries Dependent Information (FDI) public data recording landings and gross tonnage (GT), among other variables, of all the EU fleet segments. We used the FDI data to look into total GT per fleet segment, deduced catch per unit effort (CPUE) per fishery/fleet segment, multiplied actual GT by the remaining available GT that GT ceiling would allow.

Ideally, in a second phase, we would also multiply by actual GT with each innovative solution identified in our review to estimate the target GT, and deduce the extra GT required given the limiting GT. This would help concluding about the limitation of current ceilings, and deduce an extra ability to fish induced by extra GT that would make EU fleet even more at risk of imbalance. However, our findings showed that if or how innovative solutions would require extra GT is uncertain, and we therefore conclude it was too premature to apply phase 2.

This approach recognizes the "potential fishing capacity" concept. Fishing capacity is defined as the maximum amount of fish over a period (year, season) that can be produced by a fishing fleet if fully utilized, given the biomass and age structure of the fish stock and the present state of the technology following Lindebo et al. (2002). Overcapacity therefore results from an excess in potential fishing capacity compared to the target capacity which is the one required to capture the Maximum Sustainable Yield (MSY). MSY sets the target for deciding upon the fishing opportunities set within the EU CFP (CFP 2013 Art. 2). For this exercise, recorded landings in 2023 from the FDI were assumed to fully reflect those MSY targets for 2023.

3 Challenges identified to the future EU fleet

3.1 Current utilization of the fishing capacity by the EU fleet and imbalance status

Fishing capacity ceilings established in the Annex II of EU Regulation 1380/2013 have been deemed essential for Member States to adjust fishing capacity to prevent overfishing and promote sustainability, by setting an upper boundary to the total volume and

1 () https://webgate.ec.europa.eu/fleet-europa/index_en

2 () Regulation (EU) 2017/218: "MS shall submit to the Commission any event (..) no later than at the end of the working day when the event has been fully registered".

3 () https://oceans-and-fisheries.ec.europa.eu/fisheries/rules/fishing-fleetcapacities/fleet-capacity-reports-2024_en

power of the fleet. Fleet balance indicators calculated in 2024 for 2022 show that there were 619 active fleet segments across the EU including 52,820 vessels (STECF, 2024) across several indicators. For simplicity, we have only focused on the biological-related Sustainable Harvest Indicator (SHI, see the 2014 "Balance Indicator" Guidelines) Other biological and economic related indicators can be found in the review provided in Bastardie et al. (2026) while detecting imbalance situations as a result of overfishing is key here. SHI is precisely defined to detect such overfishing situation by calculating a weighted average with the value of landings of the ratio of the management target F, which is F_{MSY} in Europe, with the actual assessed F. Overall, we assessed that a large proportion of the EU fleet was found out of balance in the 2024 assessment or the year 2022: In the NAO region, out of 143 fleet segments for which biological indicator SHI could be calculated, a total of 29 segments (20.3%) were out of balance and 114 (79.7%) in balance with fishing opportunities in 2022. Of those 29 out of balance, 12 (41.4%) segments were improving, 5 (17.2%) were deteriorating and 12 (41.4%) either had no trend (flat) or could not be calculated. In the MBS, out of a total of 15,563 active vessels for which SHI could be calculated, a total of 13,748 vessels (88.3%) were out of balance. Out of these, 11,179 (81.3%) active vessels were improving, 819 (6%) were deteriorating, and 1,750 (12.7%) either had no trend (flat) or could not be calculated. In the OFR region: Out of 39 segments for which SHI could be calculated, a total of 6 (15.4%) were out of balance and 33 in balance with fishing opportunities in 2022.

The current imbalance of many EU fisheries would justify maintaining fleet policy rules to also prevent further increases in fishing capacity, when it comes along with better ability to catch fish resulting from technological and gear improvements. Meanwhile, the CFP allows new fishing vessels to be built with private money along with safeguards to prevent the fleet's total fishing capacity from increasing. Concretely, any new fishing capacity [quantified in GT and engine power (kW of vessels)] entering the fleet must be compensated for by at least the same amount of capacity being withdrawn (CFP Article 23 describing the entry exit scheme). This withdrawal assumes no gain in harvesting capacity (i.e. efficiency in catching fish).

At present time, we found that none of the Member States' fishing capacities are limited by their fishing capacity ceilings (Figure 1). As stipulated in the 2013 amendment to the CFP Regulation, where the fishing fleet capacity of the Member States is controlled by fishing capacity ceilings and an entry/exit scheme (Article 23, 2013 CFP), a new vessel can only enter a fleet after the equivalent fishing capacity (in kW and GT) is removed from the same fleet. Besides, the EMFAF funds only allow increasing the GT of a particular vessel (<24m) to improve safety, working conditions or energy efficiency and only if this vessel belongs to a segment for which the fishing capacity is in balance with the fishing opportunities available to that segment. Despite a reduction in absolute value in the metrics used to define fishing fleet capacity resulting from various public scrapping programs and voluntary exit, numerous cases of imbalance between fleet and fishing opportunities have been reported from 2000 to the present. Hence, the observed decrease in EU fishing fleet capacity (by means of total kW and GT) did not translate into an overall balanced capacity with the available fishing opportunities. Because imbalance was widespread this contributed to a gap between actual GT and GT ceilings observed for all EU Member States. Consequently, all 22 coastal Member States have shown an annual decrease in both their GT and kW since the year 2000.

Therefore, it appears that Member States have the flexibility to allocate the margin between capacity ceilings and actual active capacity to fishing vessels requiring energy-efficient propulsion systems or modernisation. This margin in GT and kW can be allocated to the fleet in need by the Member State itself as each Member State decides on its own allocation mechanism.

3.2 Possible capacity requirements to address EU´s future fleet challenges

Meanwhile, according to the stakeholders´ opinion (e.g., ERGOSPACE, 2017), the existing constraints on fishing capacity might limit the ability of the sector to adjust to new challenges, such as energy transition and vessel modernisation for better and safer working conditions and improved well-being of crew on board fishing vessels. The need for extra space is perceived as being further aggravated by the Landing Obligation implemented in 2019 in the EU CFP (Article 15), which might increase pressure on fish hold storage capacity in case unmarketable fish is not discarded. Safety features and improved living space compete for priority with aspects that affect profitability, particularly fish hold space (to store more fish) and fuel tank volume (to allow the vessel to fish for longer periods). To address these issues, the following subsections will evaluate possible technical adjustments to the definition of fishing capacity, introducing new concepts such as "decarbonisation-related tonnage" and "safety-related tonnage."

3.2.1 Vessel modernisation for safety

To encourage better working conditions and safety, the EU developed the concept of 'safety tonnage'. This concept was first included as part of the Multiannual Guidance Program IV (MAGP IV) through a clause in Article 4(2) of Decision 97/413/EC ([4]). Although limitations on gross tonnage aim to prevent any modifications of vessels and equipment that would increase the ability to catch fish, these limitations appear to conflict with vessel improvements that would make the vessel safer even if it means an increase in their GT or more kW engine (Table 1). In addition, as noted in European Commission (2016), there is a need to clearly define what constitutes "safety tonnage" and how to control for living space usage whenever there is the wish for enhancing the crew accommodation above minimum requirements (following the International Labour Organization "Work in Fishing" Convention 188[5], for the member states that signed it). This definition would specify the pieces of equipment that contribute to the improvement of safety and working conditions, and how to measure their GT. These modifications

4 OJ L 175, 3.7.1997, ELI: http://data.europa.eu/eli/dec/1997/413/oj

5 ILO C188. https://normlex.ilo.org/dyn/nrmlx_en/f?p=NORMLEXPUB:12100:0::NO::P12100_INSTRUMENT_ID:312333

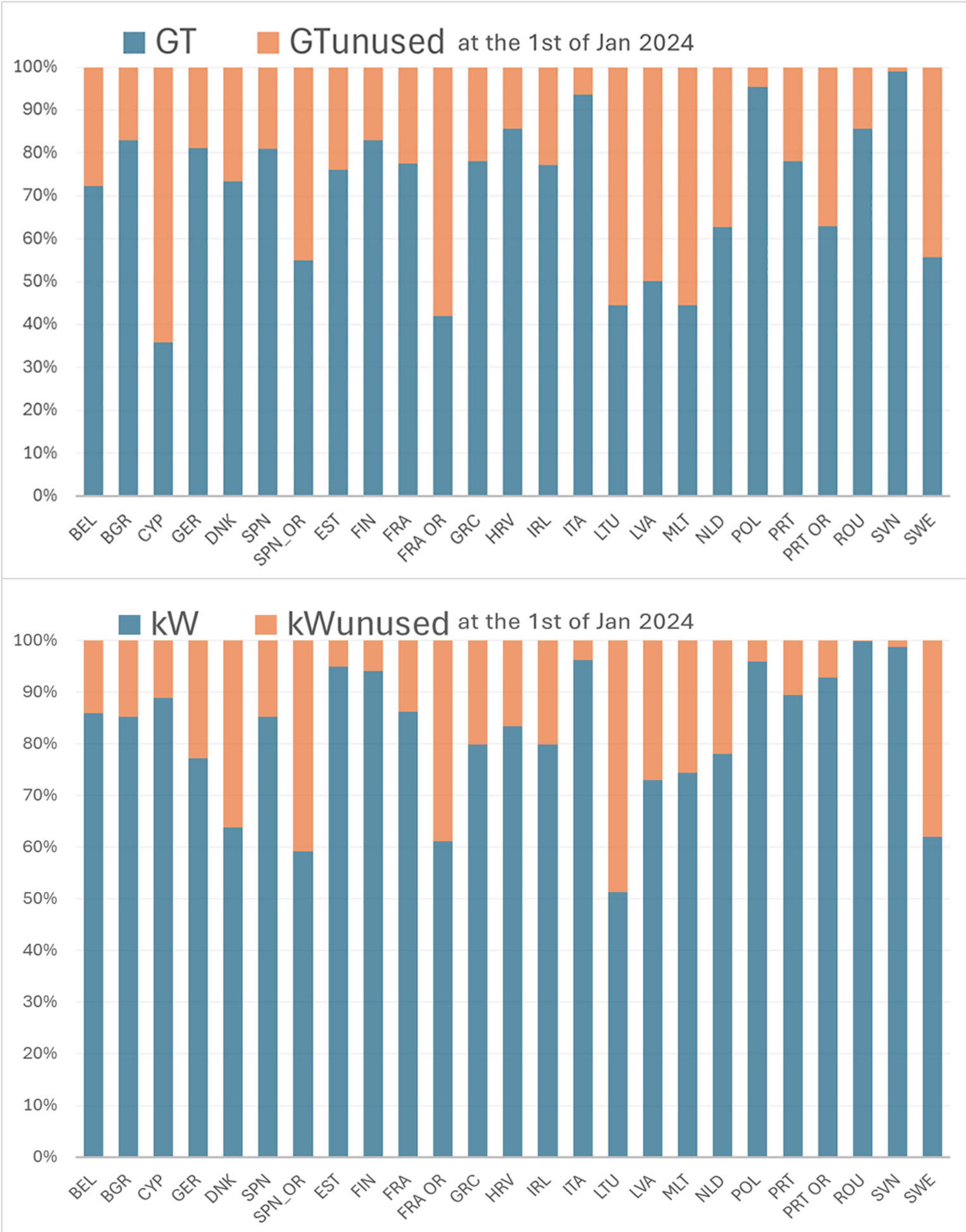


FIGURE 1
Proportion of Gross tonnage GT (GT) or kW and unused tonnage (Unused) or unused kW left under the country-specific capacity ceilings as per 1st of January 2024.

include superstructures above the vessel deck (e.g., covering the deck to protect the crew against the sea and weather conditions), effective rest areas, enough separated living space and sufficiently insulated against noise, safety-related superstructures installed above the deck to avoid risk for submersion, dedicated cabin space for observers onboard, improvements to visibility on deck, and the need for ballasts to improve vessel stability.

However, the safety-tonnage concept was not clearly defined, and no outline was provided on what could or could not be classified as a safety improvement. All in all, only Spain introduced 3,776 GT for safety-related reasons during the period between 1st January 2003 and 31st December 2013 (European Commission, 2019a). This gave extra capacity to individual vessels and led to unintended negative effects. For vessels over 15 m, the GT could be increased by a factor between 1.35 and 1.7, depending on the type of vessel, while the volume below deck could only be increased by 10%. This led to the addition of closed spaces, heavy cargo, fishing gear and other elements above the deck, directly raising the center of gravity of the vessels and deteriorating their stability. As stated by Mata-Álvarez-Santullano and Souto-Iglesias (2013), the safety at sea and the working conditions might have counterproductively been degraded rather than improved.

If fishing capacity limitations may counteract efforts for improving working conditions and safety, it is however required to check for initiatives aimed at adding extra safety, comfort, and quality improvements to vessels. This calls for examining the possibility of new fleet

TABLE 1 Safety, risk and well-being actions in fishing vessels (extracted from EC 2016) and their potential impact on vessel dimensions.

Type of safety measure	Description	Potential impact on needing more space onboard
Ensure vessel suitability. Avoid vessel excessive deterioration with time.	Watertight integrity. Check that hull, deck, doors etc. are in good condition to hold out the water.	Low
	Review of the stability and structural changes. Layout of fishing gear, new superstructures added on deck or other changes might affect the stability and therefore structural modifications would be necessary to maintain vessel stability in safe margins.	High
	Anodic protection. Review their condition to protect shaft, propeller etc.	Low
	Steering gear in correct conditions.	Moderate
	Pumping system revision.	Low
	Propulsion condition check.	Moderate
	Seawater systems. Heat exchangers, discharge valves, pipe circuits etc.	Moderate
	Electrics.	Low
	Navigation and communication systems.	Low
	Conditions for working single handed	Moderate
Emergency procedures	Personal flotation device for all persons onboard.	Moderate
	Fire-fighting equipment.	Low
	Inclusion of life rafts onboard.	Moderate
Stability	Changes to increase vessel stability that might require more space onboard. Excessive gear/fish storage above deck might negatively affect stability. Appropriate storing under deck with safety and stability purposes might require considerable space.	High
General working areas	Keeping the boat tidy and safe. Movement around working areas should not be obstructed.	Moderate
Watchkeeping	The skipper must have provisions to control the vessel and to see what is around.	Low
Accommodation	Accommodation areas of the vessels with comfortable ambient temperature and adequate ventilation.	High
	Appropriate dimensions for living space include insulation against noise and thermal insulation.	High
	Cabin space for observer onboard	Moderate
Engine room/space	Preventive maintenance, including filter changes. Revision of belts.	Low
	Ensure it is a safe area to move around.	Moderate
	Good ventilation to remove heat and fumes.	Moderate
Boarding and leaving the vessel	Ensure that your vessel is safe to cross; the deck is not slippery, handrails are in place and secure and there is an obstruction free route.	Moderate
Fouled gear	Fishing gear, nets etc. should have enough space on deck to work safely.	Moderate

capacity metrics deducted from the capacity measurement, crew spaces and other vessel parts that do not contribute to cargo storage. Measures that enable changes that modernize vessels and improve living and working conditions might compete with fish hold volume and the volume of the engine room and fuel tanks, with unintended side effects. For example, when the fish hold volume and the processing facilities onboard are a constraint, reducing fishing capacity on an individual vessel would likely make the vessel end the trip early and return to port. Hence, setting aside some capacity for modernizing the vessel (e.g., more accommodation space) would be perceived as an impairment of short-term profitability of the fishing activity, unless such extra capacity is not accounted for.

3.2.2 Vessel modernization for energy transition

Reducing fuel consumption and achieving the energy transition call for implementing new fishing technologies to complement or substitute existing ones. Limitations on GT, kW and vessel length have induced the development of non-optimal vessels in the past (e.g., Standal and Ahlquist 2025) given different ways of calculating GT (depending on LOA is <15 m or >15 m), and different taxation schemes depending on LOA thresholds (e.g., <12 m) further impairing some necessary adaptation to accommodate energy transition technologies. At the same time, some stakeholders (e.g. eNGOs) consider that fuel subsidies or any empowering capacity change could delay adaptations to growing costs and contribute to unsustainable fishing practices (e.g., Skerritt et al., 2023). Lowering the cost of fuel reduces the incentive to use it more efficiently, with potential adverse effects on the sector's productivity and investment in emission-reducing technologies (OECD, 2025).

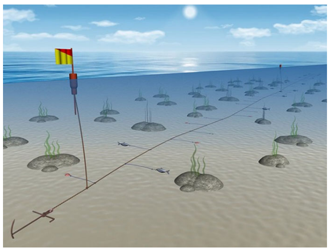
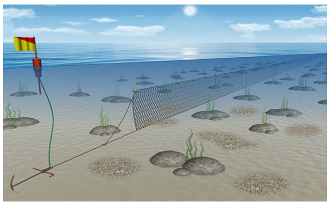
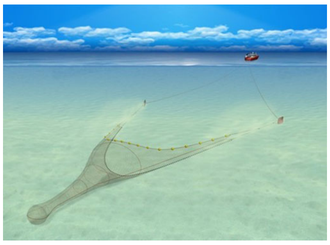
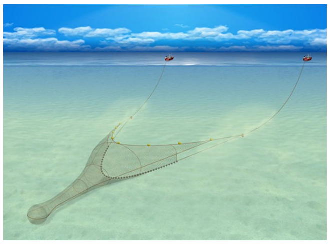
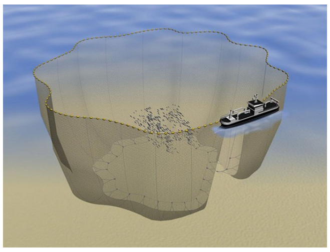
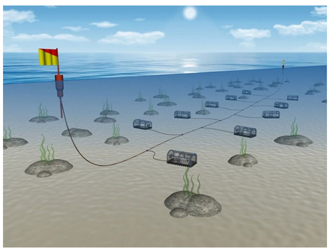
A recent EU techno-economic analysis (EC, 2024) identified that multiple technological solutions are available to reduce the carbon footprint of the fishing fleet. However, these solutions vary in technological readiness (TRL), fuel storage requirements, and the geographical range of exploration (i.e., autonomy) they offer to fishing vessels. Depending on these factors, the space required on board a vessel may differ, leading to variations in the use of GT and kW to provide the same service as the baseline. Hence, implementing some of these solutions while keeping the same individual vessel capacity might lower the ability of the fishing vessel to catch the same amount of fish per trip.

Among the vessel improvements identified (e.g., see Aleixendri 2021; Ammar, 2019; Baird-Maritime 2021; Balcombe et al., 2019; Bastardie et al., 2022a; Bastardie et al., 2022b; Basurko et al., 2023; Center, 2017; Chang et al., 2016; Corvus-Energy 2024; Gabiña et al., 2016; Gabrielii and Jafarzadeh, 2020; Goikoetxea et al., 2024; Granado et al., 2024; Grimaldo et al., 2015; Jafarzadeh et al., 2016; Jafarzadeh et al., 2017; Kemp et al., 2021; Latorre, 2001; Lee et al., 2018; Leira, 2018; Lindstad and Eskeland, 2015; Maritime-Cleantech 2019; Moecke et al., 2016; Norwegian-Hydrogen 2024; Notti et al., 2019; Ocean-Fisheries 2010; Parente et al., 2008; Romano and Yang, 2021; Sakthivel et al., 2018; Sala et al., 2011) there are solutions that would make the vessel more energy efficient without necessarily increasing their GT or power see Supplementary Table S2, all of which would increase fuel cost savings per unit of effort. In these cases, fuel savings might also translate into fitting a smaller fuel tank onboard a vessel, also freeing some cargo space. However, some other solutions would require extra space (e.g., vessel design and vessel operations listed in Table 2), such as those related to the need for a larger engine room to fit propulsion systems powered by alternative fuels.

There are solutions linked to improving fuel efficiency, while some others are related to the use of greener new fuels for the vessel propulsion. Depending on the type of solution, the probability of inducing a need for extra space in the fishing capacity is different. The solutions that would require more GT in vessels should be assessed individually, consulting naval architects, engineers or other independent entities to technically justify that the extra space in vessel capacity is exclusively given by the space needed for the energy transition solutions, further reviewed by independent technical experts in the field.

Short-term energy transition solutions that improve energy efficiency, other than more radical changes like switching to alternative propulsion solutions or designing new hull shapes for new vessels, are unlikely to require additional space onboard. Technical solutions not requiring an increment in the vessel capacity do not apparently present a high probability of increasing ability to catch fish, unless improvements in energy efficiency would relax capacity constraints driven by fuel use or operational range. These kinds of changes that help to reduce fuel consumption in the short term might be promoted, always revising for any change in risk of increasing the fishing capacity. Energy efficient solutions that can be implemented on existing vessels would include (see Supplementary Table 2 in Supplementary Material): the

TABLE 2 Beyond controlling for the physical characteristics of the vessel at play, Regulation (EC) 2347/2002 repealed by Regulation (EU) 2016/2336, presented some fishing gear characteristics that vessels holding a deep-sea fishing permit shall annotate to control their capacity and effort.

Fishing technique	Harvesting capacity
Longliners 	Average number of hooks used in longlines, average time per 24 h that lines have been in the sea with a number of shots and at various fishing depths. If the distance per hook is constant, the total distance of the line could be measured.
Vessels using fixed nets 	The mesh size, average length and average height of the nets, time in the sea with number of hauls, and fishing depths. Vessel GT is more likely to determine the harvesting capacity since the size of the vessel will determine the amount of gear and size of crew on board.
Trawlers 	The mesh size of the net, the time that the nets have been in the sea with a number of hauls, fishing depths and the surface opening of the net. The beam length would also be representative in the case of beam trawlers.
Pair trawlers 	Fishing in pairs can enable small vessels to combine their fishing power and tow much bigger trawl sizes than would be expected from individual vessels, gaining more than the sum, also avoiding scaring away fish schools when vessels are departed from the gear path.
Seiners 	Total net length deployed and depth of the net. Attention should be paid to number of fish-aggregating devices (FAD).
Pots 	Number and size of the pots.

Source: Pictures extracted from Popescu and Breuer (2024), after Montgomerie, 2022, originally published in the Seafish public media library, https://seafish.dash.app/home?portal=seafish-public-media-library. © Seafish, reproduced with permission.

use of fuel monitoring and management devices, biodiesel fuel, propeller-rudder upgrades, larger propellers, nozzle and optimized sterns, on-board electric consumption (e.g., for cranes and winches, cooling and freezing systems, pumps), frequency converters, oil filtration systems, anti-fouling measures, shore supply of electricity, fins and stators, bulbous bows, and anti-roll systems/use of stabilizer fins. When assessing the potential resistance from the fishing sector or Member States to adopting new technologies or practices (i.e. political risk), as well as assessing their potential for adverse environmental impacts beyond carbon emissions, such as pollution, noise, or the risk of overfishing (i.e. environmental risk), these solutions were found to be feasible, posing low political and environmental risks (see the complete inventory of solutions in the EC techno-economic study (EC, 2024). Improving the energy efficiency of fishing gears also offers promising potential without altering their catchability. In addition, making fishing gear more selective in targeting commercial species or marketable fish can enhance sustainability while reducing fuel use intensity (kg of fuel use per kg of catch) and promoting healthier stocks and ecosystems. However, for certain fishing techniques, such as bottom trawling for certain species, it remains uncertain whether fuel consumption can be reduced without affecting the catchability of the gear. Given this potential loss in catch rates, any beneficial gear modifications may further face resistance to implementation (STOA, 2024).

Vessel retrofit or new build is a more demanding solution. As an example, new vessel designs or retrofits may include adding a bulbous bow (as a protuberant bulb) to the hull of the vessel or installing hybrid/electric propulsion systems. These possible actions would reduce fuel consumption but result in an increase in GT, which is perceived as a drawback, but without compromising safety on board. The addition of a bulbous bow for saving fuel (Szelangiewicz et al., 2021) may require adding a few cubic meters (for small vessels) to the hull. This is prohibited by the current CFP regulation overall and individual 'GT/kW/fishing effort' cap requirement as stipulated in Articles 22 and 23 of the CFP, unless Article 19 of the EMFAF is used, which first requires some fishing capacity to be removed.

Some interest for designing new build and larger vessels to operate with new energy sources and greener fuels (LNG, methanol, hydrogen obtained from water catalysis, electrification, etc.) of fishing vessels is also growing (see prototypes reviewed in EC, 2023c). The change of the propulsion system itself might not require much more space, but the storage systems for alternative fuels, the addition of batteries or other technologies will need more space due to their lower volumetric energy density than diesel (Figure 2). For example, a methanol engine could be similar in dimensions when compared to a marine gasoil engine (MGO), but the storage of methanol requires twice the space required for MGO (Sjerić et al., 2026), hence requiring more GT, and extra safety facilities onboard. Electrification also requires a much larger space onboard (room for electronic systems and battery-packs) vessels than energy storage via conventional diesel (FIS, 2023; Figure 3).

Thus, maintaining the same vessel GT, but using alternative greener fuels with lower energy density, may reduce available space and performance. Moreover, the installation of some energy transition technologies may increase vessel weight (Figure 3). For instance, converting a 15 m trawler to methanol-ready vessel could increase the weight of the empty vessel (e.g., the weight of the empty vessel with machinery and equipment) by 21.4% compared to using conventional MGO. In the case of LNG, the extra vessel weight could be up to 54% (FIS, 2023).

Hence, according to Damian et al. (2022), one of the main drawbacks of hybrid power systems or dual fuel systems in vessels, apart from the large space needed for the installation of components such as Energy Storage Systems (ESS) for alternative fuel (L, m3) or electric power (kWh), is the potential increase in vessel weight. According to Gray et al. (2021), energy transition solutions such as Li-ion batteries, methanol or hydrogen, would require additional space and add more weight than conventional diesel to achieve equivalent ranges for their studied cargo ship. In the fishing sector this could also require additional kW compared to the conventional propulsion system in some cases. If maintaining the same level of effort at sea is assumed, the heavier and larger size of gas or battery/electric engines compared to diesel counterparts, may require more kW or an increase in GT to be installed on the same vessel.

4 Scenarios for EU fleet modernisation. What would be the effect of fleet management allowing extra fishing capacity in the EU?

Meeting the future needs of the fishing sector while maintaining a balance between fishing opportunities and fishing capacity

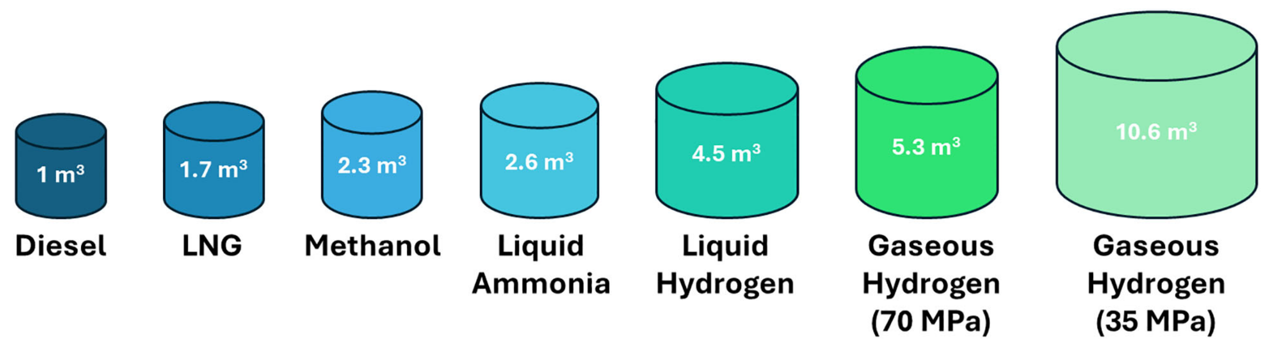


FIGURE 2
Fuel volume taken by 10 MWh of energy for different fuels (after estimates by Panić et al., 2022 for energy densities of: Diesel, LNG, Methanol, Liquid and gaseous hydrogens, and Foretich et al., 2021 for Liquid ammonia).

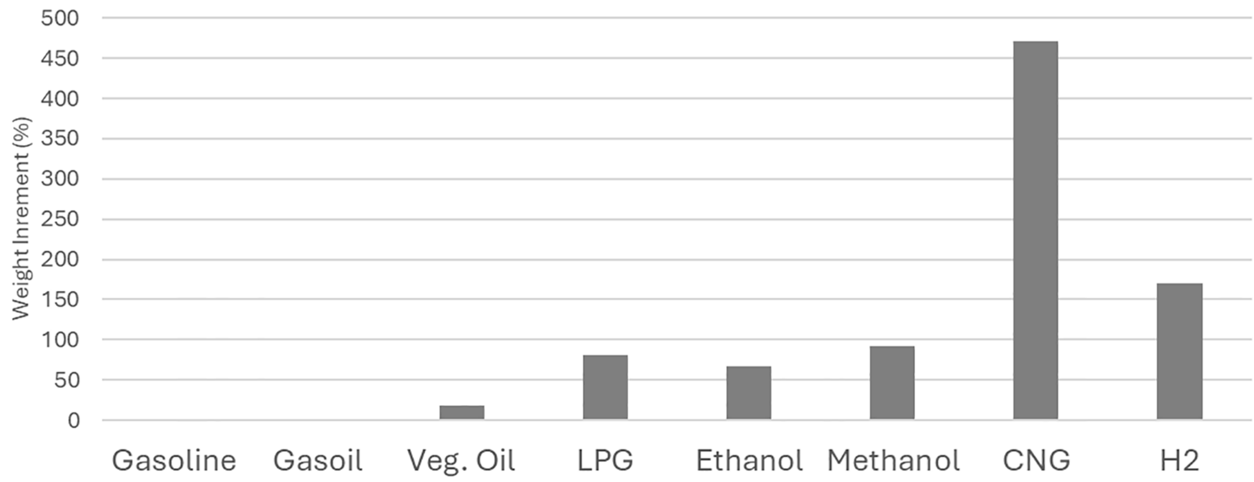


FIGURE 3
Increments given in a 55-litre gasoline tank when considering different alternative fuels according to Martins and Brito (2020). Note that these increments are only based on the weight of the tank. LPG (liquified petroleum gas), CNG (compressed natural gas), H2 (Hydrogen).

remains a significant challenge. Under the current policy framework, this may result in an overall reduction in the number of vessels, with the aim of removing those that are out of balance. At the same time, existing regulations include instruments that can help address specific requirements for vessel modernisation, facilitating the energy transition, improving working conditions, and reducing negative externalities (e.g., by adopting alternative fishing gears to reduce impacts on marine habitats). Hereafter, we discuss the impacts of the policy on the EU fleet, including limitations and barriers to its modernisation or renewal and in light of the currently unused fishing capacity identified in this analysis (Figure 1). When examining impacts of fishing capacity management approaches, it is also important to account for the management regime in place, including TACs and quota- or effort-based management systems.

Examining the impacts of fleet policy on the EU fleet involves identifying both the limitations that constrain progress and the barriers that must be overcome for fleet modernisation or renewal. It also requires assessing whether these constraints help explain the currently low levels of investment in new vessels (average age of the EU fleet reported in STECF (2025b) is 42 years in the Mediterranean and Black Sea, 36 years in the North Atlantic, and over 25 years in the other fishing regions). Hence, within the framework of the CFP and associated legislation, certain barriers to the development of fishing capacity have been deliberately established (e.g., the ban of subsidies for new vessels). While these measures were designed to control overcapacity, they may now hinder the sector's ability to retrofit vessels, modernize engines, renew the fleet and adopt the latest innovations (e.g., Nunez-Sanchez et al., 2026). Indeed, regulatory barriers can delay or prevent the authorization of innovative solutions, such as using greener fuels that conflict with the urgent need to renew and modernize an ageing fleet.

New technologies continue to improve under all conditions (e.g., by increasing vessel efficiency). The effectiveness of fleet policies in preventing fleet imbalances will likely depend on the type of fisheries management system in place, particularly whether management relies on effort control or catch limits. Under an effort-based management regime, improvements in efficiency may necessitate continuous reductions in effort levels (e.g., STECF, 2025b). Hence, it is important to examine how increases in fishing capacity may affect fisheries depending on whether target stocks are managed under strict catch limits or regulated primarily through effort controls (e.g., limits on fishing days or in the number of licensed vessels).

In this context, fishers may invest in improved technology, including more efficient or larger fishing gear (e.g., increased gear length, width, or mouth opening), use the smallest legally permitted mesh size, or increase the volume dedicated to fish holds or fishing gear, all of which increase their overall ability to catch fish. Increasing the ability to catch fish can lead to higher bycatch levels, increased operating costs, and economic imbalance due to overcapitalization. Under an effort-based management regime, vessels are incentivized to increase their fishing efficiency to maximize their economic returns per unit of effort. This could lead to a 'race to fish', where investments in better technology result in an imbalance and contribute to overfishing without effective output controls such as TACs and quotas.

Key considerations regarding barriers to fleet renewal have been identified (see for example Standal and Ahlquist, 2024; Bastardie et al., 2026), showing how current regulations, such as capacity ceilings and the CFP requirement to withdraw equivalent capacity when introducing new vessels, may constrain fleet modernisation. Ensuring energy transition and improving safer working conditions pose special challenges considering the existing country-specific ceilings on GT (see section 3.2.2). For example, opportunities for green solutions, such as batteries or hydrogen, would require more GT on board reserved for the propulsion engine, while could be subtracted from the GT of a vessel currently monitored by the CFP, if it appeared it would not count as a volume that affects the catch efficiency of that vessel. However, since fish holds represent only a small proportion of the vessel's total GT, implementing such a proposal would undermine the effectiveness of existing capacity ceilings, which are currently based on overall vessel GT. It is also unclear whether these national capacity ceilings may limit the ability of fleets to adapt, depending on how much implementing these innovative solutions would require additional space to maintain profitability. Besides, if vessel or engine modernisation, such as the adoption of greener fuel than diesel, results in increased space onboard and possibly greater harvesting capacity (if not only affecting the engine room), it would jeopardize the balance between fleet capacity and available fishing opportunities.

Various outcomes of hypothetical scenarios could be expected (Figure 4) where the scaling of energy transition and modernisation requirements across the entire active fleet may reveal incompatibilities with Member States' capacity ceilings:

- An alternative scenario (the "underused scenario") would result from maintaining current limitation on fishing capacity while redirecting some capacity to modernize or decarbonize the vessels. This would rebalance the baseline situation with the fishing opportunities whenever part of the existing unused capacity is redirected to address modernisation or energy transition challenges (Figure 4). This could result from a transition pathway that enables retrofitting existing vessels keeping similar GT, or from the construction of less but larger, more efficient and modernized vessels and not increasing the overall ability to catch fish. As this might provide a surplus of opportunities from more individually efficient fishing but undercapacity overall which would indicate non-optimal use of resources.
- Another scenario, the "optimal scenario" would enable the fishing capacity (in GT) to increase up to reach a national ceiling level, while maintaining harvesting capacity in balance or even rebalancing it with fishing opportunities. However, at first glance it appears that the "optimal scenario" is the less likely scenario to rebalance the fleet, given it seems logically difficult to understand how extra capacity that would correct for current imbalance that link to this capacity, unless a modernized fleet would come with less overfishing.
- If the baseline shows an already imbalanced situation as currently assessed for the EU fleet overall (see section 3.1), a completely "worsening scenario" would occur if both future reactivated fishing capacity or any extra fishing capacity granted to address modernisation or energy transition issues would make the harvesting capacity even more inclined to worsening the balance with fishing opportunities. This scenario would be the most likely if monetary compensation would be given to individual vessels to keep an oversized, imbalanced fleet in business, while simultaneously allowing extra fishing capacity to address modernisation needs.

What creates some uncertainty in anticipating the most likely scenario is the balance status corresponding to the fishing capacity ceilings for Member States because those ceilings were originally set based on the capacity levels at that time (the "reference" period). It is not at all certain that reaching those levels with a renewed fleet and even more true exceeding these national thresholds might restore a balance given the imbalanced situation observed with the actual capacity far below those thresholds. These hypothetical scenarios also highlight the importance of assessing whether current ceilings can accommodate the necessary changes or whether they would be exceeded, leading to further situations of imbalance. In the next section, the review further explores how likely these scenarios are. There might also be some possible solutions to identify to help controlling for the input that would make reaching the balance under the optimal scenario more likely.

5 Risk of imbalance alongside reactivating unused capacity or allowing extra fishing capacity

5.1 Different fishing techniques affecting the harvesting capacity

This study thus lists the challenges posed by the current metrics used in defining fishing capacity that ignore differences among

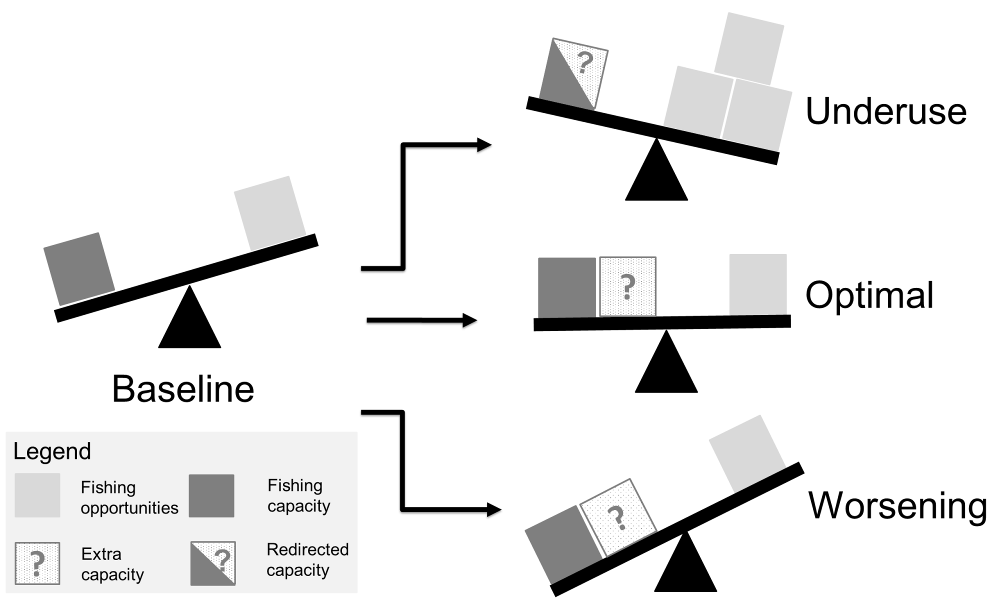


FIGURE 4
Conceptual representation of hypothetical scenarios to show alternative balance outcomes under both EU fishing capacity measured in GT (dark grey boxes) and fishing opportunities (light grey boxes). Note that if the harvesting capacity can silently exceed the cap, the fishing capacity cannot exceed the national capacity ceiling as for the CFP Art 22.

fishing practices. For example, those metrics are challenged by other input factors such as the fishing gear characteristics explaining catching productivity, given evidence that the ability to catch fish can still increase even if kW or GT are kept constant (e.g., Reid et al, 2011). In parallel, these other inputs, if not monitored, might allow an increase in effective capacity through input substitution (for example, when labor is substituted with some equipment while providing the same or better output). As a result, fishing capacity increases over the long term (Lindebo et al., 2002).

Indeed, the harvesting capacity varies among fleet segments/fisheries/vessels, especially between vessels of different sizes, and increases on average with vessel length (also because of more storage and processing facilities onboard, see Supplementary Material). Larger storage space may mean longer fishing trips. Large high-seas trawlers have a complete fish processing plant on board and large storage facilities for frozen fish fillets. In the future, with changes in species, changing market requirements, and improvements in fish processing, more space may be necessary for 'non-fishing' requirements. Such extra space may come with a better ability to fish.

However, the "ability to catch fish" concept is difficult to grasp. In a former version of the CFP, Article 11.5 of the CFP 2002 stipulated that "On fishing vessels of 5 years of age or more, modernisation over the main deck to improve safety on board, working conditions, hygiene and product quality may increase the tonnage of the vessel, provided that such modernisation does not increase the ability of the vessel to catch fish" without defining this ability. However, it is likely that modernisation for improving "product quality" is contributing to more ability to catch fish, if it refers for example to installing catch conservation methods such as a refrigeration room onboard, which increases the geographical mobility range of a vessel (e.g., ASD Ship Design, 2018).

Changing fishing capacity allowance should avoid posing a risk to increasing overcapacity and imbalance if those adaptations do not come with some improvements in the fleet´s ability to catch fish. This requires evaluating whether there is a weak or strong link between fishing capacity (defined as the physical characteristics of the fishing production tools) and harvesting capacity (defined as the "ability to catch fish"). Ultimately, redefining the metrics for fleet capacity, which will be monitored, depends on the extent of this association. In case of a weak correlation, increasing the physical fleet capacity would not come with increased risk for overcapacity, as other factors are more at play. On the contrary, a strong correlation would require a close monitoring of the current metrics, complemented with additional or refined metrics to address the energy transition and modernisation challenges. If, as a worst-case scenario in a conceptual exercise, we assume such a strong link, we then see that the potential landings that would come from reactivating the unused capacity (Figure 5) would make the overall landings by EU Fleet grow very much, all other factors being equal (e.g., no catch limits).

5.2 Technological advances affecting the harvesting capacity

An alternative fishing capacity metric should consider the 'technological creep' effect, where advances in technology increase fleets' ability to catch fish and risk overexploitation. Harvesting capacity grows due to increased engine power, improved gear, changes in fishing strategies, and technical adaptations like more efficient propulsion systems. Electronic and computer technologies further boost harvesting by making it easier to locate fish. Skipper experience, use of satellite data, and specialized fishing aids also play a role. Harvesting capacity varies with gear use, fish behavior, onboard equipment, and weather. Reducing fuel costs can also increase fishing ability if fuel was previously a limiting factor. Hence, when more operations are performed per fishing day by a vessel, or when an old vessel is replaced with a new one, or when an existing vessel is modernized, all are expected to increase the harvesting capacity. Such a change in the ability to catch fish per unit of fishing effort could also decrease, depending on the type of fishing techniques to which the reallocated fishing capacity is directed, as the same species can be caught using different techniques with varying efficiency (e.g., Danish seine vs. bottom trawling vs. semi-pelagic trawling vs. bottom set netting).

The likely annual percentage increase in the ability to fish may be included in guidelines as a corrective measure for the measurement of fishing capacity. Technological advances such as GPS, echo sounders or enhancements in fishing gears may have accounted for an average increase of 2% per year in fishing capacity according to Palomares and Pauly (2019). These authors analyzed 51 case studies spanning 4 to 129 years. According to this result, the fishing capacity of commercial fishing would double in 35 years due to technological creeping. Other studies estimated an annual increase of up to 3% in harvesting capacity due to technological advances (Auditors, 2011). Damalas et al. (2014) estimated the "technological creeping" effect of the Greek demersal fleet to be less than 1% overall over the period 1994-2008. Negative values were also found due to overexploitation. Quantitative analysis of the progression of the ability to fish over time can provide corrective statistical analysis by examining the time series of Catch Per Unit Effort across fisheries to correct the fishing capacity evolution against a change in harvesting capacity (e.g., Damalas et al., 2014; Mahévas et al., 2011; Hoyle et al., 2024). Such analysis would warrant being repeated with more disaggregated data if national logbook data and national fleet registers are made available (possibly collating more information than that kept in the EU Fleet Register, such as fishers 'targeting behavior, and soaking time of the fishing nets).

6 Actionable recommendations to ensure sustainable, resilient and modernized EU Fleet

Addressing the energy transition and modernisation of the fishing fleet in Europe must consider ways for maintaining strict measures on fleet capacity to remain within ecological limits, as required by the European Green Deal and 2030 Biodiversity Strategy. Within the CFP, the challenge is to ensure this energy transition towards cleaner propulsion systems, improved working conditions, and greater crew comfort, without increasing the ability to catch fish, as imbalances with the resources´ states are already occurring. Fleet renewal is also ineligible for EU funding for fleet

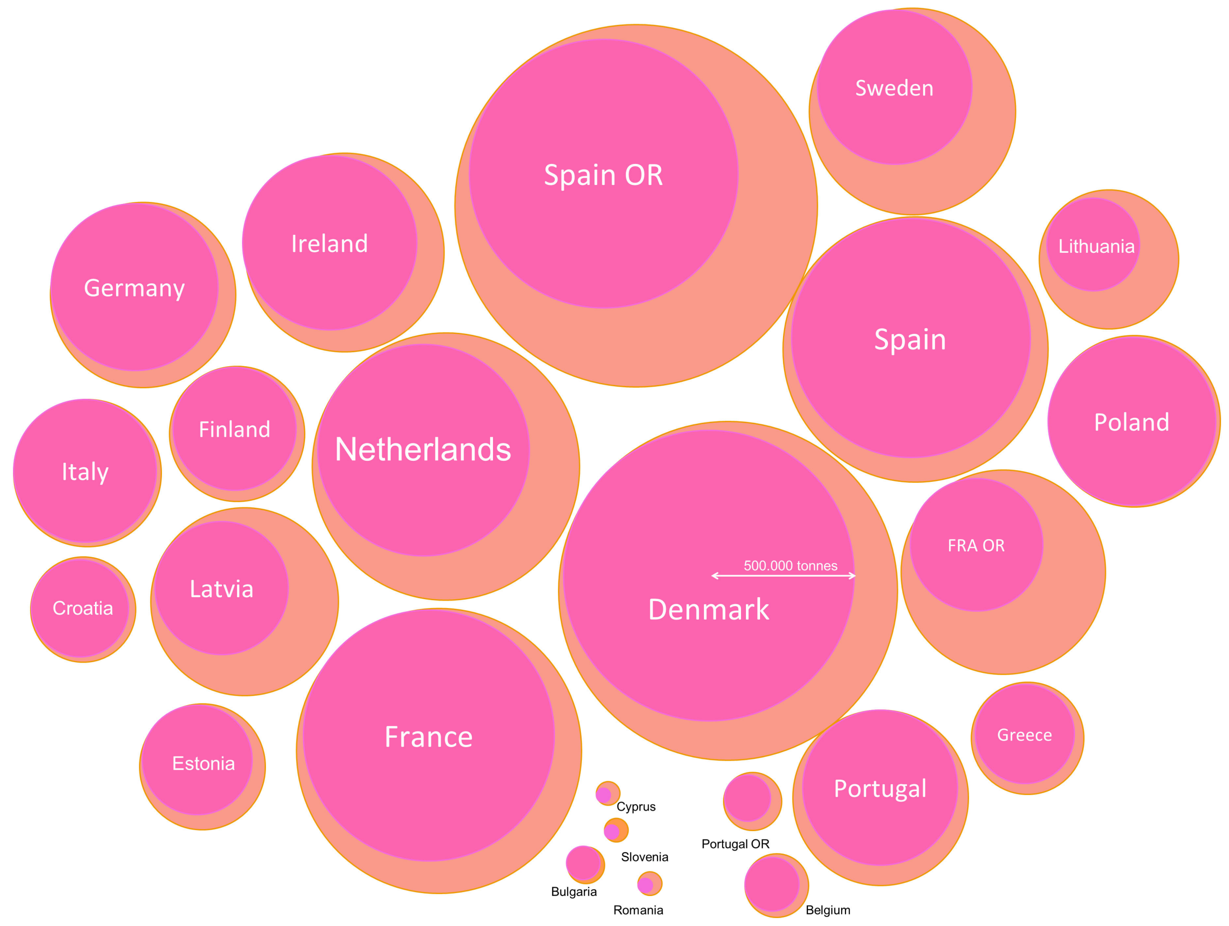


FIGURE 5
Actual (2023) landings' contribution per Member States (in pink, with circle radius proportional to tons) and Predicted catch supplement (and OR region) (in Soft pink) if the GT unused would have been fully used in 2023. Based on 2023 catch and GT data as recorded in the EU FDI database. This comes with the strong assumption that the catches would not be limited by anything else than the GT, and that any extra GT would translate into a proportional extra ability to catch fish. (See Supp Mat 3 for underlying data).

segments out of balance. The fleet renewal should be based on the objective that "the fishing and aquaculture activities are environmentally sustainable in the long-term and are managed in a way that is consistent with the objectives of achieving economic, social and employment benefits, and of contributing to the availability of food supplies" (Article 2 of the 2013 CFP).

An overarching challenge of the fishing sector is to make optimal use of the remaining capacity available or substitute it with modernized tools. If this is not sufficient, the EU may need to offer more flexibility in fleet renewal policies to allow modernisation without permanently reducing fishing capacity. At the same time, the EU fleet policy should continue ensuring that fleet renewal and modernisation, which may require additional capacity or not, alongside improved efficiency over time, does not result in an improved ability to catch fish that would exacerbate fleet imbalances, create overcapacity, or put more pressure on exploited stocks.

Given these general findings, the following recommendations (Figure 6) are proposed in order of priority to support better management of the challenges (fleet renewal and vessel modernisation for the energy transition and better and safer working conditions) and the future of the EU fishing fleet:

6.1 Conduct member states and segment-specific studies to evaluate whether there is a need for additional capacity

Allowing extra space onboard vessels for the required modernisation solutions only makes sense if the fleet segment is considered to be in balance with the available fishing opportunities. Still, the actual fishing capacity of individual Member States is well below capacity limits. In this context, Member States could use their remaining capacity if needed to address modernisation, energy transition needs, and fleet renewal, given the key challenges the fishing sector will face in the future. However, while some EU countries maintain a reserve margin of GT or kW to allow for flexibility, these margins are maybe limited. Therefore, targeted studies at both the Member State and fleet-segment level are required to evaluate whether sufficient capacity remains available for future changes alongside different levels of ambition and local circumstances. Without such documentation, country-specific data, and pieces of evidence demonstrating that the anticipated gain that will result from the fleet adaptation will not be sufficient to catch the same volume or more, it is still unclear whether additional capacity is required.

FIGURE 6
Four policy recommendations, derived from the review of challenges faced by the fishing sector, to promote sustainable, balanced EU fisheries while modernizing the EU fleets for the energy transition and improved working conditions.

Hence, there is a need to continue efforts to provide tools and documentation to evaluate and assess the onboard space requirements associated with energy transition solutions or other modernisation equipment (safe space around more hazardous fuels, modernized storage and handling systems, individual cabin per crew member, etc.). These tools should be used to determine to what extent Member State capacity ceilings would be limiting, after accounting for future adaptations, if such solutions were implemented across all currently active vessels. These baseline studies would be a starting point for Member States to plan fleet capacity use for modernisation. Part of both the existing and "virtual" GT and kW capacity should be reserved for improvements in safety, better working conditions, and sustainable technologies, governed by rigorous control mechanisms. While vessels may need increased GT capacity to improve efficiency and onboard conditions, increases in kW are not necessarily required. It is therefore essential to establish procedures to control vessel modernisation with metrics accounting for a possible change in vessel's fishing ability.

Fisheries currently identified by fishing area, target species and type of fishing gear may represent the most suitable level for implementing capacity and effort limitations based on fishing techniques. For example, if the segment definitions remain too broad, fisheries managers would be unable to identify which proportion of capacity within each segment is excessive, or the reasons for this excess. This could lead to requesting action plans on already balanced fisheries. Managing capacity per fishery allows for clearer authorization of maximum capacity to specific activities but requires standardized capacity units to fairly compare different fisheries. Analyzing fleet segments by operational needs, such as gear, vessel mobility, and fishing areas, enables more tailored capacity adjustments and better management of vulnerable stocks. Ultimately, estimates of additional capacity can then be scaled up to the level of the Member State level by combining the individual requirements on a fishery-by-fishery basis. Prototype vessels developed without the constraints imposed by the current EU regulations (European Commission, 2023c) already exist for certain fisheries.

However, we can also anticipate that scaling up modernized designs across the entire Member State fleet would be a costly investment (CAPEX). Hence the barrier to energy transition is really regulatory-related but more on the economic feasibility of the transition. On the economic feasibility it is likely that the combined operating expenses (OPEX) and fuel cost savings will result in a net cost, leaving cash flow negative and preventing a payback. In such cases, a financial gap required for payback arises if it cannot be reached within the solution's lifetime. Previous studies have shown that this is true for most innovative solutions (EC 2024 Technical Study). However, the cost-benefit evaluation should also consider potential changes in catch rates for some solutions, as these changes may result in either a loss or a gain.

6.2 Explore distinguishing vessel volume unrelated to harvesting capacity

It should be explored if the current fishing capacity metrics can be revised so that to well identify the ability to catch fish from other factors in the fleet capacity, thanks to an evaluation of the feasibility for splitting the GT use into different categories. One could decompose vessel volume by distinguishing a GT related to safety, GT_safety, for example linked to some more room on the vessel deck etc., from a GT linked to new energy requirement, GT_energy_transition, for example linked to room to store batteries, some cubic meters for setting a bulbous bow or an inverted bow etc., from a GT linked to working conditions and wellbeing, GT_well_being, from a GT finally repeated to the catching power i.e. GT_harvesting_capacity. Technical engineering expertise can advise on possibilities for decomposing the overall GT allowance into subcomponents that address different functional purposes, such as GT_safety, GT_energy_transition, GT_harvesting_cap, and GT_well_being. Naval architects could suggest alternatives to GT metrics and assess how easy it is to distinguish between GT components based on their intended function. The drafting process would list all the pieces of equipment that contribute to improved safety and working conditions, and how to measure their GT. These include superstructure above the desk (e.g., covering the deck to protect the crew against the sea weather conditions); adequate and well-separated living space sufficiently insulated against noise and installed above the deck to avoid risk for submersion; dedicated cabin space for onboard observers; improved visibility from the bridge to the deck; and additional ballast systems to improve vessel stability.

However, onboard an individual vessel it is apparent from Figure 7 that increasing the GT_energy_transition without affecting the GT_harvesting_cap is a challenge. Indeed, the harvesting capacity of a vessel, which can be approximated as its hypothetical maximum annual catch, is determined by the rates at which the fish hold is filled and emptied. These rates depend on several factors, including the crew available to operate the vessel and process the catch, the capacity of the fish hold itself, which, once filled, ends the trip, the catch rates that dictate how quickly the hold can be filled, and the distance to the fishing grounds, which adds time to each trip. From this, we deduce that the harvesting capacity could increase if, (i) there is an increase of the internal volume of the vessel from an optimized vessel configuration or a larger vessel that come with an in increase the fish hold volume, or (ii) The catch rates are increased due to larger gear size (from larger kW), and harvested stocks in better shape, or the main bulb of the stock distribution is made more accessible, all factors that are unrelated to GT. On the contrary, the harvesting capacity could decrease if (i), The engine room grows to the detriment of the fish hold volume; (ii) The accommodation is made larger for each crew, and if better working conditions require more space onboard, (iii) The autonomy/range of the vessel is decreased from using less efficient vessel propulsion; (iv). The distance to reach the fishing ground increases over time from depletion effects or changing spatial distribution of the harvested stocks.

The possibility of decomposing the overall GT allowance into subcomponents addressing different purposes (i.e. GT_safety, GT_energy_transition, GT_harvesting_cap, GT_wellbeing) should be approached with caution and carefully designed. Once extra capacity is granted to a fishery, it would be extremely challenging to reduce it later, especially if it exceeds the available fishing opportunities. This is due to the long lifespan of fishing vessels, which makes capacity adjustments costly and inefficient, potentially wasting assets and resources. Furthermore, fish stocks are inherently variable and cause fluctuations in fishing opportunities that may conflict with previously agreed capacity limits. This risk of persistent imbalance is more likely for highly specialized fleets, which have less flexibility to adapt to changing stock availability. These distinctions would also require coming with protocols for the marine surveyors (class surveyors, insurance surveyors, or fishing vessel inspectors) to implement the best way to control it and for the declaration of the number of gears in use as a vessel could then get more room to store more nets or other fishing equipment onboard, including refrigerated fish hold and tanks, or larger and more mobile vessels. Indeed, once extra capacity enters the fisheries, it would be very difficult to adjust it to less if they exceeded the fishing

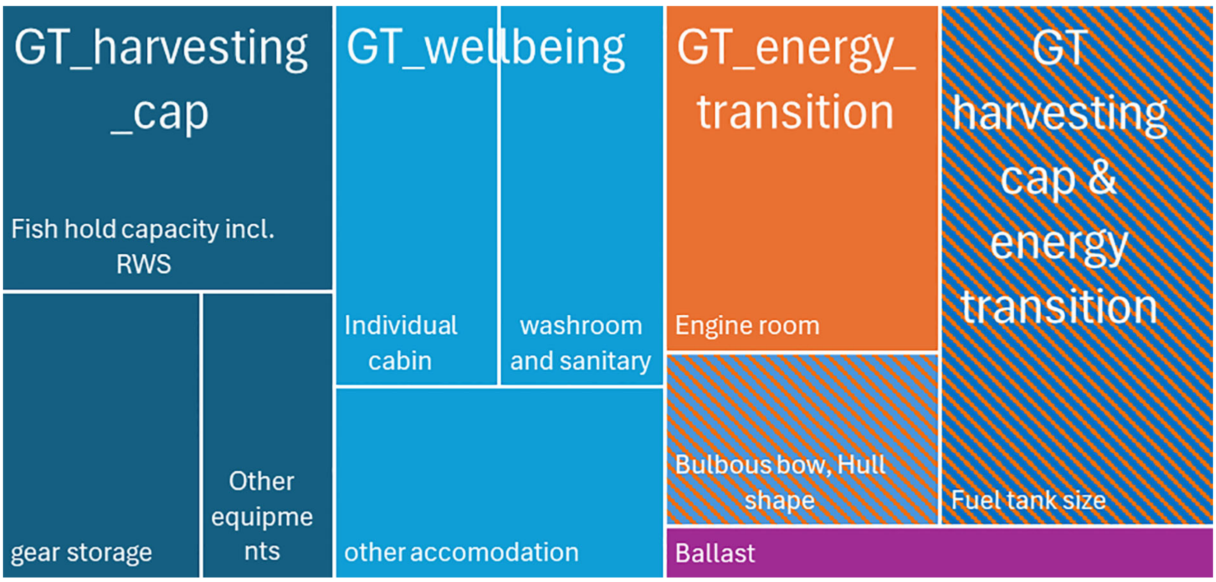


FIGURE 7
Hypothetical split of the overall GT of a fishing vessel into subcomponents alongside with four compartments: GT_energy_transition, GT_harvesting_cap and GT_safety, and GT_wellbeing. For example, the fish hold capacity is linked to the harvesting capacity (constraining the trip duration), while the fish tank capacity is ambiguous because coming with a trade-off whenever linking to the autonomy constraining the mobility range of the vessel and eventually its harvesting capacity.

opportunities, as the longevity of the fishing vessels is making such adjustments cumbersome. Besides, lifting the GT ceiling should be considered only as a last resort, as it may entirely remove limits on fishing capacity due to the currently high risk of inaccurate reporting of vessel kW. The monitoring, control and surveillance department in each Member State must ensure compliance with kW limitations.

Controlling and monitoring both the extra onboard space allowances and engine power remains essential to prevent unintended increases in fishing capacity. While vessel widening and lengthening may be acceptable, this should only be permitted under robust control procedures that ensure any additional GT is used to improve safety, working conditions, or support the energy transition. With respect to GT, controls should be considered for unintended impacts, such as storing catches in living spaces. The study found that, in the Spanish case, increases in GT granted for safety concerns came with additional facilities for storing more nets, and onboard infrastructure. These changes were also found to reduce vessel stability. Due to potential non-compliance, new legislation has been developed to prevent the installation of engines that exceed the vessel's licensed power. For example, Italy restricts engine types as operators are not allowed to install an engine type, if the engine manufacturer's product range includes a less powerful engine model that also equals or exceeds the vessel's licensed power, a restriction that could potentially reduce the likelihood of high-impact infringements.

According to the Control Regulation (EC) No 1224/2009), EU Member States are responsible for monitoring the capacity of their vessels and verifying that they align with officially stated tonnage and engine power. For certain categories of catching vessels with a high risk of non-compliance, the use of devices that continuously monitor engine power may be required as of 10th January 2028 (as outlined in the amendments to the Control Regulation EU Reg 2023/2842). Articles 38, 39, 40 and 41 of the 2023 Control Regulation (concerning "Fishing Capacity") state that Member States are responsible for the certification and verification of engine power ([6]) and the verification of tonnage.

The EC is required to adopt implementing acts, laying down detailed rules concerning the installation, technical requirements, and characteristics of continuous engine power monitoring devices that will apply from 10 January 2028 ([7]). These acts define rules focusing on verifying (a) engine power of catching vessels, (b) tonnage of catching vessels, (c) type, number, and characteristics of the fishing gear. More specifically, Article 41 addresses the verification of kW, while the newly introduced Article 41a addresses the verification of catching vessel tonnage. The EC may also use technical engineering expertise, such as naval architects, to help draft the requirements for verification into such implemented acts. The EC could also make the reporting of the power of auxiliary engines mandatory, at least for those vessels in which a considerable percentage of fuel consumption is derived from auxiliary engines.

6.3 Explore potential for reallocating fishing capacity among fleet segments

Restriction to fishing capacity could be implemented per fleet segment or fleet level rather than to individual vessels, as per CFP Article 23, which also require careful vessel volume decomposition as seen in previous section 6.2. In this context, it is advisable to encourage Member States to take action for converting or reallocating capacity from imbalanced fleets toward those fishing practices with lower environmental impacts. The CFP governance framework already incentivizes Member States for the redistribution of GT or kW across fisheries (e.g., Article 17 of the 2013 CFP), to maintain capacity and to reduce overall harvesting capacity for overfished stock. To reduce fuel consumption and improve fuel efficiency, there is a possibility to shift fishing practices from fuel-intense fishing techniques towards low-carbon fishing techniques and practices (Bastardie et al., 2022b; Hilborn. et al., 2026). This should consider the flexibility in redistributing GT or kW across fisheries so that to eventually allow stock recovery with subsequent fishing opportunities increase, as those opportunities are biologically determined and cannot be increased without being sustained by the stock. However, if the reallocation of some fishing effort from unbalanced fleets can rebalance those fleets, the redirection towards fleets that currently present a certain margin and are less carbon-intensive might potentially create new imbalances or affect social equity whenever the resilience of coastal communities is impaired.

There are three major ways to develop a control strategy of the fishing capacity and effort indicators under the CFP, namely based on: i) vessel characteristics; ii) fishing gear characteristics and iii) the fisheries management in place, which also influences the development of the harvesting capacity.

About vessel characteristics, previous studies documented that the ability to catch fish link can vary alongside the vessel's length and unexpectedly, sometimes larger vessels do not deploy larger nets (Reid et al., 2011; Eigaard et al., 2016). However, vessel auxiliary power (not included in the definition of the capacity in kW; see EEC No 930/86) has allowed the use of larger nets and made fishing possible at greater depths (by powering electric winches), as well as powering Refrigerated System Water (RSW) tanks onboard or electric fish pumps. There is certainly a need to declare and account for auxiliary engine power, at least in vessels where a considerable percentage of fuel consumption is derived from auxiliary engines (e.g., Basurko et al., 2013) and contribute to better catch efficiency.

Regarding fishing gear influence, when reallocating effort among segments, what is at stake is to establish how effort from trawlers, longliners, and other passive gears is equivalent. For example, passive fishing gears are left on the fishing spots while vessels leave the grounds, which complicates measurement of fishing effort across fisheries (Table 2). The western Mediterranean multiannual plan, also known as the West Med MAP, provides methodologies to convert nominal effort reductions into effective reductions for different

6 () To support Member States in the full and harmonised implementation of a suitable system for monitoring, certifying and verifying the engine power in accordance with applicable EU regulations, the European Commission published Technical guidance for the monitoring, certification and verification of engine power in EU fisheries control (European Commission, 2025d).

7 () To assist Member States in preparing for these new rules, the European Commission published Technical specifications and guidance for the implementation of devices for the continuous monitoring of catching vessels' engine power (European Commission, 2025d).

fisheries (STECF, 2025b). To improve definitions of EU fleet capacity, data on gear characteristics (size, geometry, and mesh size) and their influence on vessels' fishing ability to catch fish should complement traditional capacity measures like kW and GT. In the future, systematic collection of data on gear, vessel capacity, and operational characteristics will enable a reflection of the actual fishing power and its distribution across fleet segments.

Hence, from analyzing the historical catches and standardizing the capacity metrics to ensure comparability across fisheries, a translation/transition matrix in kW or GT might be used (Bastardie et al., 2026). Such matrix could be the base for testing prospective scenarios for fleet conversion or fisheries development, depending on fleet renewal requirements (including increased safety, better working conditions/habitability, modernisation for energy transition), and to measure the subsequent change of the overall EU fishing capacity change for a given kW or GT level or increase. This will also substantially refine the rough assumption made in the present study to anticipate the potential landings from reactivating the unused capacity (see Figure 1).

On the influence of management regime, little correlation might be expected between main engine power (kW) and harvesting capacity if the fishing vessels operate with quotas. With an increase in the kW engine under the implementation of catch limits, vessels would reach fishing grounds faster, trips would be shorter (less time exposed to sea conditions), but the catches would remain the same (limited by quota, and assuming full compliance and catch declared correctly, and no technical interactions among fisheries), and therefore the kW in use would be decoupled from the ability to catch fish. In practice, a strong correlation might be found, however, as soon as the "race for fish" is determinant whenever to be the first at fishing the quotas can incentive bigger engines to fish longer and further away (Branch et al., 2006). In the case of vessels operating without quotas (e.g., in the Mediterranean), or in mixed fisheries situations (typical of demersal fisheries where quotas mismatch opportunities), there may exist a stronger correlation between the kW power increment and the fishing capacity. In these cases, vessels could cover longer distances at higher speeds and operate with larger nets or other fishing gears, resulting in higher catch rates.

Adding more flexibility in exchanging fishing capacity is key. By nature, there are inherent variations in fish stocks that make fishing opportunities fluctuations conflicting with a fixed fishing capacity which likely induce a situation of short-term imbalance (under- or over-capacity). We expect such a risk for imbalance persistence to be more likely particularly for specialized fleets that might not adapt if the fishing opportunities on their unique target would decline. On the contrary, more capacity allocated to polyvalent vessels fishing upon diversifying catch portfolios (i.e., the number of species targeted by an operator) may counteract this risk (Thébaud et al., 2023). The transition and diversification involve significant initial capital and installation costs that affect the uptake (e.g., Eayrs and Pol, 2019), and the payback time depends on operating and maintenance costs over vessel lifetime. Feasibility studies are needed to assess economic returns, considering future fuel availability, fishing opportunities, capacity flexibility, market conditions, and perverse incentives like fossil fuel tax exemptions. A critical factor for success in ensuring the transition while limiting the risk for overfishing is reducing the primary concern of the lack of fish; without sustainable fish stocks, transition efforts will be inefficient.

In fisheries with effort in excess or overcapacity, management systems with individual vessel quotas were predicted to reduce fleet imbalance by increasing the fishing capacity of the more economically viable fishing vessels, but with an assumed zero-change in overall capacity, as this capacity moved from fishers wishing to trade their own capacity and cease fishing. The implementation of such kinds of quotas led to the reduction in the number of fishing vessels in different countries such as Norway or Denmark (Asche et al., 2014; Dinesen et al., 2018). For large-scale fleets, such a framework for market-based instruments could be introduced to motivate private investment in fleet adaptation (Byrne et al., 2021). For small-scale fleets, sector-specific solutions, such as direct sales, could be prioritized (Guyader et al., 2013). In redesigning the fleet, these strategies offer the potential to promote economic sustainability alongside reducing catch volumes to remove situations of imbalance and support energy transition. This is aligned with prohibiting public funding for the construction and modernisation of fishing vessels and equipment. According to the World Trade Organization (WTO) and bodies like the Organization for Economic Co-operation and Development (OECD, 2025) and Food and Agriculture Organization (FAO), public funding for fleet renewal may lead to harmful subsidies that directly or indirectly contribute to overfishing or overcapacity (Skerritt et al., 2023).

In the long term, market-based instruments can be used to facilitate the use of licenses when vessels are decommissioned. Licenses are generally tied to a vessel and in some cases also to individual catch rights. Additional flexibility to allow the removal of a given fishing vessel, while also allowing the owner to hold the license temporarily, may provide incentives to adapt the fleet to new needs. This would allow the owner to trade the license and quotas with other vessel owners for fishing purposes, or the license for the adaptation of the fishing vessel to environmental protection and crew habitability. The United Kingdom (UK) is an example of the use of licenses detached from a physical vessel ("license entitlements"), where these virtual entitlement licenses are included in the UK fleet register instead of vessel licenses for a period of three years.

Increasing flexibility would mean promoting possibilities for quota swaps and quota (harbor) pools. The need for quota redistribution would require more flexibility under a "rights-based management" regime. Quota swap and exchange also provide flexibility to adapt. Increased involvement of co-management in quota appropriation could help reduce social and economic impacts associated with quota usage and fleet inactivity (Bastardie et al., 2026). This could be addressed with quota pools managed by (harbor) communities or Producer Organizations (POs). In addition to allocating rights among quota-pool members as needed, avoiding quota underutilization would also require, for example, more flexibility regarding target species, as vessels may no longer be able to remain highly specialized in certain fisheries. This would allow them to target alternative species during periods of low stock abundance organized by POs allocations among their members.

6.4 Control for unintended side effects of effort control and complement with catch limits

Limiting fishing ability by restricting the number of days at sea specific to fleet segments (for example, coastal versus offshore fisheries), remains relevant. In imbalanced situations there is a need to continue limiting the ability to catch fish with an effort control. However, limiting effort is often seen by some stakeholders as inefficient and counterproductive, as it can lead to wasted steaming time and operational inefficiencies (ASFD, 2018). This was shown in the Western Mediterranean, which is usually compensated with public aid to compensate for temporary inactivity and maintain a fleet presence (STECF, 2025b). The justification for such help stand in the fact that reducing the number of allowable fishing days may disproportionately impact different operators: larger vessels, which are at the greatest financial risk, as their operational days fall below the threshold required for economic viability, smaller vessels as well, even if having smaller operating costs, in case their catch rates are far below large operators (STECF, 2025a).

In reaction to effort control, fishers can bypass input controls. For example, when limits are placed on the number of or size of vessels, fishers may adapt by increasing boat size or engine power to maintain or even increase their fishing capacity (Damalas et al., 2014). Besides, coastal fisheries are particularly sensitive to weather conditions, limiting available fishing time. While larger vessels can operate in rougher sea conditions, they may increase the risk of accidents, and operating trawl gear in rough weather remains less effective.

Demonstrating that a healthy environment also leads to more immediate rewards can however motivate positive change. For instance, reduced and balanced fishing capacity to fishing opportunities protect resources and offer direct advantages in the long term (Bastardie et al., 2024): less impact on the seabed means a lower risk of net damage, less fatigue, and fewer repairs or losses. More selective fishing also leads to less manual sorting, more sustainable fishing alongside certifications like MSC that can secure price premiums. Securing such rewards calls for a robust control for unintended side effects of effort control that would include regular control for the change in catch efficiency. Input controls should also be carefully tailored with local circumstances and complement, rather than substitute, output controls. The implementation of catch limits may be promoted to avoid relying on effort control only with risk of overfishing which could have inadvertently led to an ageing fishing fleet not equipped to operate in rough offshore areas and saving costs, thus encouraging more fishing in coastal areas. A shift in fishing effort can lead to overexploitation of coastal resources, which are important habitats for commercial species. In addition, fishing in coastal areas can lead to conflicts between different fishing segments, further exacerbating resource depletion (Molina and Gourguet, 2025).

On the GT claim, in the past, adjustments to the EU law have already been suggested to allow fleets to accommodate the additional storage volume needed by implementation of the landing obligation (LO) under Article 15 of the 2013 CFP Regulation. However, such a rationale may directly contradict the intended objectives of the LO. Therefore, justification for requesting additional vessel volume should be carefully checked for possible inconsistencies with the objectives of the CFP.

In terms of kW, there is also indication of preference for over-motorized kW engines (European Commission, 2019b, European Commission, 2025). Some propulsion setup exists where the installed engine provides more power than the vessel strictly needs for its primary fishing operations (most likely for ensuring more safety in rough weather conditions). In parallel, opportunities exist to install lower kW engine requirements by promoting fuel-saving technologies and encouraging the adoption of vessels and fishing techniques with reduced kW requirements. This can help ensure that increases in catch efficiency do not come with more harvesting capacity that could compromise sustainability.

7 Discussion and conclusion

The objective of this study was to build upon the findings of previous investigations into the past, present and future development of fishing capacity (sections 3 and 4), to summarize the key findings, identify future challenges (section 5), and provide general recommendations (section 6) for managing the fishing fleet capacity in Europe. It provides a concise analysis of the current state of the EU fishing fleet with the aim of informing future management strategies.

Within the CFP, fisheries regulations are designed to protect fishing resources and ensure sustainable fishing practices. These regulations include reducing fishing capacities by imposing strict limits on vessel tonnage and engine power (2013 CFP, Articles 22 and 23) and prohibiting public funding for the construction and modernisation of fishing vessels and equipment. The total capacity of the EU fishing fleet is capped to prevent too many or too large vessels from competing for limited fish resources. Despite these regulations, a key present and future challenge remains to limit the risk of overexploitation of fishing resources, which is still a concern. Moreover, despite these current limitations, there is no guarantee that these limitations on fishing capacity are sufficient to ensure the fleets are balanced with the available resources.

Strict measures on fleet capacity are taken to align with ecological limits as introduced through the European Green Deal and 2030 Biodiversity Strategy (EC, 2020). The need for organizing an energy transition of the EU fleet and ensuring its renewal and modernisation is happening in that context. Hence, the challenge for the EU fleet policy is to ensure that such renewal and modernisation do not come with an improved ability to catch fish that will be detrimental to some of the underlying exploited living marine resources, while our baseline showed an already imbalanced situation of some segment of the EU fleet with the available resources. EU fleet renewal is also dependent on it as, at the time of writing, some segments are ineligible, by law, for EC funding whenever assessed out of balance (Regulation (EU) 2021/1139) Articles 18 and 19).

It is not clear if facing future challenges, such as energy transition, attracting young fishers, and improving profitability, may require extra capacity to accommodate more efficient or alternative engines for greener fuels, and better working conditions given the country-specific capacity ceilings limiting the fishing capacity are not reached. However, current policies may impact profitability of the current active fleet by limiting for example the catch storage space on board. Moreover, the current legislation requires that introducing new, more energy-efficient new built vessels come with removing an equivalent amount of capacity from the fleet. Similarly, modernizing existing vessels by increasing their internal volume is not allowed unless that added GT is offset elsewhere in the fleet.

This study also identifies a range of different factors that should be considered when calculating the harvesting capacity of a vessel. There exists trade-offs between onboard space for harvesting capacity, energy transition and safety. These trade-offs can be resolved by increasing vessel size and/or increasing the rate of filling the fish hold (e.g., higher catch rates). In addition, the study indicates that different gear specifications, such as gear size, mesh size, number of hooks, and net length, will affect harvesting capacity, yet these are not monitored ([8]). Furthermore, the effects of technological improvements must be taken into consideration and reflected in the analysis when assessing the feasibility of increasing a vessel's GT and/or kW without increasing its ability to catch fish. Our findings indicate that capacity metrics require refinement to avoid creating unintended imbalance when changing fishing capacity levels. A thorough comparison of how vessel size affects harvesting capacity would also be conducted. This analysis would be completed before considering any changes to the current restrictions on vessel length to not recommend a solution that would increase the vessel's harvesting capacity in a situation of imbalance.

The study found that such a split of GT vessel volume is challenging to implement in practice, besides adding an additional layer of complexity to fleet management, as some solutions cannot contribute to modernisation without increasing the ability to catch fish. In particular, the fish hold volume, which is closely linked to harvesting capacity, is currently not being monitored. Therefore, it is essential to begin measuring and monitoring fish holds based on other more readily available information, such as the length of the vessel or GT, when estimating the harvesting capacity. Hence, elongating vessel for example adding a bulbous bow that helps to make the vessel more hydrodynamic and therefore more energy-efficient may inadvertently create additional room to store fish (if not a solid, sealed bulb). This requires strong control and enforcement to avoid this. In addition, given GT is calculated differently for vessels above and below 15 meters in length, there is an incentive to retrofit vessels by making them wider to increase storage capacity, but also making them unsafe.

In such an apparently locked situation, the study has documented the current EU fleet capacity to encourage Member States to investigate their own fleet situation and to consider using the remaining fishing capacity to support the energy transition and fleet renewal, given the key future challenges the fishing sectors will face. The study aimed to shed light on opportunities and challenges by documenting the likelihood of possible scenarios. Our findings indicate that EU fleet imbalance (as reported in section 2) will likely worsen (the "worsening scenario" of Figure 4) whenever capacity is reused, or extra capacity is granted without controlling for the ability to catch fish, and without monitoring for the right metrics beside fleet or vessels kW and GT (alongside risks described in section 5). For the same reason, it appears optimistic to assume that reactivating unused fishing capacity or granting extra fishing capacity will not be used to catch even more fish.

An alternative, suboptimal but more precautionary, scenario is to underuse fishing opportunities in the short term to restore balance on a longer time horizon. The surplus of opportunities will ensure their long-term maintenance. Adhering to the scientifically advised TACs, effort limitations, and other regulatory measures should help mitigate the risk for imbalance in line with the precautionary principle (2013 CFP, Article 2). The precautionary approach may also result in some under-exploitation in the short term, but it would help the EU fleet regain balance in the longer term. If it aligns with the precautionary principle, in the short term, it is unclear how capable the current fleet is of addressing such missed opportunities when profitability is on the edge. Hence, we provided a set of recommendations to mitigate this risk for overexploiting or underexploiting fishing opportunities by promoting (i) the evaluation of the capacity need at the EU Member State level, (ii) investigate to what extent a decomposition of the vessel volume is possible to monitor and control for volume unrelated to catching ability, (iii) reallocating fishing opportunities towards less fuel intensive and alternative more sustainable fishing techniques. Many fleet segments may also remain imbalanced if a precautionary approach is not followed, especially as climate change and other environmental factors external to fishing are likely to further exacerbate these imbalances. Achieving a better balance between fleet capacity and fishing opportunities would not only ensure the fishing industry is eligible for public aid but also make it possible for vessel modernisation without public aid, as healthier fish stocks enhance the economic viability of fisheries.

Meanwhile, we found that an increase in vessel efficiency will happen while continuing implementing catch and effort limits. Implementing catch and effort limits is also required where they do not yet exist as gains in efficiency are a drive for overcapacity, increasing the risk for overfishing EU fish stocks on board vessels. However, a core challenge in controlling fishing capacity is that efficiency improvements are often essential for enhancing the economic performance of certain fleet segments, especially smaller vessels operating on the margins of profitability. Therefore, the goal should not be to reduce individual vessel efficiency, but rather to manage fleet-level efficiency. In fact, low efficiency on individual vessels can result in poorer working conditions and make the profession less attractive to younger generations. In addition, an ageing fleet sometimes encourages fishers to work harder to compensate for reduced technical efficiency, which can lead to the overexploitation of fishery resources.

This is a critical moment to implement effective fleet management and rebalance the EU fleet. Priority should be given to document the existing knowledge gaps and improve predictability

8 But see COMMISSION IMPLEMENTING REGULATION (EU) 2025/2196 where gear dimensions and specifications will have to be monitored from 2026 onwards as specified in Annexe Tables XV and XVI .

related to fishing capacity effects and metrics before irreversible investment are made, while continuing to apply precautionary catch and effort limits. A core challenge for fleet management in controlling fishing capacity is that efficiency improvements are often essential for enhancing the economic performance of certain fleet segments. Therefore, the goal of the fleet management should not be to reduce individual vessel efficiency, but rather to manage fleet-level efficiency, in order to improve safety, working conditions, and environmental performance, including ensuring a persistent balance with fishing opportunities. Achieving this balance is a prerequisite for a successful EU fleet renewal alongside fleet modernisation and an energy transition toward low-carbon, low-impact fisheries.

Author contributions

FB: Investigation, Writing – original draft, Resources, Visualization, Funding acquisition, Software, Formal analysis, Validation, Project administration, Data curation, Writing – review & editing, Methodology, Conceptualization. RW: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization, Funding acquisition, Formal analysis, Resources, Writing – review & editing, Project administration. ET: Data curation, Writing – review & editing, Investigation. MA: Writing – review & editing, Data curation, Investigation. RD: Investigation, Writing – review & editing, Data curation. AL: Data curation, Writing – review & editing, Investigation. IM: Data curation, Writing – review & editing, Investigation. JL: Data curation, Writing – review & editing, Investigation. GG: Writing – review & editing, Data curation, Investigation. SM: Writing – review & editing, Data curation, Investigation. RS: Writing – review & editing, Data curation, Investigation. LM: Data curation, Writing – review & editing, Investigation.

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Conflict of interest

RW, IM were employed by company MRAG Europe Ltd.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2026.1812898/full#supplementary-material

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