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Techno-economic analysis for the energy transition of the EU fisheries and aquaculture sector

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EXECUTIVE SUMMARY

A Sustainable Blue Economy offers many solutions to achieve the European Green Deal objectives. However, this requires current activities, technologies and processes to reduce their carbon footprint. In response, the European Commission adopted a package of measures in February 2023 including most importantly for this study the Communication on the Energy Transition of the EU Fisheries and Aquaculture sector. The package proposes a series of actions to reduce greenhouse gas emissions and achieve carbon climate neutrality by 2050. This study maps out low-carbon energy innovations and efficiency solutions; analyses current energy use; associated CO_2e emissions; the cost to reduce them; and the viability of decarbonisation technologies. It identifies potential solutions for the fisheries and aquaculture sector, assesses their financial viability and provides recommendations for overcoming barriers to implementation. The specificities of fisheries and aquaculture are addressed separately, with recommendations for the two provided accordingly. Potential synergies for the energy transition within the sectors, are also identified.

Fisheries sector analysis

The EU's fishing sector is exploring technological innovations to reduce fuel costs and CO_2e emissions, taking cues from the wider maritime sector which has already implemented various measures. However, the fisheries sector's adoption of innovations is relatively recent (motivated primarily by rising energy prices) and faces challenges including regulatory interactions, lack of experimentation and pilot projects, as well as limited fleet renewal. Despite these challenges, a systematic review by the study team has identified 45 relevant potential solutions across seven categories.

The analysis of CO_2e emissions shows that the Large-Scale Fleet (LSF), the largest segment by landings is the primary contributor, accounting for 3.7 million tonnes of CO_2e, around 73% of the total emissions from the fisheries sector, followed closely by the Distant-Water Fleet (DWF) at 0.97 million tonnes of CO_2e, around 19%. The Small-Scale Coastal Fleet (SSCF) produces a relatively small portion of the total emissions of the sector with 0.4 million tonnes of CO_2e, around 8%. All fleets have similar CO_2e emissions per tonne of fish (1.1 – 1.3 tonnes of CO_2e per tonne of product) and all have reduced emissions intensity between 2013 and 2023, with SSCF remaining slightly higher than other fleet segments, but also showing the largest improvement. These emission indicators highlight that potential decarbonisation solutions in the LSF segment would have the most immediate impact.

The financial analysis – in particular of the SSCF – underscores the complexity of decarbonising the fisheries sector, highlighting the need for further innovations, targeted investments and incentives to make these solutions more attractive to fishers. While some current technologies offer promising returns or savings, others may not be financially viable without significant reductions in costs, increases in fuel prices, or both.

The best performer for DWF is the use of sumwings instead of trawling, with an EAA of EUR 72,095 in returns. Following that, software for real-time performance monitoring, antifouling, smart steaming, wind turbines, energy audits, energy efficient lighting, route optimisation and using larger propellers all produce positive EAAs between EUR 42,421 and EUR 8,383 and CO_2e reductions, between 4% and 40%. Diesel-electric propulsion, propeller-rudder upgrades and improved hull design on their part, while they reach a payback period, they account for negative EAAs between EUR 920 and EUR 16,077 in losses due to the time value of money.

Focusing on LSF, with an EAA of EUR 9,265 and EUR 3,151 in returns (respectively) using outriggers and sumwings in place of trawling would be the best performing solution found (up to 12.5% and 40% reductions of CO_2e). Subsequently, positive EAAs between EUR 2,430 and EUR 267 are produced by smart steaming, software for real-time performance monitoring, antifouling and waste heat recovery systems (between 2.5% and 25% of CO_2e abatement). Although installing wind turbines appears to achieve a simple payback (in 19 years), it results in annual losses (a negative EAA) of EUR 139 due to the time value of money. Route optimisation using modern route planning devices can achieve emissions reductions with a relatively small total financial gap of (on average) around EUR 16,000. The most promising single option to meet decarbonisation goals could be a switch to biodiesel, but the current estimated total financial gap is around EUR 357,000 on average per vessel.

Based on financial performance and marginal abatement cost, all of the options found for the typical EU SSCF have uncertain payback durations and financial challenges. Over the short to medium term technological innovation and the outcomes of ongoing pilots (i.e. scale and risk reduction) will be critical to address the specificities and needs of this segment.

Aquaculture sector analysis

The EU's aquaculture sector is economically strained due to increased energy prices, influenced by geopolitical tensions and post-pandemic inflation. This study identified several, economically viable, potential solutions to substantially reduce GHG emissions, as well as the energy dependence, of the sector. Estimating energy use and CO_2e emissions in EU aquaculture involves complexities due to diverse species and farming methods, including marine and land-based aquaculture. The study adopts a Life Cycle Assessment (LCA) approach along the value chain, estimating emission intensities based on production volumes for 2019.

The study, which provides for the first time an attempt of calculation for the total emissions (in the EU) of the sector, being approximately 2 million tonnes of CO_2e (2019), highlights that GHG emissions from intensive farming systems of carnivorous fish are markedly higher than those related to shellfish farming. This is also due to the emissions related to feed use as this constitutes a major part of the GHG emissions, especially for marine fish, due to the higher Feed Conversion Ratios (FCRs), compared with freshwater species. The study identified knowledge gaps related to the mitigation of environmental impact of certain typologies of aquaculture.

The study identified three main solutions which could be implemented across the sector, namely:

1) Energy Management and Audits
This involves the identification of energy-intensive units, conducting energy audits, setting energy-related goals and improving competencies: its implementation could reduce energy usage by 2-10%.

2) Precision Fish Farming (PFF)

This aims to optimise mainly feed rations and oxygen supply, PFF can significantly reduce the Feed Conversion Ratio (FCR), potentially leading to notable decreases in GHG emissions. For example: the ongoing EU-funded project 'NewTechAqua' suggests that a 10% decrease in liquid oxygen and FCR could be achieved by implementing PFF in a land-based seabass/seabream farm. ([1]) It relies on real-time data collection, dynamic modelling and decision support systems. The main limitation is the cost and availability of non-invasive monitoring devices for fish size/weight, behaviour and welfare indicators. However, advancements in AI and pattern recognition are making these technologies more accessible.

3) Novel Feed Formulations

This involves substituting traditional ingredients like Fish Meal (FM) and Fish Oil (FO) with emerging ingredients (e.g., insects, single-cell proteins and by-products from other sectors), which could markedly reduce GHG emissions. However, at present, the environmental impact of these novel ingredients varies, with some still exhibiting high CO_2e emissions. Utilising by-products from other agrifood sectors as feed ingredients appears to be a feasible short-term solution to reduce the carbon footprint of fish feeds, while single cell proteins, obtained by biotechnological processes, seem the most promising long-term solution.

The case study analysis presented in the study underscores that the energy transition within the EU aquaculture sector is technically feasible and, in certain cases, financially viable, with potential payback periods for investments ranging from 2 to 11 years. It depends on tailored strategies for different farming types. In marine aquaculture, this means electrifying service vessels and using renewable energy. Freshwater farms should switch to solar power and produce their own oxygen, reducing reliance on liquid oxygen. These approaches vary by farm type, offering different levels of greenhouse gas (GHG) reduction and costs, potentially cutting emissions by 26%.

Solar power is effective for both land farms and hatcheries, potentially reducing GHG emissions by 5-14% and 43%, though costs vary. Oxygen generators for land farms could lower emissions by 16-33% for an initial outlay of EUR 150,000 to EUR 500,000. Electrifying marine farm barges could cut emissions by 8-13%, but with high setup and running costs. Boat electrification also shows promise for significant GHG reduction, but feasibility varies by country and distance from the coast.

Focus on renewable energy and operational efficiency, like onsite oxygen production, is the most practical route to meet 2030 sustainability targets. However, marine electrification faces obstacles like high costs and the need for renewable power sources and port infrastructure. A targeted approach, favouring solutions with low implementation barriers and high emission reduction potential, especially in land-based and hatchery operations, is essential for progress. Adapting strategies to national contexts and incentives is crucial for a successful, sustainable transition.

([1]) Royer, E., & Pastres, R. (2023). Data assimilation as a key step towards the implementation of an efficient management of dissolved oxygen in land-based aquaculture. *Aquaculture International*, *31*(3), 1287-1301.

COMMENTS AND POSSIBLE LIMITATIONS

For the purposes of the study, it was requested that we align with the *2023 Annual Economic Report on the EU Fishing Fleet (STECF 23-07)* by using a marine diesel to carbon equivalent emissions factor of 2.64 kgCO2e/l. ([2]) While the conversion factor is published refers to Scientific Data paper on trawl fisheries, the study team has not been able to verify the result using the references provided. Using the underlying information from the FuelEU maritime regulation and a density of 860 g/l the study team calculated an alternate marine diesel to carbon equivalent emissions factor of 2.8 kgCO2e/l. ([3]) Using the factor associated with the FuelEU maritime regulation would result in around a 5% increase in the total estimated emissions associated with the EU fisheries fleet.

The STECF fleet economic dataset, crucial for this analysis, intermittently lacks information including details on fuel consumption for different fleet segments. This is partly because revealing data for small fleet segments could unintentionally expose details about individual vessels. Additionally, gaps in the data due to reporting issues at the national level might be common. These missing or zero values for fuel consumption could lead to possible discrepancies in the EU fisheries sector's total emissions. In order to align the current study with the *2023 Annual Economic Report on the EU Fishing Fleet (STECF 23-07)* the study calculates emissions per vessel based on aggregate data where missing data is not explicitly addressed. The AER acknowledges the potential issue and proposes estimating fuel use based on metrics like total kW fishing days to mitigate data gaps. The approach to aligning with the AER results in a probable further underestimation of baseline emissions from the fisheries sector, highlighting the importance of addressing data gaps. Direct engagement with national officials responsible for data or employing statistical methods could enhance the analysis.

This study is supported by a series of Annexes (of which Annex C: Factsheets of Innovative Solutions) which are available upon request to CINEA. Other additional materials will be published on the DG MARE website, providing valuable information on the study results.

([2]) Sala, A., Damalas, D., Labanchi, L., Martinsohn, J., Moro, F., Sabatella, R., & Notti, E. (2022). Energy audit and carbon footprint in trawl fisheries. Scientific Data, 9(1), 428.

([3]) European Commission (2021). Proposal for a Regulation of the European Parliament and of the Council on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
AER	Annual Economic Report
CAPEX	Capital Expenditures
CFD	Computational Fluid Design
CFP	Common Fisheries Policy
CII	Carbon Intensity Index
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent
DCF	Data Collection Framework for EU fisheries
DWF	Distant Water Fleet
EC	European Commission
EAA	Equivalent Annual Annuity
EEA	European Environment Agency
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ships Index
EMFAF	European Maritime, Fisheries and Aquaculture Funds
EU	European Union
EUROSTAT	Statistical office of the European Union
FAD	Fish Aggregating Devices
FAO	Food and Agriculture Organisation of the United Nations
FCR	Feed Conversion Ratio
FM	Fish Meal
FO	Fish Oil
FU	Functional Unit
GHG	Greenhouse Gas
GloMEEP	Global Maritime Energy Efficiency Partnerships
GT	Gross Tonnage
GWP	Global Warming Potential
ICES	International Council for the Exploration of the Sea
IMO	International Maritime Organization
LNG	Liquified Natural Gas
LSF	Large Scale Fleet
OPEX	Operational Expenditures (yearly)
PV	Photovoltaic
RESs	Renewable Energy Sources
SEEMP	Ship Energy Efficiency Management Plan
SSCF	Small Scale Coastal Fleet
STECF	Scientific, Technical and Economic Committee for Fisheries
TRL	Technology Readiness Level
TtW	Tank-to-Wake
WtW	Well-to-Wake

GLOSSARY

Term	Definition
Active gear	Type of fishing gear that has to be moved or activated by the fishing vessel in order to catch fish. According to the DCF gear definitions these include: 'dredgers', 'demersal trawlers and/or demersal seiners', 'other active gears', 'polyvalent active gears only', 'purse seiners', 'beam trawlers', 'pelagic trawlers'.
Bycatch	The catch of non-target species and undersized fish of the target species.
Catches	Live weight of fish products caught by fishing vessels and their gears
CO_2 equivalents	Measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential, by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential.
Distant Water Fleet (DWF)	EU registered vessels over 24 metres operating in 'other fishing regions' including EU outermost regions
Fishing gear	See gear type.
Fishing technology	See gear type.
Gear type	Standardised classification of the tools (gears) used to capture aquatic animals
Global Warming Potential	Measure used to describe the relative potency of gases in terms of their contribution to global warming, using carbon dioxide as a basis.
Greenhouse gases	Gases that contribute to the natural greenhouse effect and their increase is associated with global warming and climate change.
Landings	Weight of fish that is caught (and potentially processed onboard) and subsequently brought to domestic or foreign ports.
Large Scale Fleet (LSF)	EU vessels over 12 metres using static gears and all vessels using towed gears operating predominately in EU waters
Marine diesel	Main type of fuel used in fishing vessels.
Marine gas oil (or gasoil)	See marine diesel.
Passive gear	Type of fishing gear that is left out for periods of time and relies solely on the movement and interaction of the animal towards it to catch fish. According to the DCF gear definitions these include: 'drift and/or fixed netters', 'pots and/or traps', 'hooks', 'passive gears only', 'other passive gears', 'polyvalent passive gears only', 'active and passive gears'.
Polyvalent vessel	Vessels that may employ both passive and active gears.
Static gear	See passive gear.
Small Scale Coastal Fleet (SSCF)	Vessels under 12 metres using static gears.
Tank-to-Wake	Scope of emissions calculations for vessels that implies considering the emissions from fuel use once the fuel is already in the tank, without accounting for fuel production and transportation.
Towed gear	See active gear
Vessel size	Classification of fishing vessels based on their length.
Well-to-Wake	Scope of emissions calculations for vessels that include the net effect of fuel production and transport, instead of only considering the combustion of the fuel.

1 INTRODUCTION

The European Union's fisheries and aquaculture sector are facing economic challenges due to the surge in energy prices, primarily fuelled by *Russia's unprovoked act of aggression against Ukraine,* post-pandemic inflation and in some basins fish stock availability. In 2022, this led to a situation where parts of the EU fishing fleet could not sustain operations without financial assistance. ([4]) The sector's reliance on diesel and high energy feed sources has not only financial implications, but also environmental ones, with fisheries contributing to CO_2e emissions and thus climate change.

This situation underscores the need for the sector to transition toward sustainability, which is the subject of a package of measures released in February 2023 including most importantly for this study the Communication from the Commission: On the Energy Transition of the EU Fisheries and Aquaculture sector. ([5]) The package emphasises reducing greenhouse gas emissions and achieving climate neutrality by 2050. Reducing fuel consumption is the most effective measure for mitigating the climate impact of fisheries. ([6]) The aquaculture sector, while able to provide sustainable seafood, is set back by high energy demands associated with feed and farming practices.

Efforts to reduce the energy consumption in fisheries include adopting recent technologies that lower energy use per kilogram of fish produced and switching to renewable (alternative) energy sources. In aquaculture, efforts can be made to reduce emissions associated with feed and (the energy used for) farming practices. However, these major changes face barriers such as financial constraints, limited technology transfer and a general hesitance towards innovation. Infrastructure changes, like the development of alternative fuels in ports, are also necessary for this transition.

The EU fisheries and aquaculture sector are at a crossroads where they should seek to adapt by reducing their carbon footprint and energy dependence. That's why the Commission published the communication on the energy transition in EU fisheries and aquaculture in February 2023, identifying these 4 main barriers and enablers for action to accelerate the transition in the sector. This study is one of the actions, included in the need to close the gap in research and innovation. This transition not only aligns with the EU's climate goals but could also lead to lower operational costs and new economic prospects while minimising pollution and fostering resilience against volatile energy prices.

The objective of this study ([7]) is to map the low-carbon energy innovations and energy efficiency solutions within the EU fisheries and aquaculture sector by:

- Determining the energy costs and related CO_2e emissions of the current status of EU fisheries and aquaculture sector.
- Developing a "Techno-economic analysis" of the innovative low-carbon technologies and energy efficiency solutions in fisheries and aquaculture.
- Defining the main barriers and bottlenecks, as well as the possibilities of synergies by design for an efficient transition path.

([4]) See for example the EMFAF crisis mechanism: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_2003
([5]) COM/2023/100 On the Energy Transition of the EU Fisheries and Aquaculture sector
([6]) See for example Bastardie, F., Hornborg, S., Ziegler, F., Gislason, H., & Eigaard, O. R. (2022). Reducing the fuel use intensity of fisheries: through efficient fishing techniques and recovered fish stocks. Frontiers in Marine Science, 9, 817335.
([7]) Under contract CINEA/EMFAF/2022/3.5.1/Lot2/01/SC02/SI2.892588– Techno-economic analysis for the energy transition of the fisheries and aquaculture sector)

The report begins by specifying in detail the current energy use, costs and CO_2e emissions in both the fisheries and aquaculture sector. It then systematically identifies the possible decarbonisation innovations or solutions for each sector and presents a technoeconomic analysis in an attempt to prioritise these innovations or solutions. The report concludes with an analysis of other factors that might influence prioritisation or implementation of identified innovations or solutions.

The analysis begins by identifying all potential solutions, assessing their maturity and financial viability early on. Solutions are preliminarily ranked based on these factors only. Specifically for fisheries, for solutions with available data, insight is offered into which technologies and solutions are best from a decarbonisation and cost effectiveness perspective by calculating a marginal abatement cost curve for the fishery fleet: an economic model taking into account availability and applicability of each solution to the vessels in different fishery fleet segments. ([8]) Additionally, an evaluation of challenges and opportunities beyond financial aspects provides further guidance on decarbonisation priorities. The final recommendations aim to integrate and balance all these perspectives, while making it clear what each individual analysis has shown. The separate executive summary document brings all perspectives and analysis outputs into one place.

([8]) A marginal abatement cost curve is a graph that represents the cost associated with eliminating an additional unit of pollution, plotted against the total amount of pollution reduction achieved.

2 DEVELOPMENT AND CURRENT STATUS OF THE ENERGY COSTS AND CO_2e EMISSIONS OF EU FISHERIES AND AQUACULTURE SECTOR

This descriptive chapter serves as a reference against which to compare innovative low-carbon technologies and energy efficiency solutions that could be implemented in the European fisheries and aquaculture sector. This chapter provides indicators on the energy use, energy costs and emissions associated with the production of fish products in the EU, including their trends over time.

2.1 Fisheries

This section maps and describes the current status of the EU fleet in terms of its energy costs and CO_2e emissions, considering the fuel used, the fishing gear efficiency, the vessel size and the life expectancy of the vessels. The fuel use CO_2e emissions considered are Tank-to-Wake emissions of the fuel used by the fleet. Lastly, this description is made per fleet segments as specified in the Data Collection Framework for fisheries ([9]) based on vessel size and fishing gear, to make use of available data and provide outputs that are comparable with other relevant studies in the sector (see more information about fleet segments in Annex A) ([10]).

Two units of measurement have been selected for the CO_2e emissions of the different fleet segments. The first one is the total emissions from the entire fleet segment in the EU (measured in tonnes CO_2e) and the second one is the emissions per quantity of fish landed (measured in tonnes CO_2e/tonnes fish) per each fleet segment. For energy costs similar measurements have been selected and these costs have also been compared against the revenues of fishers.

Figure 2.1 details the progression of average yearly fuel prices from 2008 to 2023 (limited from the availability of data from the STECF and the European Market Observatory for Fisheries and Aquaculture Products, EUMOFA ([11]), obtained from dividing the energy costs by the total fuel consumed by the fleet and which evidences the high variability that fuel prices have over time. The figure also highlights a period of high fuel prices between 2011 and 2013 and then again in 2022. It is also worth to note that fuels used in navigation (including for fishing) are exempt from taxation in the EU, therefore the prices here calculated are also without taxation and would not vary between Member States on this basis. ([12])

([9]) European Commission (2001). Commission Regulation (EC) No 1639/2001 of 25 July 2001 establishing the minimum and extended Community programmes for the collection of data in the fisheries sector and laying down detailed rules for the application of Council Regulation (EC) No 1543/2000. Official Journal of the European Communities, L 222/53. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32001R1639.

([10]) All annexes are available under request to the contracting authority CINEA, please make the request here https://cinea.ec.europa.eu/contact-0_en

([11]) EUMOFA (2023). Data Download. Available from: https://www.eumofa.eu/bulk-download-page.

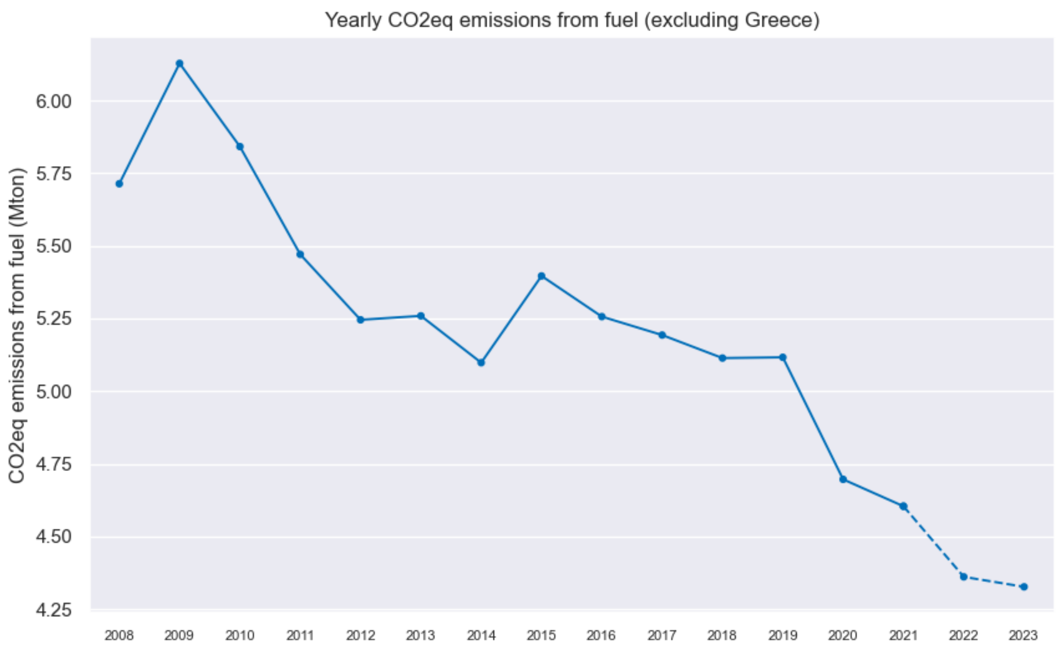
([12]) Council Directive 2003/96/EC of 27 October 2003 restructuring the Community framework for taxation of energy products and electricity. Available from: http://data.europa.eu/eli/dir/2003/96/oj,

Figure 2.1 Average yearly prices per litre

Source: consortium elaboration based on STECF data and Annual Economic Report (2023); dashed lines represent nowcasted data. Costs expressed in 2020 constant prices.

Carbon equivalent emissions associated with fuel use in the EU fishing fleet have reduced over the period as shown in Figure 2.2 below. The emissions reduction is likely due to both overall reduction in fleet size and possible energy efficiency gains associated with fleet renewal (e.g. in fuel use, efficient engines, lighter fishing gear and smart navigation and fishing methods). ([13])

Figure 2.2 Annual CO_2e emissions from the EU fishing fleet fuel (excluding Greece)

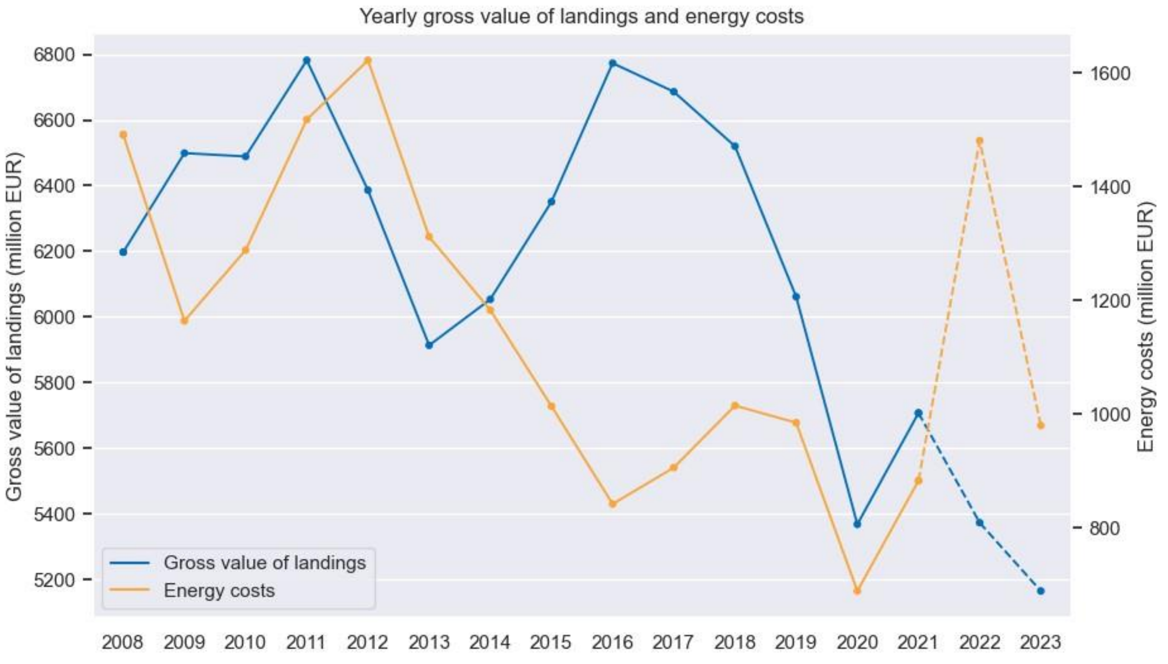


Source: consortium elaboration based on STECF data and Annual Economic Report (2023); dashed lines represent nowcasted data.

([13]) Energy transition of fishing fleets: UNCTAD/DITC/TED/2023/5

The total energy costs for the EU fishing fleet in Figure 2.3 below follow the trend of fuel prices (see Figure 2.1) showing peaks when fuel prices are higher, as between 2011 and 2013 and in 2022. At the same time, Figure 2.3 below shows that the income received by fishers ([14]) decreases concurrently in these periods of higher energy costs ([15]) and recovers when costs are lower (e.g., after 2013).

Figure 2.3 Gross value of landings and energy costs from 2008 to 2023 for the EU fishing fleet



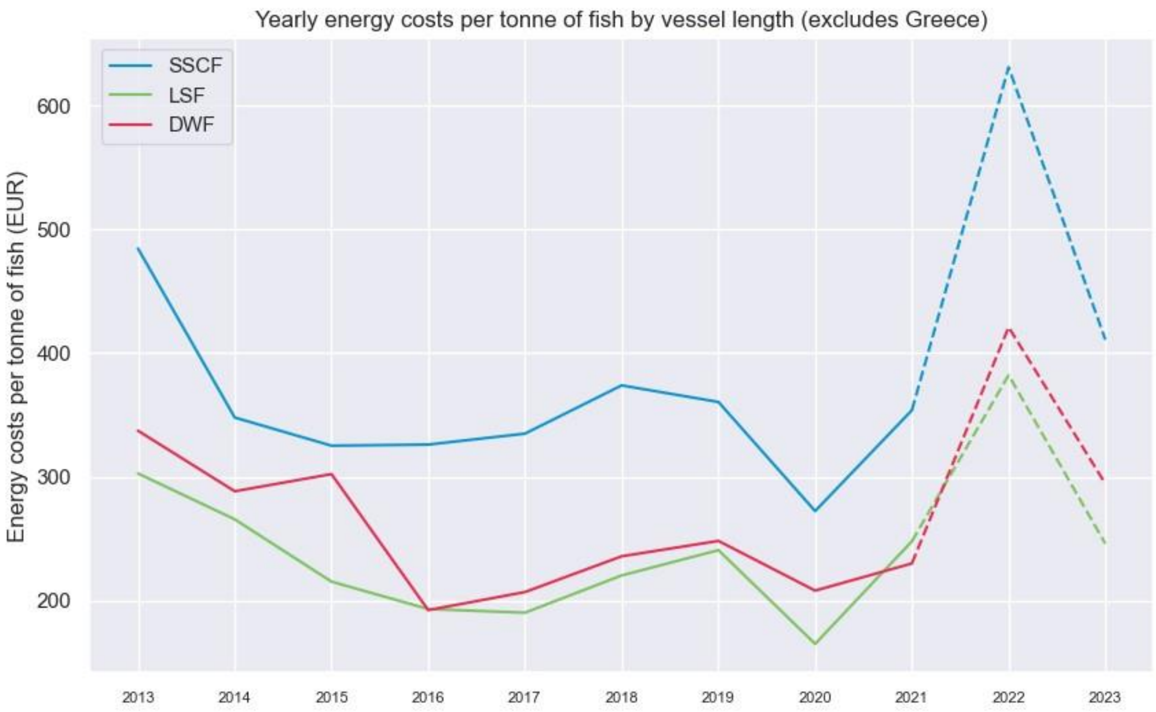
Source: consortium elaboration based on STECF data and Annual Economic Report (2023); dashed lines represent nowcasted data. Costs expressed in 2020 constant prices.

This trend of the gross value of landings, which partially follows the inverse of the trend for total energy costs, enhances the fact that fishers reduce economic activity when fuel prices are higher. In periods of higher fuel prices, it could be possible that the prices fishers get from landing fish do not or barely cover the costs of spending the day at sea, especially if their margins are already low.

As evidenced by Figure 2.4 below, the average energy costs per tonne of live weight of landings were lower in 2019 than they were in 2013 for all size category segments of the fleet, influenced by lower fuel prices and energy costs in 2019. The energy costs per tonne of fish over time follow the same trends of fuel prices and total energy costs with costs decreasing from 2013 for all vessel length segments alike, with a notable dip in costs in 2020 due to lower fuel prices and a very pronounced peak in 2022 for all segments following the energy crisis. The SSCF (mostly <12 m) segment spends the most on fuel per tonne of fish in total, followed by DWF and then by LSF (12-40 m). By fishing gear, active, passive and polyvalent vessels follow similar trends, with active gears spending the most, followed by passive and polyvalent vessels.

([14]) Gross value of landings measured by the price of first sale
([15]) These periods of lower income from landings seems to be concurrent with periods where the weight of fish landed is lower, according to consortium elaborations based on EUROSTAT landings data.

Figure 2.4 Energy costs per tonne of fish landed by vessel size from 2013 to 2023

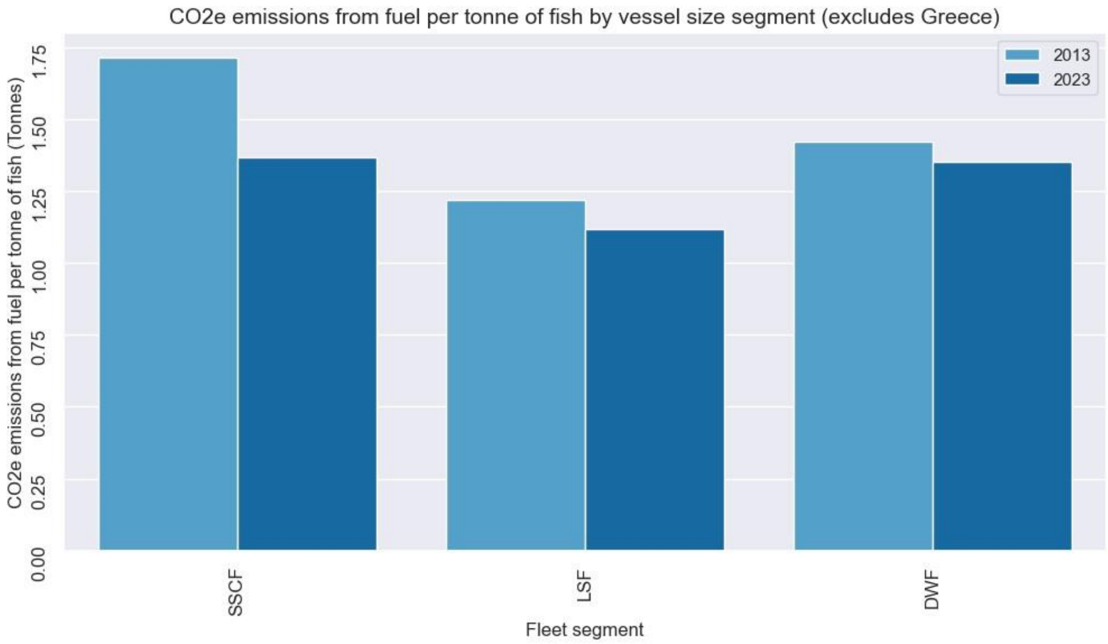


Source: consortium elaboration based on STECF Annual Economic Report (2023); dashed lines represent nowcasted data. Costs expressed in 2020 constant prices.

It is clear from the data that the LSF segment has remained responsible for the majority (i.e. 3.7 Mtonnes of CO_2e, or 73%) of the total emissions from the fisheries sector, followed closely by DWF segment (i.e. 970 thousand tonnes, or 19% of CO_2e). The SSCF amounts a small portion (i.e. 404 thousand tonnes, or 8% of CO_2e) of the total emissions of the sector. It should of course be noted that LSF is also the largest segment by landings, so a more informative measurement would be emissions intensity per tonne of fish.

All fleet segments have similar CO_2e emissions per tonne of fish and all have improved between 2013 and 2023, with SSCF being slightly higher, but also having the largest improvement when compared to the other segments. These factors point to a need for a special focus on the LSF segment when it comes to identifying potential decarbonisation solutions due to it being responsible for the largest fraction of the emissions of the fleet, but there is also a need to address the specific conditions of the SSCF to reduce its CO_2e intensity even more.

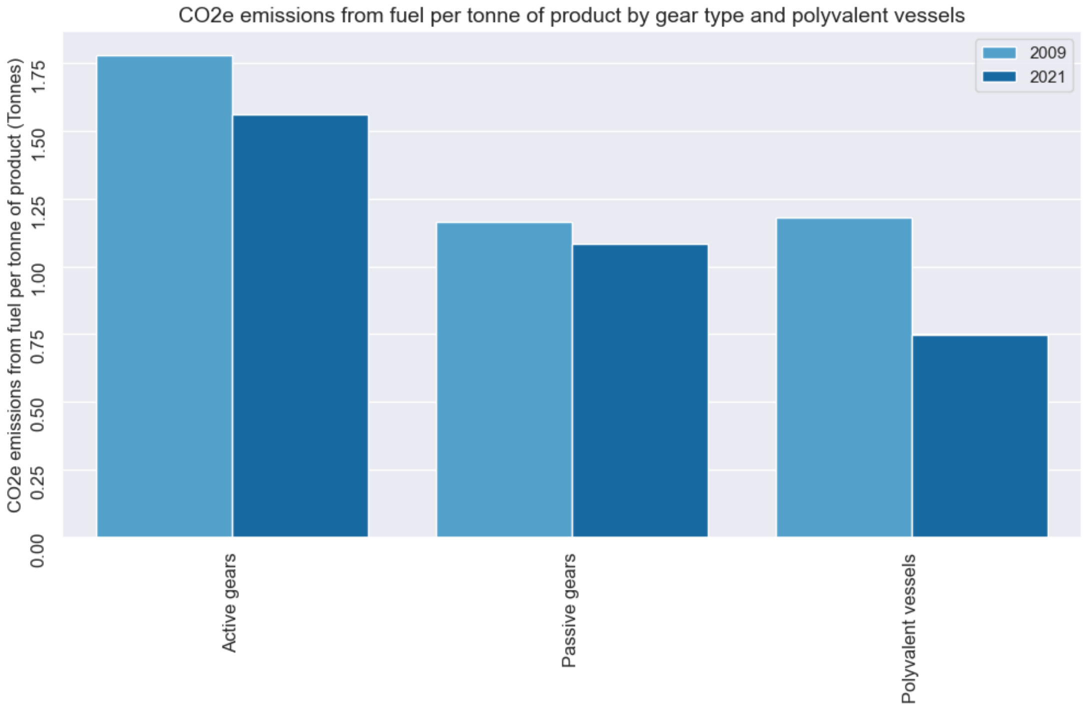
Figure 2.5 CO_2e emissions per tonne of product by vessel size in 2013 and 2023



Source: consortium elaboration based on STECF AER.

In terms of fishing gear, the total CO_2e emissions per tonne of product of all gear types have slightly decreased between 2009 and 2021. ([16])

Figure 2.6 Total CO_2e emissions by fishing gear type and polyvalent vessels in 2009 and 2021



Source: consortium elaboration based on STECF data.

([16]) Some gears have been reclassified by Member States within this time frame, including from active to passive and thus this affects the magnitude of the results. Regardless, all segments have decreased their carbon intensity.

Fleet renewal and modernisation over time can account for reductions in energy consumption, costs and emissions, as the vessels in the fleet are made more efficient. According to data extracted from the EU Fleet Register, ([17]) the average life expectancy of fishing vessels does not vary too much across different size categories of the vessel, with the life expectancy of the LSF segment being slightly longer than the rest by less than five years. This life expectancy, however, has slightly increased from 2005 (and 2009) to 2022, as can be seen in Table 2-1.

Table 2-1 below also shows that the trend across the fleet is that many more vessels are retired from the EU fishing fleet than new vessels are incorporated every year, which has led to a shrinking of the size of the fleet over time in terms of the number of vessels. ([18]) The proportion of the fleet that is renewed every year is also very small in comparison to the total size of the fleet, so in this sense natural renewal of the fleet happens at a very slow pace. As evidenced, this renewal is also slowing down over time, which is in line with the extension of lifespan of vessels.

In addition to fleet renewal in the form of vessels being retired and substituted by newer ones, fleet modernisation also happens in the shape of retrofitting and modifying engines on fishing vessels. This is relevant from an energy perspective given that these changes also imply changes on the energy consumption of the vessels. In this sense, the proportion of vessels that have been modernised or modified since 2005 had been increasing at least until 2019, which is in contrast to the otherwise downward trend in yearly fleet renewal.

Table 2-1 Summary of fishing fleet renewal trends from 2005 to 2022

Variable	2005	2009	2019	2022
Mean life expectancy SSCF	29.78 years	27.84 years (-7%)	34.62 years (+16%)	36.47 years (+22%)
Mean life expectancy LSF and DWF	33.15 years	32.76 years (-1%)	37.96 years (+15%)	43.92 years (+32%)
Number of vessels SSCF	61,902	59,464 (-4%)	58,748 (-5%)	56,481 (-9%)
Number of vessels LSF and DWF	20,065	18,024 (-10%)	15,626 (-22%)	15,295 (-24%)
Incorporated vessels SSCF	1,971 (3.18% of total)	997 (1.68% of total)	1,068 (1.82% of total)	1,046 (1.85% of total)
Incorporated vessels LSF and DWF	410 (2.04% of total)	205 (0.2034% of total)	151 (0.97% of total)	127 (0.83% of total)
Retired vessels SSCF	3,533 (5.71% of total)	1,560 (2.62% of total)	1,667 (2.84% of total)	1,291 (2.29% of total)

([17]) European Commission (2023). EU Fleet Register. Available from: https://webgate.ec.europa.eu/fleet-europa/index_en;jsessionid=JnH2kDBOv9gEfuua5gn1dhLfc_iW1-tSXAYNBr57rMwSkLw8A2bQ!-1630674640

([18]) It is possible however that the capacity of the fleet is not reduced proportionally if the vessels being incorporated are larger in terms of GT or kW.

Variable	2005	2009	2019	2022
Retired vessels LSF and DWF	853 (4.25% of total)	637 (1.07% of total)	228 (1463% of total)	194 (1.27% of total)
Modified vessels SSCF	1,139 (1.71% of total)	863 (1.34% of total)	1,201 (1.90% of total)	612 (1.00% of total)
Modified vessels LSF and DWF	236 (1.21% of total)	138 (0.21% of total)	131 (1.26% of total)	111 (1.07% of total)

Source: consortium elaboration based on EU Fleet Register data.

Table 2-2 below also summarises the number of vessels that could be retired in the future based on their age if current trends persist. It could be important to mention as well that a change in the requirements for the fleet could possibly accelerate the renewal rate, as it was the case in some Member States ([19]) after the entry into force of Directive 97/70/EC setting up a harmonised safety regime for fishing vessels of 24 metres in length and over. ([20])

Table 2-2 Summary of potential fleet renewal in 5 and 10 years

Vessel size segment	5 years (2028)	10 years (2033)
Number of vessels SSCF	28,683 (51% of current fleet)	32,157 (57% of current fleet)
Number of vessels LSF and DWF	4,874 (32% of current fleet)	5,496 (36% of current fleet)

Source: consortium elaboration based on EU Fleet Register data.

In general, it can be seen that energy costs for fishers follow the trend of fuel prices, meaning they face higher costs when fuel prices are high and lower costs when fuel prices are low. Given the prominence of energy costs in the cost structure of fisheries production, this means that the overall cost would also follow the same trends.

Despite high fuel prices being following the same trends of high energy costs, the relationship with fuel consumption (and thus its related emissions) is less straight forward. Most segments of the fleet have managed small improvements their performance measured in tonnes of CO_2e per tonne of product between 2009 and 2022, with years of high fuel prices evidencing a small decrease in fuel consumption (and thus emissions), as an effort to reduce costs.

An explanation for the decreased income of vessels during periods of high fuel prices (such as between 2011 and 2013) is that cost savings measures during these periods have translated in less economic activity overall for the sector, with the total gross value of landings decreasing during them. For larger vessels that use more fuel per kilogram of fish landed in their operations, ([21]) the increase in price could be sharp enough that it makes their operations not viable, while for (more fuel intensive) smaller scale vessels

([19]) This is the case for Spain, but it is also possible that a similar phenomenon occurred in Denmark, France, Ireland, Malta and Romania.

([20]) Ecorys (2023). Evaluation of Directive 97/70/EC setting up a harmonised safety regime for fishing vessels of 24 metres in length and over. *Forthcoming.*

([21]) With fuel use as obtained from the STECF dataset and landings cross-referenced with EUROSTAT data. Given that emissions are directly linked with fuel use, emissions per kilogram of fish landed can also be used to compare the fuel intensity of the different segments.

their smaller revenues mean these fishers would have more trouble absorbing the increased costs, especially is fish prices do not immediately increase.

That being said, the improvement of fuel efficiency across all segments is good news in terms of CO_2e emissions and for the vulnerability of the sector to fuel price shocks. This primarily happens through fleet renewal and fleet modernisation, as efficiency measures implemented have to do with vessel shape (especially in the case of new vessels), propeller design and new engine efficiency technologies, however, the pace of fleet renewal and engine modification is very slow, ([22]) with only a small fraction of the fleet being renewed every year and the new vessels and technologies applied are still reliant on the use of fossil fuels.

2.1.1. External factors affecting the EU fisheries ecosystem between 2020 and 2023.

Three main external factors have affected EU fisheries since 2020. ([23]) The first one was the outbreak of the *COVID-19 or coronavirus pandemic*, which caused Member States to take far-reaching measures to prevent the virus from spreading which for the sector meant a temporary seizure of activities (as fishers were not allowed to go out to sea) and disruptions in the sales markets.

The second external factor was the fulfilment of *Brexit*. As a consequence, fishing ports in the UK are no longer part of the internal market and EU vessels that used to land their catches in UK ports had to re-route to other ports, which often means travelling more and thus consuming more fuel. ([24]) Additionally, the loss of fishing rights by some segments of the EU fleet as a product of Brexit also reduces the income that these segments receive. Vessels active in the North Sea and Atlantic Ocean are especially affected by Brexit.

The third external factor is *Russia's unprovoked act of aggression against Ukraine* in February 2022 and the ongoing armed conflict. The conflict on the one hand leads to blockages on the Black Sea, preventing vessels from visiting some of the Black Sea ports. On the other hand, the conflict leads to scarcity, also in fossil fuels, which in turn leads to an increase in fuel prices. As these three external factors are concurrent in time, it is also hard to distinguish their separate impact on the system.

The analysis of the STECF data shows a clear impact of the shocks, especially the conflict in Ukraine, on the average fuel price which is reflected in the energy costs. Although the costs were already rising in 2021, the start of the conflict spurred the increase in fuel price and energy costs. It seems that vessels with a high fuel consumption (either due to their length or gear type used, or simply engine efficiency) are more prone and vulnerable to higher fuel prices than their counterparts with a lower fuel consumption. Examples are trawlers (using beam or demersal) and LSF which operate further ashore and therefore need more fuel. A way of mitigating part of the impact of high fuel prices is by buying fuel at times fuel prices are low and keep fuel in storage. The *2022 Annual Economic Report on the EU Fishing Fleet (STECF 22-06)* mentions that for example, fuel is collectively bought in Belgium as a strategic reserve ensuring lower prices per vessel.

([22]) As previously evidenced by EU Fleet Register data.
([23]) These external factors and their impacts have been recurrent themes in editions from the STECF Annual Economic Report in the past years.
([24]) This issue was also noted by fishing industry stakeholders.

The impact of COVID-19 on the fishing system is hard to predict. The data available are limited and do not provide much insight, nor does the available literature. Its impact however could have been less severe than expected in part due to low fuel prices, however, catch data does reflect a decrease in fishing activity in 2020, averaging an 11% decrease in the EU, but with significant variation across Member States (between 1% and 58% decreases). ([25]) It is possible that fleets in the Black Sea and Mediterranean Sea as well as the SSCF were more vulnerable, ([26]) while trawling segments seem to have been mostly spared and even in some cases seen increases in activity. ([27])

It must be highlighted that while this trend is true in general terms, differences can be present between Member States or even fishing ports (e.g. whether a fishing port relies on demand for fresh fishery products stemming from tourism could mean heavily decreased performance of its fishing fleet during COVID-19 restrictions). The general trend is possibly explained by the different markets to which each fish segment caters; while the SSCF generally focuses on fresh fish whose demand went down during the pandemic (landings decreased significantly and the gross value added and gross profits fell 4% and 5%), the LSF and DWF fleets focus on processed fish, whose demand rose, ([28]) however, this cannot be directly assessed due to lack of data even if this argument is also supported by fishing industry stakeholders interviewed.

2.2 Aquaculture

The estimation of energy use and CO_2e emission from EU aquaculture present several challenges, as this sector includes several species and farming typologies, e.g., marine species vs freshwater, furthermore, as underlined also in a very recent study on Irish seafood carbon footprint ([29]), direct emissions due to energy use often are not good proxies of the total ones, associated with the whole production process. Therefore, it is necessary to approach this task from a value chain perspective: for this reason, in this study CO_2e emissions were estimated based on the results of Life Cycle Assessment (LCA) studies, relying, as far as possible, on peer-reviewed literature, in order to ensure the transparency of the results. The methodology that was adopted, i.e., LCA, is recommended by the Aquaculture Advisory Council and is also consistent with the Product Category Rules for the estimation of seafood Product Environmental Footprint.

2.2.1 Methodological approach

An LCA models a product, service, or system life cycle. According to the ISO 14040:2006 and ISO 14044:2006 standards, the modelling includes four main steps:

- Goal and Scope
- Life Cycle Inventory (LCI)
- Life Cycle Impact Assessment (LCIA)
- Interpretation of the result

Goal and Scope. The goal requires clearly stating the reasons for conducting the analysis and the definition of the potential use and audience of an LCA case study. The scope

([25]) Dentes De Carvalho Gaspar, N., Guillen Garcia, J. and Calvo Santos, A. (2020) The impact of COVID-19 on the EU-27 fishing fleet, doi:10.2760/419959
([26]) Carpenter et al. (2023), 'The economic performance of the EU fishing fleet during the COVID-19 pandemic' in Aquatic Living Resources, 2023, 36, 2.
([27]) Dentes De Carvalho Gaspar, N., Guillen Garcia, J. and Calvo Santos, A. (2020) The impact of COVID-19 on the EU-27 fishing fleet, doi:10.2760/419959
([28]) Carpenter et al. (2023), 'The economic performance of the EU fishing fleet during the COVID-19 pandemic' in Aquatic Living Resources, 2023, 36, 2.
([29]) BIM, 2023. Carbon footprint report of the Irish food sector.

specifies the most important methodological choices, assumptions and limitations, providing: 1) a description of the product system, of its functions and the definition of the Functional Unit (FU), i.e. the quantified description of the function of a product that serves as the reference basis for assessing its impact; 2) a description of the system boundaries, of the data and data quality requirements and of the main assumption concerning the input data; 3) the methodology used in the LCIA phase, e.g., the impact categories and indicators.

Life Cycle Inventory (LCI). This stage is usually the most time-consuming, as it involves the collection of data for quantifying the flows of matter and energy across the system boundaries and, in the case of complex systems, within each unit process.

Life Cycle Impact Assessment (LCIA). This crucial step leads to the evaluation of the environmental performance of a product system, determining the relevance of the environmental impacts, based on the inventory. This goal is accomplished by associating the inventory data to a set of environmental impact categories and their corresponding indicators, through the characterisation, i.e., the conversion of the life cycle inventory results to common units and the addition of the converted results belonging to the same impact category, to obtain a quantitative result for each impact indicator. The characterisation can be conducted in accordance with different methodologies, e.g., CML, ReCiPe. The results can be post-processed by normalising and weighting the indicators.

Interpretation of the results. In this final stage, according to the goal and scope defined for the LCA study, the results of the second and third steps are summarised and discussed, to identify the most relevant issues, e.g., 'hot spots', i.e. steps of the production process which contributes most to the environmental impact and provide conclusions, e.g. alternative processes for reducing the hot spots, as well as recommendations for decision making.

In this study, aquaculture CO_2e emissions are estimated based on the results of Life Cycle Assessment (LCA) studies, relying on peer-reviewed literature to ensure transparency and robustness of the results. LCA methodology is recommended by the Aquaculture Advisory Council and is also consistent with the Product Category Rules for the estimation of seafood Product Environmental Footprint.

This study is focused on **one impact category,** Climate Change and one indicator, i.e., the **Global Warming Potential (GWP), expressed as mass of CO_2e**. Therefore, CO_2e emissions were quantified in four steps:

1) the most important species farmed in the EU and the main farming typologies were selected, based on publicly available data.
2) a literature search was conducted: peer-reviewed papers concerning the application of LCA to the aquaculture production processes identified in step one was searched and screened, in order to select the most reliable sources;
3) the consistency of the results presented in the papers used for quantifying the emissions was checked using a purposely developed LCA model portfolio, which was subsequently used in the Techno-Economic analysis for assessing the cost-effectiveness of the innovations aimed at reducing CO_2e emissions: this step led to estimate the emission intensities, i.e.CO_2e per tonne of product, for each species, farming typology and, whenever necessary, the most important EU producing countries .
4) the total emissions for each species for the reference year 2019 were estimated based on the emission intensities and the production volumes.

The role of "biogenic" carbon, i.e., CO_2 which can be released or captured due to the physiological activity of farmed organisms was not considered. This contribution could be important for shellfish: however, on one side, the biogenic carbon budget can be estimated using different approaches (Feng & al., 2023, Bertolini & al., 2023) and on the other, from an LCA perspective, the assessment strongly depends on the end of life of the products. This choice is also consistent with the scope of this study, which is to indicate how the energy transition could contribute to reducing CO_2e emissions from the aquaculture sector.

Aquatic species are farmed in the EU both in-shore and near-shore/off-shore. Therefore, they were grouped into-two segments, namely: S1: Marine Aquaculture and S2: Land-based aquaculture. Each segment was then partitioned into two sub-ones, in order to distinguish between intensive and semi-intensive/extensive farming practices, as summarised in Table 5.3. Intensive fish farming systems require higher feeds and energy inputs from the 'Technosphere' and are usually characterised by higher biomass yields per space unit (surface/ volume), compared with semi-intensive and extensive ones. In the latter the growth of farmed organisms is partially or totally supported by resources provided by the surrounding environment. In S1, extensive farming includes shellfish, which do not require any feeding: in perspective, seaweed farming could become relevant: these productions are grouped into sub-segment S1.1. Low Trophic Aquaculture species. Intensive marine fish farming is usually conducted in cages, sub-segment S1.2. Land-based farming includes only fish, again partitioned based on farming intensity.

Table 2-3 lists the segments included in this study. In addition, illustrative pictures can be found in Annex B with examples of different typologies considered in this study.

Table 2-3 Aquaculture segments considered in this study.

Segment	Aquaculture typologies
S1 Marine Aquaculture	S1.1 Low Trophic Aquaculture (extensive, non-fed) S1.2 Intensive Cage Culture (fed)
S2 Land-based Aquaculture	S2.1 Extensive (non-fed) /Semi-intensive systems e.g., ponds (fed) S2.2 Intensive systems, e.g., raceways, RAS (fed)

Table 2-4 summarises the main commercial species farmed in the EU which account for the bulk of the production. Volumes and values in the pre-pandemic year 2019, are given in the second and the third column, the main producers in the fourth one. This study focuses on energy use and CO_2e emissions related to the farming of these species and producers Which accounted for 92% of the EU production volume in 2019.

Table 2-4 Production volumes and values for the commercial species selected for estimating the current status of energy use and CO_2e emissions in the EU.

Species	EU production 2019 [tonnes/year]	EU production 2019 – Value [Million Euros /year]	Main EU Producers [tonnes/year]
S1.1. Mussel	453,459	423	Spain (228,195), France (60,255), Italy (52,547), Netherlands (38,094)
S1.1 Oyster	101,683	459	France (85,947)
S1.1 Clam	32,734	246	Italy (25,995)
S1.2 Gilthead seabream	92,476	468	Greece (55,500), Spain (12,475)
S1.2 European seabass	83,872	477	Greece (41,255), Spain (25,260)
S2.1 Common carp	80,195	175	Poland (20,001), Czech Rep. (19,039), Hungary (12,804)
S2.2 Rainbow trout	196,837	691	Italy (38,906), France (35,097), Denmark (30,904)
Total selected species.	**1,041,256**	**2,939**	
EU Total	**1,128,309**	**3,697**	

In agreement with Jones and coauthors 2022 research (and the large majority of LCA studies), aquaculture production processes can be partitioned into three phases, namely: 1) upstream, 2) grow-out; and 3) downstream. ([30]) This approach is also consistent with the evaluation of the Product Environmental Footprint of seafood. The Footprint is based on a LCA analysis, which should be carried out in accordance with and harmonised approach, defined by the Product Category Rules. ([31]) As was mentioned, the same commercial species can be farmed in different ways: the main farming typologies and processes pertaining to each of the three phases are summarised in Table 2-5. Table 2-6 presents the Functional Unit used as a reference for the emission intensities.

Table 2-5 Main processes involved in the supply chains of the species considered in this study and the selected Functional Units, i.e., the reference units for estimating the CO_2e emission intensities using the LCA methodology.

Production Stage	Source of emissions	Mussel	Oyster	Clam	Seabass & Seabream	Carp	Rainbow Trout
Upstream	Recruitment of wild seeds	ü	×	×	×	×	×
	Production of seeds in hatcheries.	ü	ü	ü	×	×	×
	Transport of seeds to farms	ü	ü	ü	×	×	×
	Production of juveniles in hatcheries.	×	×	×	ü	ü	ü
	Fish feed production.	×	×	×	ü		ü
	Transport of feed and juveniles to fish farms.	×	×	×	ü	×	ü

([30]) Jones, A.R., H. K. Alleway H.K., McFee D., Reis-Santos P., Theuerkauf, S. J. and Jones, R.C, 2022. Climate-Friendly Seafood: The Potential for Emissions Reduction and Carbon Capture in Marine Aquaculture. Bioscience, 72: 123–143.

([31]) Supporting studies to define them can be found at https://www.marinefishpefcr.eu/supporting-studies.

Grow-Out	Seed fattening using four main systems: raft; bouchot; long-line; seeding in shallow areas for bottom culture.	ü	×	×	×	×	×
	Harvesting	ü	ü	ü	ü	ü	ü
	Seed pre-fattening and fattening in trestles, used in intertidal areas: long-line.	×	ü	×	×	×	×
	Seed pre-fattening in suspended systems and bottom culture in leased areas.	×	×	ü	×	×	×
	Fattening of juveniles In fish cages located in coastal areas.	×	×	×	ü	×	×
	Fattening of juveniles in ponds. Feed is supplied in semi-intensive carp farming.	×	×	×	×	ü	×
	Pond maintenance.	×	×	×	×	ü	×
	Fattening of juveniles in Flow Through Systems, e.g., raceways Recirculation Aquaculture Systems (RAS).	×	×	×	×	×	ü
Downstream	Depuration of farmed species in Class B waters.	ü	ü	ü	×	×	×
Note: ü and × indicate relevance to each sector							

Table 2-6 Main commercial species and functional unit

Species	Functional Unit
Mussel	1 tonne of mussel, ready to be commercialized.
Oyster	1 tonne of oyster, ready to be commercialized.
Clam	1 tonne of clam, ready to be commercialized.
Seabass & Seabream	1 tonne of seabass/seabream, at farm gate.
Carp	1 tonne of carp, at farm gate.
Rainbow Trout	1 tonne of rainbow trout, at farm gate.

As shown in Table 2-5, this study focuses on the upstream and grow-out phases, However, to ensure the comparability of the Functional Units, the depuration stage was also included for shellfish, which can be farmed both in Class A and Class B waters as defined in the EU Regulations No 854/2004. The classification is based on the concentration of faecal bacteria: shellfish farmed in Class A water can be commercialised after harvesting and those farmed in Class B require, at least, a depuration stage.

2.2.2 Historic energy use, cost and associated emissions (2009 – 2019)

CO_2e emissions from the farming of the commercial species listed in Table 2-4 were inventoried for the period 2005-2019 based on a thorough literature review using species-specific keywords. The search was conducted on the Scopus database and Google Scholar. The results of the automatic search were manually screened to extract papers dealing with EU case studies:

Segment 1, the highest number of papers (19) concerns mussel production, which is also the most important EU one, in volume. Clams (3) and oysters (5) were less investigated. European seabass and gilthead seabream, 10 and 5 papers, respectively, are farmed in similar systems and very often co-farmed on the same site. Therefore, the literature provides a sound basis for assessing CO_2e emission intensities and energy use in the grow-out phase for these species. Segment 2, trout farming, has been investigated using LCA since 2006: 13 LCA studies were found. Carp production seems the least investigated, with **only one study presenting results concerning an EU case study**.

These papers were further scrutinized and those to be used for estimating the EU CO_2e emissions were finally selected. Data presented in the selected papers were harmonized and, checked for consistency using the LCA model portfolio. LCA models for each species and farmed typologies were developed, based on the data presented in the inventories of these papers. The model results were then compared with the published ones. Whenever major differences were found, the corresponding authors were contacted for clarification. The results are presented in the following for each species and farming typology.

S1.1 Mussel

Mussels account for the bulk of EU aquaculture production in volume, about 40% in 2019. This commercial species is farmed in several EU countries using different rearing systems, as summarised in Table -2-7: floating rafts are used in Spain, which accounted for 50% of the EU production in 2019. The second most important farming system is long line, in use in Italy and France, among other EU MS. 'Bouchot' culture is specific to France's intertidal areas. Mussel bottom culture is practised in the Netherlands and Ireland.

Mussel – floating rafts

This farming system is typical of Galicia, Spain, which accounts for 90% of Spanish production ([32]) Mussels farmed in rafts require depuration before being commercialised as fresh mussels. Furthermore, the mussel canning industry is important in Spain: therefore, we included in the analysis three products:

- Fresh mussels, ready to be commercialised.
- Canned mussels.
- Cooked mussels.

This production system was thoroughly investigated in a number of papers which, however, were published more than a decade ago. Therefore, the results were critically reviewed and, whenever necessary, updated, based on more recent findings. According to Iribarren and coauthors the total emissions associated with the production of 100 kg of mussels ready to be commercialised was equal to 153.83 kg CO_2e, i.e., 1.54 kg [CO_2e/kg mussel lw].[17] This estimate was based on the following processing percentages: fresh, depurated mussels: 40%; Canned mussels: 35%; Cooked mussels: 25%. The data presented were normalised to estimate the CO_2e intensities for each downstream process listed in Table -2-7. ([33])

([32]) EUMOFA. The EU fish market - 2022 Edition, 2023
([33]) Iribarren D.; Moreira M.T.; Feijoo G., 2010a. Life Cycle Assessment of fresh and canned mussel processing and consumption in Galicia (NW Spain). Resources, Conservation and Recycling, 55: 106–117.

Table -2-7 Downstream CO_2e emission intensities, according to the following share of product minimal processing: 40% fresh mussel, 35% Canned, 25% Cooked (34).

Fresh depurated mussel [CO_2e/kg]	Canned mussels [CO_2e/kg]	Cooked mussels [CO_2e/kg]
2.38	0.261	0.298

Table -2-7 shows that fresh mussels,, accounted for a much higher CO_2e per tonne, compared with canned and cooked mussels: this was due to the low technological level of depuration and dispatch centres Therefore, to quantify the CO_2e emissions for the reference year 2019, it was assumed that the technology used for mussel depuration has improved in the last 25 years and is now similar to that used in Italy for the same purpose. According to Martini and coauthors 0.104 [CO_2e/kg]. (35) Furthermore, due to the start of massive mussel farming in Chile, the canning and cooking industry has diversified its sources and is currently processing about 37% of Spanish production, (36), compared with 60% in 2008. As this report does not provide details about mussel processing, we assumed that the emission related to the downstream phase is 0.28 [kg CO_2e/tonne mussel], which is the average of the two values given in the second and third columns of Table 2-6 Energy use was estimated based on diesel consumption of 15.56 [mL/kg mussels] as electricity, 2.7 [MJ/kg mussels] was used mainly for infrastructure. A maritime diesel energy density of 43.2 [MJ/kg] was used (see Annex B. Based on these assumptions, the current CO_2e emissions and energy use for raft fresh mussel production are summarised in Table 2-8, which presents in the first three columns the CO_2e emissions related to the three production stages described in Table 2-5 and in the fourth one the total emissions referenced to the Functional Unit (FU), i.e. per tonne of fresh mussels, ready to be commercialized. The total energy use, expressed as kWh referenced to the FU and the CO_2e emissions due to the direct energy use in grow-out are given in the last two columns.

Table 2-8 Emission intensities (upstream, grow-out, downstream, total) and direct energy use in grow-out per Functional Unit (FU), e.g., 1 tonne of fresh mussels, depurated, ready to be commercialised.

Source	Up-stream-Hatchery [tonne/FU]	Grow-out CO_2e [tonne /FU]	Down-stream (Depuration)	CO_2e per FU [tonne/FU]	Energy use/FU [kWh/FU]	CO_2e due to energy use [tonne /FU]
Irribarren&al., 2011, Martini&al., 2022	0	0.428	0.104	0.532	157	0.03

(34) Iribarren D.; Moreira M.T.; Feijoo G., 2010a. Life Cycle Assessment of fresh and canned mussel processing and consumption in Galicia (NW Spain). Resources, Conservation and Recycling, 55: 106–117.

(35) Martini A.; Calì M.; Capoccioni F.; Martinoli M.; Pulcini D.; Buttazzoni L.; Moranduzzo T.; Pirlo G. 2022. Environmental performance and shell formation-related carbon flows for mussel farming systems. Sci. of the Total Environment, 831 (2022) 154891

(36) EUMOFA. The EU fish market - 2022 Edition, 2023

Mussel – bouchot

This farming system is adopted in France, in intertidal areas. The total French bouchot production in 2019 was about 50,000 tonnes. ([37]) The results concerning CO_2e emissions are summarised in Table 2-9. ([38])

Table 2-9 Emission intensities (upstream, grow-out, downstream, total) and direct energy use in grow-out per Functional Unit, e.g., 1 tonne of fresh mussels, depurated, ready to be commercialised.

Source	Up-stream-Hatchery [tonne/FU]	Grow-out CO_2e [tonne/FU]	Down-stream (Depuration)	CO_2e per FU [tonne/FU]	Energy use/FU [kWh/FU]	CO_2e due to energy use [tonne/FU]
Aubin&al., 2018	0	0.325	0	0.325	Not available	0.188

Mussel – long-lines

This suspended farming system is the most widespread one in the EU, except in Spain. CO_2e emissions were recently estimated, based on data concerning typical Italian farms located in Italy, Northern Adriatic in both Class A and Class B waters. ([39]) Shellfish farmed in Class A waters can be commercialised after harvesting, without any further processing, those farmed in Class B need to be depurated, which implies further economic and environmental costs, as seen for the raft cultivation method. On the other hand, the distance from the coast of farms located in A waters is higher, which implies a higher use of fossil fuel per harvested tonne of mussel. Even though the Italian production in Class B waters is small, the paper provides interesting insights into the emissions related to depuration. The main findings of the paper are summarised in Table 2-10. The emission intensity for Class A waters concerns a farm about 6 nm from the shore: according to Martini and coauthors, this is not the average distance but an upper limit. ([40]) Therefore, the CO_2e emissions listed in Table 2-10 are also likely to represent an upper limit: in order to estimate the total emissions from longline mussel farming, the fuel use was linearly rescaled assuming an average distance of 3 nm, thus obtaining the estimated presented in the third row of Table 2-10.

([37]) EUMOFA. The EU fish market - 2022 Edition, 2023.

([38]) Aubin, J., C. Fontaine, M. Callier, & E. Roque d'orbcastel. Blue mussel (Mytilus edulis) bouchot culture in Mont-St Michel Bay: potential mitigation effects on climate change and eutrophication. Int J Life Cycle Assess (2018) 23:1030–1041 DOI 10.1007/s11367-017-1403-y

([39]) Martini A.; Calì M.; Capoccioni F.; Martinoli M.; Pulcini D.; Buttazzoni L.; Moranduzzo T.; Pirlo G. 2022. Environmental performance and shell formation-related carbon flows for mussel farming systems. Sci. of the Total Environment, 831 (2022) 154891

([40]) Martini A.; Calì M.; Capoccioni F.; Martinoli M.; Pulcini D.; Buttazzoni L.; Moranduzzo T.; Pirlo G. 2022. Environmental performance and shell formation-related carbon flows for mussel farming systems. Sci. of the Total Environment, 831 (2022) 154891

Table 2-10 Emission intensities (upstream, grow-out, downstream, total) and direct energy use in grow-out per Functional Unit, e.g., 1 tonne of fresh mussels, ready to be commercialised, farmed on long-line systems.

Source	Up-stream-Hatchery [tonne/FU]	Grow-out CO_2e [tonne/FU]	Down-stream (Depuration)	CO_2e per FU [tonne /FU]	Energy use/FU [kWh/FU]	CO_2e due to energy use [tonne/FU]
Class A Martini&al., 2022*	0	0.391	0	0.391	1,000	0.308
Class B Martini&al., 2022*	0	0.186	0.104	0.290	265	0.100
Class A Representative farm 3nm offshore	0	0.237		0.237	500	0.154

*The corresponding author communicated that the figures published in the paper were not correct. An "Errata corrigendum" is being sent to the Journal. Figures in Table 2-10 are based on her communication.

Mussel – bottom culture

Mussel bottom culture is practised in the Netherlands, Belgium and Ireland. No peer-reviewed paper concerning this farming typology was found. Estimates given in Table 2-11 and Table 2-12 are based on a recent report concerning Irish seafood's carbon footprint. ([41])

Table 2-11 Emission intensities (upstream, grow-out, downstream, total) and direct energy use in grow-out per Functional Unit, e.g., 1 tonne of fresh mussels, ready to be commercialised, harvested from bottom culture.

Source	Up-stream-Hatchery [tonne/FU]	Grow-out CO_2e [tonne/FU]	Down-stream (Depuration)	CO_2e per FU [tonne/FU]	Energy use/FU [kWh/FU]	CO_2e due to energy use [tonne/FU]
BIM, 2023	0	0.824	0	0.824	Not available	0.820

Total EU emissions from mussel culture in 2019 were estimated by cumulating the results given in the previous tables based on the following assumptions: 1) raft production accounted for 90% of the Spanish one; 2) Bouchot production was 50,000 tonnes; 3) all Netherlands production came from bottom culture; 4) the remaining EU production came from long-line located in Class A areas. The results are summarised in Table 2-12.Table 2-12 which presents the production volumes in the second column and the CO_2e emissions for each mussel farming typology in the third one. The total EU emissions are given in the last row.

([41]) BIM, 2023. Carbon footprint report of the Irish food sector.

Table 2-12 Estimated CO_2e emissions from mussel culture in the EU in 2019.

Production system	Production [tonne]	CO_2e emissions [tonne]
Raft culture – Fresh (Spain)	129,387	**68,834**
Raft culture – Processed (Spain)	75,989	**53,800**
Bouchot (France)	50,000	**16,250**
Bottom (Netherlands)	38,094	**31,389**
Longline (Italy and other MS)	159,989	**37,917**
Total	453,459	**208,190**

S1.1 Oysters

Oysters are the most important EU shellfish product in value and the second one in volume. France is, by far, the most important producer, accounting for 84.5% of the EU production. Oysters are traditionally farmed in France in trestles in intertidal areas, this farming method was also adopted in Ireland and Scotland. This species can also be farmed in suspension, using infrastructure similar to long line for mussels. This production system is adopted in Mediterranean lagoon and coastal areas, where the tidal amplitude is much lower, compared with the Atlantic ones. Based on the results of the literature search, no peer-reviewed papers concerning oyster farming in France were found, this gap and also the lack of non-peer-reviewed studies were confirmed by the targeted interviews, see Annex D." The urgent need to fill it was, in fact, clearly stated by the French Committee for Shellfish Farming (*Comité National de la Conchyliculture*), which sees as highly desirable "a full LCA assessment at national level in order to work on the most emissive components along the value chain." Therefore, the estimates summarised in Table 2-13 are taken from a recent report concerning the carbon footprint of Irish seafood. ([42]) The figures provided in Table 2-14 **are very likely underestimating the carbon footprint and energy use in bottom oyster farming, as seed production in hatcheries was not considered in the BIM report**. As Irish and French oysters' production processes are similar, we assumed that the estimates given in Table 2-14 apply to both countries' production, as well as to Dutch production. We also assumed that the remaining 2019 production was conducted in suspension systems. The CO_2e emissions from long-line oyster production were estimated by Tamburini and coauthors in 2019. ([43]) this study included seed production in a hatchery and the depuration stage, as well as the pre-fattening and fattening stages at sea. However, the inventory given in the paper is not consistent with the results: the input data were corrected and CO_2e emissions were estimated using the model portfolio, which gave a total CO_2e emissions of 0.546 [tonne CO_2e/ tonne oysters]. The total CO_2e emissions for each system and for the EU oyster production are given in Table 2-14.

([42]) BIM, 2023. Carbon footprint report of the Irish food sector.
([43]) Tamburini, E., Fano, E.A., Castaldelli, G., Turolla, E. 2019. Life Cycle Assessment of Oyster Farming in the PoDelta, Northern Italy. Resources, 8, 170; doi:10.3390/resources8040170

Table 2-13 Emission intensities (upstream, grow-out, total) and direct energy use in grow-out per Functional Unit, e.g., 1 tonne of bottom cultured oysters, depurated, at farm gate.

Source	Upstream-Hatchery [tonne/FU]	Grow-out CO_2e [tonne/FU]	Downstream - Depuration	CO_2e per FU [tonne/FU]	Energy use/FU [kWh/FU]	CO_2e due to energy use [tonne/FU]
BIM, 2023	0	0.162	0.073	0.235	Not available	0.132

Table 2-14 Estimated CO_2e emissions from EU oyster farming in 2019.

Production system	EU Production 2019 [tonne]	CO_2e emissions [tonne]
Bottom culture [1]	96,301	22,631
Suspended [2]	5,382	2939
Total	101,683	**25,570**

S1.1 Clams

Clam is the third commercial shellfish species in volume produced in the EU. The main producer is Italy, which accounts for 79% of the production, followed by France and Spain. Clams are farmed in coastal lagoons: seeds are caught in the wild or produced in hatcheries. The literature concerning the carbon footprint of this commercial species is quite limited. The results which are presented hereafter, are based on three papers recently published concerning clam bottom farming in Italy. An interesting paper, focused on the hatchery stage, was recently published. ([44]) The hatchery contribution, see Table 2-15, was calculated by dividing the emissions of 1 kg of seeds (26.3 CO_2e) by the final biomass yield of 120 kg of commercial-size clams. Clam seeds can also be recruited from wild stocks, but wild seed availability has rapidly decreased in the last few years. Therefore, a growing number of farmers are relying on hatchery seeds. Unfortunately, other studies, which investigated the same system, provide inconsistent estimates of energy use and total CO_2e emissions related to the clam grow-out. ([45]) Furthermore, no estimate concerning the depuration step is given in these papers. Therefore, based on the precautionary principle, the higher value given in Turolla's research is used in Table 2-15. ([46]) Based on the same principle, EU Clam GHG emissions Table 2-16, were calculated assuming that they are produced using seed from hatcheries. As one can see, seed production leads to a marked increase in the estimated CO_2e emissions, confirming the need for further studies concerning oyster farming, as underlined in the previous section.

([44]) Martini, A., L. Aguiari, Capoccioni, F., Martinoli M., Napolitano, R., Pirlo, G., Tonachella, N., Pulcini, D., 2023. Is manila clam farming environmentally sustainable? A Life Cycle Assessment (LCA) approach applied to an Italian Ruditapes philippinarum hatchery. Sustainability, 15, 3237. https://doi.org/10.3390/su15043237

([45]) Turolla, E., Castaldelli, G:, Fano, E.A, Tamburini E., 2020. Life Cycle Assessment (LCA) Proves that manila clam farming (Ruditapes Philippinarum) is a fully sustainable aquaculture practice and a carbon sink. Sustainability, 12, 5252; doi:10.3390/su12135252.

([46]) Turolla, E., Castaldelli, G:, Fano, E.A, Tamburini E., 2020. Life Cycle Assessment (LCA) Proves that manila clam farming (Ruditapes Philippinarum) is a fully sustainable aquaculture practice and a carbon sink. Sustainability, 12, 5252; doi:10.3390/su12135252.

Table 2-15 Emission intensities (upstream, grow-out, total, downstream) and direct energy use in hatchery per Functional Unit, e.g., 1 tonne of clams, depurated, at farm gate.

Sources	Upstream-Hatchery CO_2e [tonne/FU]	Grow-out CO_2e [tonne/FU]	Down-stream - Depuration	CO_2e per FU [tonne/FU]	Energy use/FU [kWh/FU]	CO_2e due to energy use [tonne/FU] *
Martini&al., 2023 Turolla&al., 2020	0.219	0.076	Not available	0.295	463	0.199

* The energy use and associated CO_2e emissions are related to the seed production in a hatchery.

Table 2-16 Estimated CO_2e emissions from EU clam farming in 2019.

Production system	EU Production 2019 [tonne]	CO_2e emissions [tonne]
Bottom culture	32,734	9,657

S1.2 Gilthead seabream and European seabass

Gilthead seabream (*Sparus aurata*) and European seabass (*Dicentrarchus labrax*) are the two main products of EU marine fish farming. Together these species accounted for 15% of the EU aquaculture production in 2019 in volume and 26% in value. Seabass and seabream are farmed in cages: infrastructures, daily husbandry practices and very often also feeds are similar and, therefore, most companies farm both species, adapting the production to the market demand. Farms are located along the Mediterranean coasts: as can be seen from Table 2-4, Greece is the main producer, followed by Spain. For this reason, several LCA studies include the assessment of the environmental impact of both species. Compared with shellfish farming, cage farming requires higher investment costs, e.g., cages, anchoring infrastructure, nets and operational costs related to feed and feeding. As a result, energy use and CO_2e emissions are higher than shellfish ones per unit of biomass produced. The results presented in this subsection are based on three comprehensive studies by Kallitsis and coauthors in 2020 ([47]); Garcia and coauthors in 2016 ([48]); and Garcia and coauthors in 2019 ([49]) focused on typical Greek and Spanish farms.

Seabream

The results given in the source papers are summarised in Table 2-17. The energy use provided by Kallitsis includes the contribution of electricity, as fuel consumption accounted for 530.5 [kWh/tonne]. Concerning the Spanish production, the CO_2e emissions related to feed and to the grow-out phase were estimated based on the contribution analysis presented in Garcia's 2016 research, according to which feed accounted for 71% of the emissions. The remaining 21% was entirely due to fuel use. The energy use in the grow-out was estimated based on diesel consumption per tonne of seabream, 443 kg, given in (Garcia&al., 2016) converted in kWh using an energy density of 12 [kWh/kg].

([47]) Kallitsis E.; Korre A.; Mousamas D.; Avramidis P. 2020. Environmental life cycle assessment of mediterranean sea bass and sea bream. Sustainability, 12, 9617; doi:10.3390/su12229617
([48]) García B.G.; Jiménez C.R.; Aguado-Giménez F.; García J.G., 2016 Life cycle assessment of gilthead seabream (*Sparus aurata*) production in offshore fish farms. Sustainability. 8, 1228; doi:10.3390/su8121228
([49]) García, B.G.; Jiménez, C.R.; Aguado-Giménez, F.; García, J.G., 2019 Life cycle assessment of seabass (Dicentrarchus labrax) produced in off_shore fish farms: Variability and multiple regression analysis. Sustainability 11, 3523; doi:10.3390/su11133523

Table 2-17 Emission intensities (upstream, grow-out, total) and direct energy use in grow-out per Functional Unit, e.g., 1 tonne of seabream, live weight at farm gate.

Source	Upstream-feed CO_2e [tonne/FU]	Grow-out CO_2e [tonne/FU]	CO_2e per FU [tonne/FU]	Energy use/FU [kWh/FU]	CO_2e due to energy use [tonne/FU]
Kallitsis&al., 2020	3.061	0.924	3.985	1270	Not available
Garcia&al., 2016	5.058	2.066	7.124	5316	1.995

As one can see from Table 2-17, there are marked differences, both in the upstream emissions due to different feeds and FCR – Feed Conversion Ration and energy use during grow-out, which is due mainly to fuel use for the boats which deliver fish feed: for offshore fish farms in Spain, fuel accounts for 98% of grow-out emissions. The major difference between the energy use estimated in the two studies is related to the distance from the land-based infrastructure of the two fish farms. In fact, the distances from the nearest landing points for Greece and Spain estimated using GIS and Google maps, were Spain 6.32 Km, Greece 0.9 Km, Italy 4.28 Km. The specific farm investigated in (Garcia&al., 2016) was about 5 km from the coast.

Therefore, EU emissions concerning 2019 presented in Table 2-17 were estimated based on the following assumptions: 1) Greece, Table 2-17; 2) Spain, Table 2-17; 3) Italy: feed contribution based on Kallitsis&al., fuel contribution based on linear interpolation, taking as independent variable the average distance from the coast: this gives 4.935 tonnes CO_2e/tonne of seabream live weight; 5) Rest of Europe based on the average emission intensities estimated for the three main producers, i.e. 5.348 tonnes CO_2e/tonne of seabream.

Table 2-18 Estimated CO_2e emissions from EU seabream farming in 2019.

Country	Production 2019 [tonne]	CO_2e emissions [tonne]
Greece	55,500	221,168
Spain	12,475	88,872
Italy	6,783	33,475
Rest of the EU	17,718	81,415
EU	92,476	**424,930**

Seabass

Estimates for seabass CO_2e emission are close to seabream ones, as they are often farmed on the same site and husbandry practices and feeds are similar. The results for emission intensities are presented in Table 2-19. Energy uses were estimated as seabream ones. Based on the research of Garcia and coauthors the production of 1 tonne of seabass required 511 kg of diesel, which means 6103 kWh, Furthermore, 26% of the total CO_2e emissions were due to fuel use and 68% to feed production. On the other hand, Kallitsis et al. (2020) reported a fuel energy use of 803 kWh and lower emissions of seabass, compared with seabream This can be explained by the lower Feed Conversion Ratio (FCR), i.e., 1.8 for seabass and 2.5 for seabream. This leads to marked decrease in the use of feed and, therefore, to the emissions related to feed production. This is an important point, as the digitalization of Mediterranean cage farming and the implementation of management practices based on precision fish farming could play a major role in reducing this important performance indicator. As Spain and Greece accounted for 80% of the EU production, the EU emissions were estimated based on the data given in Table 2-19, assuming an average emission intensity estimated from those of the two top producers, i.e. 5.329 [tonne CO_2e/tonne seabass]. The results are presented in Table 2-20, which shows the relatively high contribution of the Spanish production, about 45%, related to 30% of the volume, which could be markedly reduced by decreasing the upstream emission intensities, i.e., feed and decarbonising the propulsion of serving vessels.

Table 2-19 Emission intensities (upstream, grow-out, total) and direct energy use in grow-out Functional Unit, e.g., 1 tonne of seabass live weight at farm gate.

Source	Upstream-feed CO_2e [tonne/FU]	Grow-out CO_2e [tonne/FU]	CO_2e per FU [tonne/FU]	Energy use/FU [kWh/FU]	CO_2e due to energy use [tonne/FU]
Kallitsis&al., 2020	2.269	1.095	3.365	1543	Not available
Garcia&al., 2016	4.959	2.334	7.293	6103	1.896

Table 2-20 Estimated CO_2e emissions from EU seabass farming in 2019.

Country	Country Production 2019 [tonne]	CO_2e emissions [tonne]
Greece	41,255	138,823
Spain	25,260	184,211
Rest of the EU	17,357	92,495
Total EU	83,872	**415,529**

S2.1 Common Carp

Common carp is a traditional activity in Central European countries and France, where it is farmed in earthen ponds, both extensively and semi-intensively. The production cycle takes years, as this species grows in spring-summer. Ponds are fertilised at the beginning of the spring, prior to stocking, in order to boost primary and secondary production. Feed, cereal-based, can be added, to increase the stocking density. LCA literature concerning carp production in the EU is still limited. According to the only paper we found, the CO_2e emission intensity related to conventional carp farming seems quite high compared with other intensive farming typologies. ([50]) Emissions are due to pond maintenance, in particular pond dredging, which accounted for 40% of the emissions. However, based on targeted interviews, this practice does not seem to be widely used. Therefore, the results, summarised in Table 2-21 may not be representative and are likely to overestimate CO_2e emissions from carp production.

([50]) Biermann, G., & Geist, J., 2019. Life cycle assessment of common carp (Cyprinus carpio L.) – A comparison of the environmental impacts of conventional and organic carp aquaculture in Germany. Aquaculture 501: 404–412

Table 2-21 Emission intensities (upstream, grow-out, total) and direct energy use in grow-out per Functional Unit, e.g., 1 tonne of carp, live weight at the farm gate. NB: the data presented here may not be representative of the CO_2e emissions of carp production due to a lack of reliable data sources.

Source	Upstream- feed CO_2e [tonne/FU]	Grow-out CO_2e [tonne/FU]	CO_2e per FU [tonne/FU]	Energy use/FU [kWh/FU]	CO_2e due to energy use [tonne/FU]
Biermann&Geist, 2019	1.326	4.674	6.0	9877	2.4

Based on the total carp production in 2019, the following estimates were obtained and presented in Table 2-22:

Table 2-22 Estimated CO_2e emissions from common EU carp farming in 2019.

Production system	EU Production 2019 [tonne]	CO_2e emissions [tonne]
Earthen ponds	80,195	**481,170**

S2.2 Rainbow trout

Rainbow trout is the most relevant species farmed in the EU in volume, see Table 2-4. It is farmed in several EU MS, the main producers in 2019 being Italy, France and Denmark. Trout is farmed in two systems: intensive Flow Through Systems (FTS) and Recirculation Aquaculture Systems (RAS).

The former takes freshwater from rivers or uses groundwater, which is then discharged into receiving surface waterbodies. In the first case, the influent provides oxygen, thus reducing the need to introduce liquid oxygen or enhancing the oxygen exchange with the atmosphere using aerators. In RAS, water is recirculated, thus energy is required for water pumping and for treating and re-oxygenating the effluent from the fish tanks before reusing it as influent. On the other hand, a RAS provides the possibility of extracting matter and energy from both fish sludge and wastewater and reduces the water withdrawal by about 90%, compared with FTS. The carbon footprint of trout farmed in FTS was estimated using LCA in several papers. However, inventories of matter and energy were not given in all studies. Therefore, energy requirements and CO_2e emissions were estimated based on the four studies listed in the first column of Table 2-23. As the farming systems are similar in the EU MS, the findings provided by these papers were averaged, to estimate the current energy use and CO_2e emission in the EU.

Table 2-23 Emission intensities (upstream, grow-out, total) and direct energy use in grow-out per Functional Unit, e.g., 1 tonne of trout, live weight at farm gate produced in FTS.

Source	Upstream-feed CO_2e [tonne/FU]	Grow-out CO_2e [tonne/FU]	CO_2e per FU [tonne/FU]	Energy use/FU [kWh/FU]	CO_2e due to energy use [tonne/FU]
Maiolo&al., 2021	2.022	0.806	2.828	1035	0.53
Samuel-Fitwi&al, 2013	1.640	1.922	3.562	2554	1.89
Sanchez-Matos&al., 2023	1.272	0.507	1.779	1095	0.29
Wind&al., 2022	1.180	0.630	1.810	238	0.25
Average	1.528	0.966	2.495	1220.5	0.74

In 2018 the rainbow trout production from RAS was 16,471 tonnes. RAS. ([51]) Energy use in RAS presents a high variability, ranging from 2.9 to 81 kWh/kg fish ([52]) and technological improvements, driven also by the rapid increase of the Norwegian post-smolt production in RAS, are likely to have decreased the energy use estimated in. ([53]) Therefore, the on-site energy use in RAS was reviewed, based on targeted interviews, reports and qualified, non-peer-reviewed studies. The data presented by Nistad in 2020 suggest that the average on-site energy use is about 8.8 kWh/kg salmon smolt: this average is based on a comprehensive collection of field data concerning Norwegian RAS. ([54]) Therefore, since the RAS plant for farming Atlantic salmon and rainbow trout are not very different, it was assumed that this estimate is closer to the current energy use in rainbow trout RAS farming in the EU then that given in the research by Samuel-Fitwi and coauthors, i.e. about 19.600 kWh/kg of trout. Based on the work of Nistad the CO_2e emissions due to grow-out in RAS is close to 7 [tonne CO_2e/tonne trout]: assuming the contribution of feed to the CO_2e would be the same for both FTS and RAS, the data presented in the second row of Table 2-24 were obtained. The results are summarised in Table 2-25, which gives the CO_2e emissions for the two production systems, assuming that RAS production in 2019 was equal to that in 2018: as one can see, the contribution of RAS production is around 20% of the total emission from rainbow trout farming. Compared with marine cage farming, the main contribution to the direct energy use comes from electricity, rather than fuel.

Table 2-24 Emission intensities (upstream, grow-out, total) and direct energy use in grow-out per Functional Unit, e.g., 1 tonne of trout, live weight at farm gate produced in a RAS.

Source	Upstream- feed CO_2e [tonne/FU]	Grow-out CO_2e [tonne/FU]	CO_2e per FU [tonne/FU]	Energy use/FU [kWh/FU]	CO_2e due to energy use [tonne/FU]
Samuel Fitwi&al., 2013	1.545	12.077	13.622	19622	12.056
Nystad, 2020	1.545	5.407	6.952	8,800	5.407

Table 2-25 Estimated CO_2e emissions from trout farming in 2019.

Production system	EU Production 2019 [tonne]	CO_2e emissions [tonne]
Flow Through Systems (FTS)	180,366	450,013
Recirculation Aquaculture Systems (RAS)	16,471	114,506
Total	196,837	**564,519**

Table 2-25 highlights that the contribution due to RAS production is still relevant but also that innovations introduced in the last ten years have led to a marked decrease in the emission intensities from this farming typology. This finding suggests that it would be highly relevant to conduct LCA studies for mapping RAS CO_2e emissions in Denmark,

([51]) EUMOFA, 2020. Recirculation Aquaculture Systems. https://op.europa.eu/en/publication-detail/-/publication/fec31328-643a-11eb-aeb5-01aa75ed71a1
([52]) Badiola, M., Mendiola, D., Bostock, J., 11 2012. Recirculating Aquaculture Systems (RAS) analysis: Main issues on management and future challenges. Aquacultural Engineering 51, 26–35
([53]) Samuel-Fitwi, B., Nagel, F., Meyer, S., Schroeder, J. P., & Schulz, C. (2013). Comparative life cycle assessment (LCA) of raising rainbow trout (Oncorhynchus mykiss) in different production systems. *Aquacultural Engineering*, *54*, 85-92.
([54]) Nistad, A., A., 2020. Current and future energy use for Atlantic Salmon farming in recirculating aquaculture systems in Norway. NTNU Master Thesis. ttps://www.ntnu.no/bridge/en/project/current-and-future-energy-use-atlantic-salmon-farming-recirculating-aquaculture-systems.

which accounted for 69% of the EU rainbow trout production in RAS. It also indicates that emission intensities can be further lowered by replacing grid electricity with Renewable Energy Sources (RESs).

Aquaculture- baseline 2019 CO_2e emissions

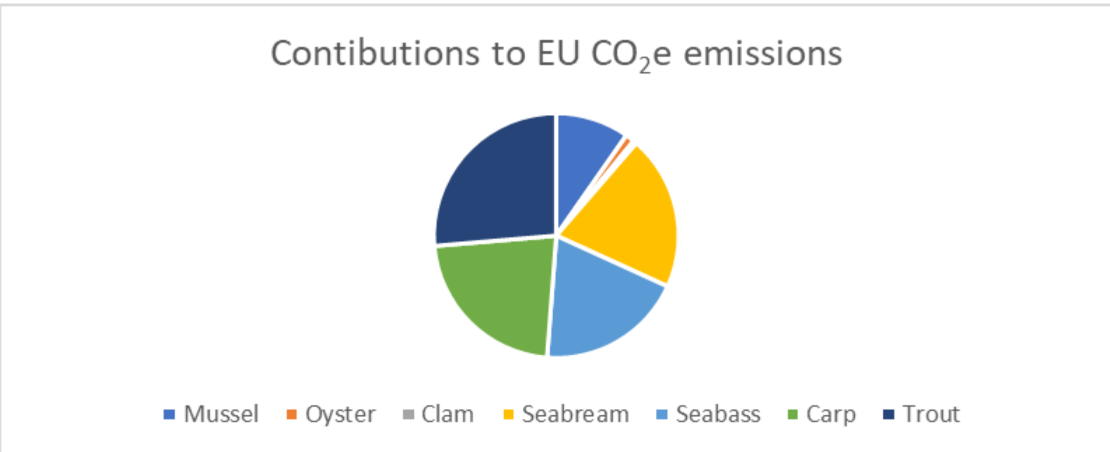
The results of the analysis presented in the previous paragraphs are summarised in Table 2-26 which presents for each commercial species the total emissions and average emission intensities in the pie chart displayed below.

A further extrapolation, based on the average emission intensity, would give a total emission of 2,480,899 tonnes of CO_2e. As expected, Low Trophic Aquaculture, i.e., shellfish farming, contributes to the total emissions, 11.8% is much lower, compared with the farming of carnivorous fish, i.e., seabass, seabream and trout, 65.7%. Less expected is the high contribution of carp semi-intensive farming: the targeted interviews confirmed the need to conduct more comprehensive LCA studied on carp farming: ongoing EU-funded projects, e.g., SAFE ([55]), are actively working in this area.

Table 2-26 Total CO_2e emissions and EU average emission intensities for the main species accounted for 92% of the EU aquaculture sector in 2019.

Commercial species	EU production 2019 [tonne]	Total CO_2e emissions [tonne]	Percentage contribution	EU Average Emission intensity [kgCO_2e/kg lw]
S1.1 Mussel	453,559	208,170	9.8	0.46
S1.1 Oyster	101,683	32,318	1.5	0.32
S1.1 Clam	32,734	9,662	0.5	0.30
S1.2 Seabream	92,476	424,930	20.0	4.59
S1.2 Seabass	83,872	407,332	19.1	4.84
S2.1 Carp	80,195	481,170	22.6	6.00
S2.2 Trout	196,837	564,472	26.5	2.87
Total EU 2019	**1,041,386**	**2,112,085**	**100**	**2.043**

Figure 2-8 Percentage contribution of the main commercial species to CO_2e emissions form EU aquaculture.



([55]) https://projectsafe.eu/

Aquaculture: estimated CO_2e emissions for the baseline year 2009

Baseline emissions for the year 2009 were estimated based on the emission intensities estimated for the year 2019 and production data available on Eurostat. In fact, technologies and husbandry practices have not markedly changed in the last 20 years for the marine segment, for carp and trout FTS. The average EU emission intensity for trout in 2009 was recalculated, based on the RAS production in Denmark of about 12,000 tonnes reported by Martins. (56) This volume was multiplied by the emission intensity estimated for RAS by Samuel-Fitwi and coauthors in 2013. The remaining volume was multiplied by the average intensity of FTS production listed in

Table 2-26. The comparison with Table 2-27 indicates that, overall, the total production volume and the total CO_2e emissions have not changed significantly in a decade. Overall, shellfish accounted for 12% and carnivorous fish for 65% of the CO_2e emissions.

Table 2-27 Total CO_2e emissions for the selected species and EU average emission intensities in 2009

Commercial species	EU production 2009 [tonne]	Total CO_2e emissions [tonne]	Percentage contribution	EU Average Emission intensity [kgCO_2e/kg lw]
S1.1 Mussel	439980	202,002	9.5	0.46
S1.1 Oyster	111211	27,966	1.3	0.25
S1.1 Clam	44513	13132	0.6	0.30
S1.2 Seabream	96278	456,289	21.6	4.74
S1.2 Seabass	57480	284,775	13.5	4.96
S2.1 Carp	81155	486930	23.0	6.00
S2.2 Trout	204878	644695	30.5	3.15
Total EU 2009	**1,035,495**	**2,115,787**	**100**	**2.04**

2.2.3 External factors affecting the sector between 2020 and 2023

Brexit

Currently, the effects of Brexit are still unfolding in all sectors, including fisheries and aquaculture. A study published earlier this year lists the potential impacts of Brexit on the EU and UK production and trade of seafood from increased costs, such as new health certificate requirements, changes in transport routes, more time spent on border crossing including veterinary border control and loss of product quality as a result of delays could be some of the consequences for the seafood sector. (57) This study reported that importers and exporters on both sides of the English Channel suffered delays, red tape and extra costs after the implementation of Brexit, however, it is highlighted that distinguishing between the effects of Brexit and the COVID-19 Pandemic is almost impossible. From the scoping interviews, it cannot be concluded that Brexit has had an impact (negative or positive) on the aquaculture sector in the EU, except for

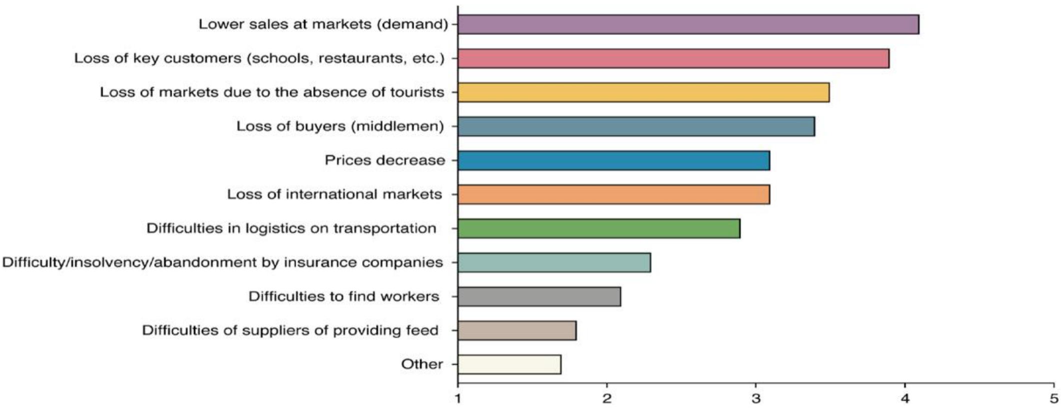
(56) Martins, C.I.M., E.H. Eding, M.C.J. Verdegem, L.T.N. Heinsbroek, O. Schneider, J.P. Blancheton, E. Roque d'Orbcastel, J.A.J. Verreth, 2010. New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. Aquacultural Engineering, 43: 83–93.
(57) Elvestad, C., & Bjørndal, T. (2023). The EU–UK Trade and Cooperation Agreement: Issue linkages and its implications for fisheries management and trade in seafood. Marine Policy, 148, 105380.

producers in Ireland where technology and products must be transported through the UK, with increasing costs due to additional checks, transport and taxes.

COVID-19 Pandemic

A study was carried out by Nielsen and coauthors in 2023 using a survey where industry representatives and experts assessed the impacts on key economic indicators as well as national production data from Spain and Denmark, which suggested that the COVID-19 pandemic had mixed effects on the EU aquaculture sector. ([58]) This translates as increasing costs and reducing profits due to a decrease in sales to restaurants because of pandemic closures, however, the production data shows on average no impact during COVID-19. In addition, the study highlighted that species mostly used by restaurants e.g., Turbot, were the products showing the most negative effects. This is supported by the study published by The Aquaculture Advisory Council (AAC) where the impacts of sales were the biggest concern and the costs of production the least. ([59]) Regarding the intra-EU exports from 2019 to 2020 were value decreases for mussels and oysters due to decreases in volumes exported. Intra-EU imports of oysters, mussels, seabass and fishmeal decreased. For extra-EU exports from 2019 to 2020 were value decreases for carp, oysters and freshwater fish. Extra-EU import volumes decreased for carp, freshwater fish and seabass. ACC expressed that according to the last data, the effects of the COVID-19 pandemic have by now been overcome by the sector.

Figure 2.9 Socioeconomic impacts suffered by the aquaculture activity due to the COVID-19 pandemic.



Based on survey results. X-axis goes from 1 to 5 where 1 is 'not important' to 5 meaning 'very important'. Nielsen et al. (2023).

Energy crisis

In 2022, energy prices were aggravated by Russia's unprovoked act of aggression against Ukraine. Citizens and industries dependent on energy are highly affected by this. Higher energy prices are a threat to profitability and viability – both directly through increased energy costs and indirectly through higher feed prices and other input costs ([60]) e.g., transport and processing of aquaculture products. As a result, the aquaculture sector has relied on the financial support provided by EU Member States and the financial tools made available at EU level to continue operations. This highlights the vulnerability of the sector, in particular of those systems that heavily depend on feed (e.g., finfish farms), as well as systems that require high-energy consumption for

([58]) Nielsen, R., Villasante, S., Polanco, J. M. F., Guillen, J., Garcia, I. L., & Asche, F. (2023). The Covid-19 impacts on the European Union aquaculture sector. Marine Policy, 147, 105361.
([59]) Recommendation on Covid-19 Impacts and Responses.
([60]) COM(2023)100 - Energy Transition of the EU Fisheries and Aquaculture sector.

maintenance e.g., RAS and its dependency on fossil fuels. The uncertainty in the energy market is linked to geopolitical instability, it is expected that energy prices will remain volatile. Consequently, this is compromising the sustainability of a sector, in particular of those segments that need high energy demands such as exploitations depending on feed e.g., finfish, which is key to securing the food supply.

In order to reduce fossil fuel dependency and ensure the sector's sustainability as well as work toward reaching climate neutrality in the EU by 2050 as one of the ambitions of the European Green Deal, the sector must move to renewable and low-carbon energy sources as quickly as possible.

2.2.4 Data gaps and estimate representativity.

This chapter presents the first attempt at estimating EU GHG emissions from the aquaculture sector. The methodology adopted, i.e., LCA, is recommended by the Aquaculture Advisory Council and is also consistent with the Product Category Rules for the estimation of seafood Product Environmental Footprint. The results presented in this chapter are based, as far as possible, on peer-reviewed papers published in international scientific journals, which were selected based on a systematic and thorough literature search. The latter, however, led to identifying relevant data gaps, namely:

1. No peer-reviewed paper providing estimates of CO_2e for the important intertidal French oyster production, including the grow-out and hatchery stages, could be found. Moreover, this was confirmed by targeted interviews and a validation workshop.
2. The literature concerning raft mussel farming in Spain is of high quality but needs to be updated, as the most relevant papers were published in the years 2010-2011, based on data collected in the years 2006-2007.
3. Emissions from carp farming were estimated based on only one paper, which may not be representative of the emissions of Central European countries. This gap is particularly relevant, as this source indicates a higher emission intensity, compared with all other production typologies, except for trout produced in RAS.
4. Results concerning seabass, seabream and trout highlight the large variability of estimates, which are related also to site-specific conditions, i.e., distance from the landing points for marine fish and emission intensities of the electricity grid for trout. Since, altogether, these species account for 70% of EU emissions, a more accurate mapping, based on country-specific studies, would certainly contribute to reducing the uncertainty in the estimates given in Table 5.25.

These data gaps increase uncertainties for some of the segments in relation to the emissions and therefore, influence the estimation of emissions reduction by the innovation and solutions discussed later in Chapter 5.

Despite the data gaps and, in some cases, limited representativity of the estimates, the result presented in Chapter 2, section 2.2, allows the identification of the main emission 'hot spots', i.e. phases/processes with high impact on CO_2e emissions from EU aquaculture, which are summarised in table below.

Table 2-28 Hot spots of CO_2e emissions from EU aquaculture, identified on the basis of the results presented in Chapter 2.

Species	Main hot spots
S1.1 Mussel	The use of fossil fuels represents the main contribution to CO_2e emissions related to the grow-out stage for long-line mussel farming. Therefore, the distance from landing points determines the extent of the impact. As far as raft culture is concerned, recent analysis is lacking based on the available literature, it seems that, in this case, infrastructure represents the main contribution, given the proximity to the shore.
S1.1 Oyster	The emission intensity of the grow-out phase does not seem to be high, but the hatchery phase may be a relevant source of GHGs, as shown by the case study on clam hatchery.
S1.1 Clam	Given the low production volume, the limited amount of infrastructure and the use of fuel, the overall emission of the grow-out phase is the lowest. Furthermore, emissions related to the grow-out phase are markedly lower than those from seed production in hatcheries. This aspect deserves attention also for oysters.
S1.2 Gilthead seabream	Feed emerges as one of the main contributors to this species' emission intensities: besides feed formulation and manufacturing, this depends also on the still relatively high Feed Conversion Ratio, FCR, of Mediterranean aquaculture, around 2, meaning two tonnes of feed are used producing 1 tonne of fish. Fossil fuel use in vessels is the most relevant hot spot concerning the grow-out stage: therefore, the distance from landing points harbours determines the extent of the impact when using boats for feed transport and delivery.
S1.2 European seabass	Conclusions are similar to those reported for seabream
S2.1 Common carp	Energy use in managing the ponds seems the main hot spot. This points to changes in pond maintenance practices and better use of the organic-rich sediment that needs to be removed after carp wintering.
S2.2 Rainbow trout	Feed is confirmed as one of the main contributors to this species' emission intensities: however, it is less impacting, compared with marine species, as the FCR is around 1, meaning 1 tonne of feed is used to produce 1 tonne of fish. Electricity is the main relevant hot spot concerning the grow-out stage and overwhelmingly so for trout farmed in RAS.

Furthermore, the findings presented in Chapter 2 confirm that CO_2e emissions in EU aquaculture are characterized by a large variability, both across segments, e.g., shellfish versus finfish and within segments/species as the location, water quality and water sources, distance from landing points, husbandry practices and production volumes all affect energy use and feeding efficiencies. As a result, it is not possible to generalise across the sector.

3 FISHERIES – TECHNO-ECONOMIC ANALYSIS OF THE INNOVATIVE LOW CARBON SOLUTIONS

This chapter provides a techno-economic analysis of innovative, low-carbon solutions for fisheries vessels. To this end, **section 3.1.** provides an overview of the potential energy efficiency and low-carbon innovations and CO_2e-reduction associated with these innovations as well as their technological readiness levels. In **section 3.2.** a marginal abatement cost curve is calculated for the innovations in the EU-fishing vessels, resulting in a short- and long-term overview of solutions and the associated CO_2e-emission potential. Also, the cost-effectiveness of each individual measure is presented. In **section 3.3.,** the result of calculating financial indicators (NPV and IRR) provides insights into the economic viability of implementing these innovations. The information obtained in order to perform this techno-economic analysis (CAPEX, OPEX) can be found on the individual factsheets for each innovation in Annex C.

3.1 Potential energy efficiency and low-carbon innovations and CO_2e emission reduction associated with these innovations.

Generally, to reduce fuel costs and CO_2e-emission, the maritime sector has already been applying various technological measures ('innovations') to ships. ([61]) The fisheries sector, however, has been reluctant to take these up and it is a rather new development that active innovations are searched for in order to reduce fuel costs (driven by the high energy prices). Also, for some solutions (especially alternative propulsion), it may hold that legal frameworks particularly regarding tonnage and vessel length may prevent the take-up. Finally, experiments as well as pilot projects in the fisheries sector are scarce, although many of such technological innovations already tested for shipping vessels, can be applied to fisheries vessels as well. ([62])

Categories of innovations

A list of innovations for fisheries vessel was drafted based on the available literature on both the maritime and fisheries sector. ([63]) After an iterative process of literature consultation and stakeholder consultation activities, 45 relevant innovations were identified and for which an individual factsheet was developed (which can be found in Annex C). These factsheets contain general information about advantages and limitations and include technological readiness levels (TRL), Capital Expenditures (CAPEX), Operational Expenditures (OPEX), the applicability on retrofit and new vessels as well as on vessels using different fishing methods and within the aquaculture sector.

The total list of innovations can be found in Table 3-1 below, where the innovations are categorised as follows:

A. Engine and propulsion.
B. Vessel operation and design.
C. Alternative propulsion.
D. Assisted propulsion.
E. Fishing Gear.
F. On-board processing.
G. Facilitating measures.

([61]) See for example: Malloupis & Yfantis 2021; Bouman et al. 2017; and IMO 2020
([62]) See for example: EC 2023; GloMEEP 2023
([63]) See for example: Bastardie et al. 2022; EC 2023; GloMEEP 2023; Malloupas & Yfantis 2021

Table 3-1 Overview of Innovations or Technological Measures for Fisheries Vessels

Category	Number	Measure
A. Engine and propulsion	1	Electric on-board consumers
	2	Frequency converters
	3	Waste heat recovery systems
	4	Oil filtration system
	5	Shore power/ shore supply of electricity
	6	Larger Propellor, Nozzle and Optimized Stem
	7	Antifouling
	8	Use pre- and post-swirl fins and stators
	9	Anti-roll systems
	10	Propeller-rudder upgrade
B. Vessel design and operation	11	Improved hull design
	12	Apply air lubrication systems
	13	Energy efficient lighting systems
C. Alternative propulsion	14	Electrification
	15	Diesel-electric
	16	Biodiesel: HVO, FAME, FT, DME
	17	Biocrudes: SVO, PO, HTL, SO
	18	Methanol (bio/e-)
	19	Ethanol (bio/e-)
	20	Ammonia (bio/e-)
	21	LNG (bio/e-)
	22	Hydrogen (bio/e-)
D. Assisted propulsion: Wind	23	Kites
	24	Suction wings
	25	Sails
	26	Wind turbine
	27	Flettner rotor
E. Fishing Gear	28	Using a Sumwing (trawlers)
	29	Outrig
	30	Twinrig
	31	Alternative trawl door
	32	Using sledges
	33	From active to passive
	34	Helix spiral-trawling net
	35	Using lighter nets
	36	Alternative netting design
F. Onboard processing	37	Multistage mono-block ice pumps
	38	Cogged V-belt instead of flat V-velt in cooling system
	39	Using natural refrigerants for freezing
G. Facilitating measures	40	Slow steaming
	41	Smart steaming
	42	Route-planning systems
	43	Energy audits
	44	On-board energy-monitoring devices
	45	Bluebox: digitalisation

A brief introduction on the identified innovations

This section presents a brief description of each of these categories, including their Technological Readiness Level, CO_2e-emission potential and literature references. Drafting the list and investigating the potential of each innovation was primarily drafted based on the available literature on both the maritime and fisheries sector. (64)

CO_2e-emission potential relates to the potential of the innovation to reduce total fuel consumption and associated CO_2e-emissions of the fisheries vessel in %. So, a 10% CO_2e-emission potential relates to a reduction of the vessel's fuel consumption by 10%. Note that the numbers provided are often ranges; in the next step estimations based on these ranges are used for the modelling (estimations can be found on the factsheets: "Assumptions for modelling").

TRL, Readiness and economic lifetimes were based on the Fourth IMO GHG study and EMSA (2022). (65) In case a certain innovation was not present in this study, other (academic or stakeholder) references are used. This is also visible on the individual factsheets.

A. Engine and propulsion

Engine and propulsion refer to innovations related to all aspects related to the vessel's combustion (see for details factsheets 1-10 in Annex C). These are technological measures that can be applied to existing or new engines and propulsion systems which leading to energy and therefore CO_2-savings. (66) Changes or additions can be made to the propellor (innovations 4, 6, 8, 9, 10), electricity could start playing a larger role as a source for propulsion and/or machinery equipment (innovations 1, 2, 3, 5), or a more innovative type of an already existing measure can be implemented (innovation 7). As visible in Table 3.2., all of these innovations are already available in the market – with the exception that shore infrastructure still lacks, preventing an immediate uptake (innovation 5). Also, for most technological measures it holds that these are already applied in the maritime sector.

Table 3-2 Innovations regarding engine and propulsion including description, CO_2e-emission reduction potential (in % of the vessel's total fuel consumption), TRL, year of Readiness and the relevant references.

Innovation	Description	CO_2e-emission reduction potential	TRL	Readiness	References
Electric on-board consumers [1]	Using electricity instead of power generated by the engines.	Up to 15	9	2023	Bastardie et al. 2022
Frequency converters [2]	Frequency converters regulate speed of engines and can serve as a better regulator of the energy consumption.	Up to 2	9	2023	Bastardie et al. 2022 ; Lee & Hsu 2015 ; GLOMEEP 2023; IMO 2021

(64) See for example: Bastardie et al. 2022; EC 2023; GloMEEP 2023; Malloupas & Yfantis 2021
(65) IMO (2020). Greenhouse Gas Study. International Maritime Organization.
(66) Fishing vessels differ from other commercial ships since the operations can be rather different, especially at the moment of active fishing. Papers dealing with commercial ships may therefore not always be applicable, but still provided useful insights.

Innovation	Description	CO_2e-emission reduction potential	TRL	Readiness	References
Waste heat-recovery systems [3]	Heat of engine can be used for other energy-saving purposes (e.g., hot tap water, crew space heating).	3-10	9	2023	Bastardie et al. 2022 ; Bouman et al. 2017 ; GLOMEEP 2023w ; IMO 2020; Liu et al. 2025 ; Malloupis & Ifantis 2021 ; Orcan 2023 ; SINTEF 2020
Oil filtration system and frequency drive [4]	An oil filtration system reduces the need for a change of engine oil (and other mechanisms). This system also keeps the engine temperature low.		9	2023	Hong & Jang 2023. See also: CJC 2023
Shore power/shore supply of electricity [5]	Using (environmentally friendly) shore power for the machines and/or apparatus instead of fossil fuel.	-	9	2030	Bastardie et al. 2022 ; GLOMEEP 2023h
Larger Propeller, Nozzle and Optimised Stern [6]	Combining a larger propeller and nozzle with an optimised stern will lead to a more optimal propulsion.	10-20	9	2023	-
Antifouling [7]	Antifouling techniques prevents growth of biofouling, lowering the ship's weight. Both environment-friendly and more efficient antifouling techniques can be used.	5-10	9	2023	Bastardie et al. 2022 ; Brenda et al. 2022 ; GloMEEP 2023a ; Legg et al. 2015 ; Trickey et al. 2022
Use post, pre-swirl fins and stators [8]	fins-based improve the propulsive performance of the vessel by equalizing the fuel inflow via the duct and reduce slipstream losses.	0.5-5	9	2023	Gaggero & Martinelli 2023; Glomeep 2023; IMO 2021
Anti-roll systems: stabiliser fins [9]	Stabiliser fins provide resistance to the (excess) rolling of a fisheries vessel, resulting in higher fuel efficiency.	Up to 2	9	2023	
Propeller-rudder upgrade [10]	A propellor rudder upgrade can be performed to improve the fisheries vessel's manoeuvrability.	Up to 5	9	2023	IMO 2021 Malloupis & Yfantis 2021

B. Vessel design and Operations

Innovations regarding *vessel design and operations* regard technologies to improve the resistance of the fisheries vessel (11, 12) as well as the general operations of the vessel by improving the use of electricity (13). ([67]) As for improved hull design (11), note that various adaptations may be part of this category including the addition of a stern post. As visible in Table 3.3, all innovations are already available in the market. The costs of an improved hull (11) and the low applicability of air lubrication systems (12) may make the take-up of these innovations however unlikely.

Table 3-3 Innovations regarding vessel design, including description, CO_2e-emission reduction potential (in % of the vessel's total fuel consumption), TRL, year of Readiness and the relevant references.

Innovation	Definition	Potential CO_2e emission reduction	TRL	Readiness	Reference(s)
Improved hull design (hull, sternpost) [11]	A vessel's hull design can be modified or changed inducing lower friction. This may include the use of a sternpost.	4-30	9	2023	Bastardie et al. 2022 ; GLOMEEP 2023 ; Prosea 2023
Apply Air Lubrication Systems [12]	Air lubrication systems reduce frictional resistance by improving the viscosity of the water in front of the hull by adding low-pressure air into the boundary layer of the wetted surface.	5-15	9	2023	Malloupas & Yfantis, 2021 Howden 2023 Kumagai et al. 2015
Energy efficient lighting systems [13]	Energy efficient lighting systems on-board of fisheries vessels such as the use of LED lights are a substitution for conventional lights.	Up to 5	9	2023	Bastardie & al. 2022

C. Alternative propulsion

Alternative propulsion regards changing the type of fuel used by the fisheries vessel and can regard the (partial) *substitution* of fossil fuel by using biofuels (EMSA, 2022). Some of these alternative fuels are drop-ins (i.e., substitutes for fossil fuels and hardly any changes are needed to current engines) (16, 17). The main bottlenecks for non-drop in alternative fuels such as hydrogen or ammonia are on-board space, crew training and safety, as well as the current lack of port infrastructure (18-22). As for the latter, for vessels in the DWF-category it holds that even if European port infrastructure would exist, non-European ports which are important for DWF may lack this infrastructure. Electrification (14) or partially electric (15) are also options, although the development of electrification for fisheries vessels is uncertain. Electrification is already used for small distance ferries, but it takes up in the fisheries sector may be hindered by onboard space as batteries are heavy and large. Diesel-electric (15) is already widespread within the maritime industry.

([67]) Note that we have not taken into account the use of solar panels, with various stakeholder indicating that there may not be sufficient on-board space and/or the amount of energy generated being too limited. Also, mostly the Northern basins, solar energy will be available only limited year-round.

Table 3-4 Innovations regarding distillates (biofuel and bio alcohol), including description, CO_2e-emission reduction potential (in % of the vessel's total fuel consumption), TRL, year of Readiness and the relevant references.

Innovation: Distillates	Description	CO_2e-% emission reduction potential	TRL	Readiness	References
Fully electric [14]	A vessel can be propelled in a fully electric way (e.g., batteries)	100	4-5	2030	Corvus Energy, 2023 ; Dale et al., 2015 ; Koumentakos, 2019 ; Nuchturee et al., 2020 ; Nguyen et al., 2020 ; CE Delft, 2023 ; ABS et al., 2022 ; Evolve Consortium 2023; Wartsila, n.d.; NFFO, 2022; SINTEF, 2020. See for experiments the Horus Project (2023) and MPENG (2023)
Diesel-electric (or hybrid) [15]	Diesel-electric propulsion implies that a vessel is (partially) propelled by diesel and electric generators.	10-25	9	2023 (2025)	CE Delft, 2023; Elkafas & Shouman, 2022; Geertsma et al., 2017; Interreg Europe, 2020 ; Karagiorgis et al., 2022; SINTEF 2020; Wärtsilä, 2016; Wageningen University Research (WUR), 2009. See also: Danfoss, 2019
Biodiesel (FAME, HVO, FT diesel, DME) [16]	Biodiesel can be used as a drop-in fuel (vegetable, animal fat-based, or waste oils). Examples are soy and fisheries waste-oil.	Up to 96	9	2023	ABS et al., 2022 ; EPRS 2023; Firoz, 2017 ; Monroe et al., 2020; Solakivi et al., 2022
Biocrudes [17]	Various biocrudes can be as an alternative for fossil fuel: SVO, HTL and solvolysis oil	Up to 100	SVO: 9 PO: 4-6 HTL: 2-4 SO: 4-9	SVO: 2023 PO: 2035 HTL: 2040 SO: 2035	ABS et al., 2022; IMO, 2020; Mat et al., 2018; Thomas, 2022
Methanol (bio/e) [18]	Methanol can be used as an alternative for fossil fuel and can be derived from both natural and synthetic production processes.	Up to 100	8-9	2023	ABS et al., 2022 ; de Fournas & Wei, 2022 ; Ellis & Tanneberger, 2015 ; EPRS 2023 ; IMO, 2020; McKinlay

Innovation: Distillates	Description	CO_2e-% emission reduction potential	TRL	Readiness	References
					et al., 2020; Radonja et al., 2019; Shi et al., 2023.
Ethanol (bio) [19]	Bioethanol is a type of biofuel (type of alcohol) made from starch or sugar-based crops	Up to 100	4-6	2035	ABS et al., 2022; Ellis & Tanneberger, 2015; IMO, 2020; Maritime Knowledge Centre, GoodFuels and TU Delft, 2023; Mićić & M. Jotanović, 2015; Radonja et al., 2019
Ammonia (bio/e)	Ammonia can be produced by using biological feedstock (e.g., by fermentation or enzymatic reactions) or renewable energy sources (e-ammonia).	100	8-9	2030	ABS et al., 2022a, 2022b ; Mallouppas et al., 2022 ; McKinlay et al., 2020a, 2020b ; Nadimi et al., 2023 ; Tornatore et al., 2022; Zincir, 2019
LNG [21]	(Bio)LNG can be used instead of fossil fuel.	25	9	2023	ABS et al., 2022; EPRS 2023; Gemba Seafood Consulting, 2021; IMO, 2020; Jafarzadeh et al. 2017; Koričan et al., 2022; Kim et al., 2020; Lindstad et al., 2020; Nerheim et al., 2021; Pavlenko et al., 2020; SEA\LNG Ltd, 2019; SEA-LNG & SGMF, 2021; SINTEF, 2020; Wang & Notteboom, 2014
Hydrogen (bio/e) [22]	Hydrogen can be produced by using biological feedstock (e.g., by fermentation) or renewable energy sources (e-hydrogen).	100	5-6	2035	Abdalla et al., 2018; Howarth & Jacobson, 2021; IMO, 2020; Jafarzadeh & Schjølberg, 2017; Jeon & Kim, 2020; McKinlay et al.,

Innovation: Distillates	Description	CO_2e-% emission reduction potential	TRL	Readiness	References
					2020; Pomaska & Acciaro, 2022; SINTEF 2020; Tlili, 2019. See also ABC-engines (2020).

D. Assisted Propulsion: Wind

Assisted propulsion relates to innovations that apply techniques to use *wind* as a (renewable) energy source (ABS et al. 2023). It is assumed that by implementing these innovations (23-27), the vessel's propulsion will be *assisted,* i.e., steam at equal speed, since otherwise no fuel cost reductions will be realised. For all innovations (23-27) it holds that these are currently being explored in both the maritime and the fisheries sector. The main bottlenecks for implementing these are deck space, interference with fishing gear and the overall stability of the vessel. Also, crew training is often required.

Table 3-5 Innovations regarding distillates (biofuel and bio alcohol), including description, CO_2e-emission reduction potential (in % of the vessel's total fuel consumption), TRL, year of Readiness and the relevant references.

Innovation	Definition	CO_2e-% emission reduction potential	TRL	Readiness	Reference(s)
Kites [23]	By attaching a kite to the fisheries vessel, the vessel could be propelled (partially) by wind force.	1-25	7-9	2025	ABS et al 2023 ; CE Delft 2009 ; Malloupas & Yfantis, 2021
Suction wings [24]	By attaching suction wings to the fisheries vessel, the vessel could be propelled (partially) by wind force while steaming.	5-25	8-9	2023	ABS et al. 2023
Sails [25]	By attaching sails to the fisheries vessel, the vessel could be propelled (partially) by wind force.	5-25	7-9	2023	ABS et al. 2023 Bastardie et al. 2022 ; CE Delft 2009, 2017 ; Malloupas & Yfantis, 2021
Wind turbine [26]	Energy can be generated through installing a wind turbine at the vessel generating electricity for the vessel's propulsion and/or other operations.	0-2	9	2023	Malloupas & Yfantis, 2021 ; Setiyobudi et al. 2023
Flettner rotor [27]	Adding one or various Flettner rotors at the ship to assist the engine in propulsion.	3-20	7-8	2023	ABS et al. 2023 ; CE Delft 2009 ; Malloupas & Yfantis 2021

E. Fishing Gear

Innovations in the category *Fishing Gear* aim at a change of the nets (alternative material, netting design), using a different type of net or method to catch fish and/or reduce bycatch with the aim of fuel reduction. Six innovations aim at changing the fuel consuming (bottom) trawling gear into a different type of gear (29, 30, 34) although not all are yet more specific and may highly depend on fishing vessel and gear (33, 35, 36). ([68]) Others are additions or changes to extant fishing gear (28, 31, 32). ([69]) ([70]) Within this category, many experiments have been carried out already on a smaller scale and many are already technological available (see for the most recent overview ICES 2023). Note that in some cases, legal frameworks may play a role as for example mesh sizes are restricted. ([71])

Table 3-6 Innovations regarding *Fishing gear,* including description, CO_2e-emission reduction potential (in % of the vessel's total fuel consumption), TRL, year of Readiness and the relevant references.

Innovation	Definition	CO_2e-% emission reduction potential	TRL	Readiness	Reference(s)
Using a Sumwing [28]	Using a Sumwing instead of a (heavy) beam in a beam trawl results in less drag force.	11-30	9	2023	Bastardie et al. 2022 ; Caslake, 2022 ; CBS et al. 2021 ; Depestele et al. 2019 ; Prosea 2023a ; Taal & Klok 2014. See also: HFK Engineering 2009
Outrig (instead of beam trawl) [29]	The outrig is an alternative to the beam trawl. The outrig does not use a boom to open the net but fishing boards. Fuel reduction results from the lower resistance of the fishing gear and because of fishing at a lower speed.	35-45	9	2023	Bastardie et al. 2022 ; CBS et al. 2023 ; Humphrey et al. 2008 ; ICES 2010 ; Prosea 2023a, Quirijns et al. 2019 ; Seafish 2023 ; Van Marlen et al. 2009b
Twinrig (instead of beam trawl) [30]	Twin rigging is a light form of trawling and a small vessel (cutter) can fish a large area of the bottom surface with relatively little power	25	9	2023	Bastardie et al. 2022 ; CBS et al. 2023 ; ICES 2010 ; Prosea 2023b; Quirijns et al. 2019
Alternative trawl door [31]	Alternative trawl doors require less energy to tow through the water, which can significantly reduce fuel consumption.	Up to 20	5-9	2023	Bastardie et al. 2022 ; Gijarro et al. 2017 ; Johnsson et al. 2015. See also : Cordis 2023

([68]) Note that pulse fishing was left out of these innovations given the current European ban on this type of fuel reducing fishing gear (Bastardie et al. 2022; Haasnoot et al. 2016; Taal & Klok 2014; Turenhout et al. 2016). Discussions are ongoing whether this will remain forbidden, awaiting further scientific research (stakeholder business/company).

([69]) Various innovations were encountered as alternatives for beam trawling but that these were not regarded as viable by various stakeholders: bolkoppen, waterspray, twinbeam and hydrorig.

([70]) Many innovations in fishing gear can be encountered in the 'grey literature', of which we have chosen those mentioned most during the stakeholder consultation activities. The most recent overview of fishing gear (including 75 factsheets) has recently been published by ICES in autumn 2023: https://ices-library.figshare.com/articles/report/Workshop_2_on_Innovative_Fishing_Gear_WKING2_/24299146.

([71]) The Minimum Mesh Size (MMS), for example, sets a minimum size of the meshes in any given type of net (ICES, 2023).

Innovation	Definition	CO_2e-% emission reduction potential	TRL	Readiness	Reference(s)
					; Ekko trawl doors (2023); EcoTrawling 2023
Sledges [32]	Sledges attached to fishing nets optimise the performance of trawl nets and support target specific species while minimizing environmental impact and bycatch.	Up to 15	9	2023	Bastardie et al. 2022
From active to passive [33]	Passive fishing instead of active fishing will result in lower fuel consumption since trawling is not necessary anymore.	Up to 90	9	2023	ILVO 2023 ; Mol, 2019 ; Van Marlen et al. 2011 ; WUR 2023
Helix spiral-trawling net [34]	A net containing helix-form spirals can be applied to the net to catch (demersal) fish.	Up to 35	4-5	2028	-
Alternative netting design [35]	Using alternative net design may reduce drag force and bycatch, contributing to fuel consumption reduction. This can consist of a change of maze, mouth opening, wings or overall net shaping, knot type, panel cuttings, or using other material.	Up to 20	1-9	2023-2030	Bastardie et al. 2022 ; Cerbule et al. 2022 ; Drakeford et al. 2023 ; Grimaldo et al., 2019, 2023 ; Karlsen et al. 2021 ; Melli et al. 2018 ; Santos et al. 2015 ; Sistiaga et al. (*In press*) ; Setins et al. 2023 ; Standal et al. 2020 ; Veiga-Malta et al. 2019 ; Zimmerman et al. 2015
Lighter nets [36]	Using lighter nets will reduce drag force and vessel load, contributing to fuel consumption reduction.	Up to 20	9	2023	Bastardie et al. 2022 ; Guijarro et al. 2017 ; Thierry et al. 2020. See also : Dyneema 2023

F. On-board processing operations

The category *on-board processing of fish* refers to all activities related to the processing of catch, of which the main one affect fuel consumption regards the freezing of the fish on-board. On SSCF, this is often done with ice, whereas on larger and especially DWF, large cooling systems are used. ([72]) Table 3-6 below shows mostly technological measures related to the cooling process of the fish and its CO_2-reduction potential is considered low. The take-up of these measures is mostly applicable to DWF, as this vessel category has the largest freezing capacities where these innovations mostly hold. ([73])

([72]) See for example: SINTEF 2020
([73]) Hardly any study has considered the on-board processing. One of the few studies on this topic regards the freezing systems vis-à-vis different alternative propulsion such as diesel-electric or hydrogen:

Table 3-7 Innovations regarding *On-board processing of fish,* including description, CO_2e-emission reduction potential (in % of the vessel's total fuel consumption), TRL, year of Readiness and the relevant references.

Innovation	Description	CO_2e-% emission reduction potential	TRL	Readiness	References
Multistage mono- block ice pumps [37]	Centrifugal pumps used in ice-making can be replaced by horizontal multistage mono-block pumps	Up to 0.5	9	2023	Murali et al. (2021)
Cogged V-belt instead of flat V-belt in cooling system [38]	Replacing flat V-belts with cogged or synchronous belt drives.	Up to 0.5	9	2023	Cutler et al. 2014 ; Murali et al. 2023
Using natural refrigerants for freezing [39]	Using ammonia, CO_2, or a cascade system (combination of the two) as a natural refrigerant in freezer systems.	varies	9	2023	Danfoss, 2023; Saeed, 2020; Söylemez et al. 2022; UNEP 2016; Welter, 2020

G. Facilitating Practices

Facilitating practices regard innovations aiming at a *reduction of fuel consumption*. All measures are technologically ready. Measurement of fuel consumption can be done either by means of a periodical control (innovation 43) or digitally, by a continuous measurement of fuel consumption that may result in facilitating certain steaming behaviour that reduces fuel consumption (44-45). Measurement and digitalisation (43 – 45) are believed to be key steps in facilitating lower fuel consumption. Not only will digitalisation and measurement make fuel consumption changes more visible to the skipper, but both will also enable more targeted and structural adaptations to the vessel. Digitalisation may however also be considered difficult to implement given privacy and competitive concerns. Another facilitating measure regards the idea of slow steaming (40). The vessel's engine can also be technologically adapted to force a slower speed of the vessel (derating), thus reducing the fuel consumption. Slow steaming can also be reached by means of a behavioural measure. Both are however difficult to implement (see also factsheet 40 in Annex C, for more a more elaborate discussion).

Table 3-8 Innovations aimed at a reduction of fuel consumption, including description, CO_2e-emission reduction potential, TRL, Year of Readiness and the relevant references.

Innovation	Definition	CO_2e-% emission reduction potential	TRL	Readiness	Reference(s)
Slow steaming [40]	Slow steaming is reducing (towing) speed to optimal fuel efficiency resulting in higher energy efficiency.	Up to 27	9	2023	Bastardie et al. 2022 Cariou 2010 ; CE Delft 2012, 2017, 2022; Granado et al. 2021 ; Poos et al. 2013 ; Ziegler & Hornborg 2023

https://www.sintef.no/contentassets/f18e738f011347999884e200f817b956/coolfish-report-propulsion_and_fuels-signed.pdf.

Innovation	Definition	CO_2e-% emission reduction potential	TRL	Readiness	Reference(s)
Smart steaming [41]	Smart steaming is optimizing the fishing vessel's speed based on the real-time state of the sea, weather and the destination port.	Up to 15	9	2023	Bastardie et al. 2022 ; Granado et al. 2021
Route-planning systems [42]	Route-planning (based on, for example, fishing ground) results in less miles on sea.	5	9	2023	Bastardie et al. 2022 ; Bradley et al. 2019 ; EC 2023; GloMEEP 2023; Granado et al. 2021; Pastoors 2023; Yang et al. 2023
Energy audits [43]	An energy audit is a systematic and periodic control of energy consumption l, based on which tailored solutions can be proposed.	Only if identified energy savings measures are put in place.	9	2023	Bastardie et al. 2022 ; Basurko et al. 2013 ; Sala et al. 2022a ; Thomas et al. 2010
On-board energy-monitoring devices and operative advice [44]	On-board energy-monitoring devices may result in more tailored opportunities to increase energy efficiency of the vessel.	Only if identified energy savings measures are put in place.	9	2023	Bastardie et al. 2022
Bluebox [45]	A 'Bluebox' is a device installed on a ship aimed at reaching a higher fuel efficiency both in terms of catch value and optimal fuel usage by connecting information derived from different monitoring devices in one digital application.	Only if identified energy savings measures are put in place.	9	2023	Coronado Mondragon et al. 2019; Ageron et al. 2020; Muntaka et al. 2023; Senturk et al. 2023; Seyedghorban et al. 2023; Global Fishing Watch 2023

3.2 Marginal Abatement Cost Curve – model for low-carbon innovations

3.2.1 Marginal Abatement Cost Curve

A Marginal Abatement Cost Curve (MACC) allows to compare all measures in their effectiveness to reduce GHG on basis of their *cost-efficiency*. This is a parameter, specific to each measure, which tells how much money it costs to gain a certain amount of GHG reduction. In other words, the cost-efficiency is given in terms of the amount of Euros needed to abate a ton of CO_2e. This is particularly relevant given that the innovations that can be taken to reduce the energy consumption and/or emission of greenhouse gases in the fisheries sector range widely in type of technology, applicability and availability.

To calculate the marginal abatement cost curve for fishing vessels, the CE-Ship model has been applied. A brief explanation of the model is provided below, with Annex E containing more information on all relevant input values and assumptions on each vessel type forming the base of the MACC-calculation.

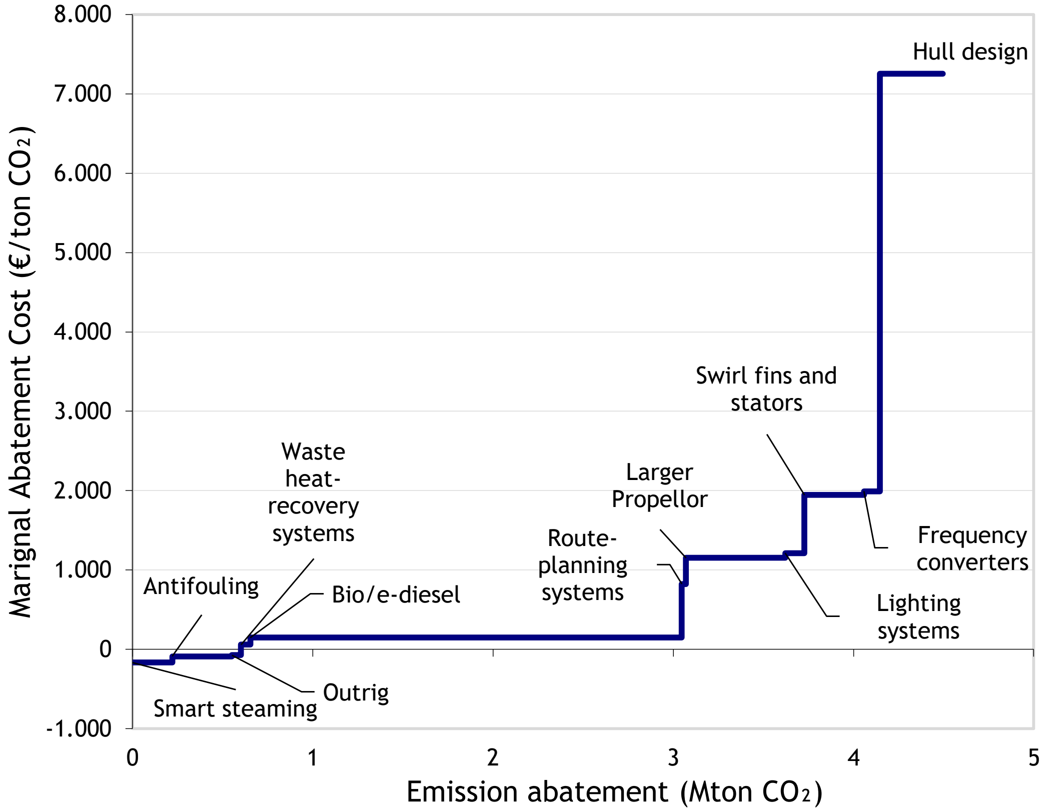
The MACCs are calculated for short term and long-term projections for the European fisheries fleet (considering relevant differences in vessel sizes and types). The difference between the short term and long-term analysis is the additional uptake of measures on the long term (before 2050) that are still limited available on short term (around 2030), due to technical and/or commercial barriers.

Moreover, the fuel prices of alternative fuels are expected to be lower further into the future (EMSA, 2023). This effect is considered in the model. Note that no reductions in cost for the technical and operational measures are assumed.

Not all measures have been considered in the figures presented below, for several reasons. First, a selection has been made on data availability regarding costs and emission reduction potential. Not for all technologies or measures, costs and emission reductions are known to satisfactory certainty. This is often the case for (new) technologies which have not been used widely yet (see Annex C for a further elaboration). Second, some innovations are incompatible with each other. For example, only one alternative fuel per vessel can be selected. Because the MACC adds each measure to the previous measures to show the total abatement on the horizontal axis, incompatible measures cannot occur in the same curve. The mac-model (CE-ship) is designed to select the most cost-efficient measures in these cases. Lastly, there are measures that are considered in the calculation, but turn out to have no effect in the overall fleet. This can be the case when the measure is only applicable to vessels that are not represented in the fleet. For example, this can mean that if a measure is only applicable to new build vessels of a certain type, which if not represented in the 2022 data, then an effect cannot be calculated for it.

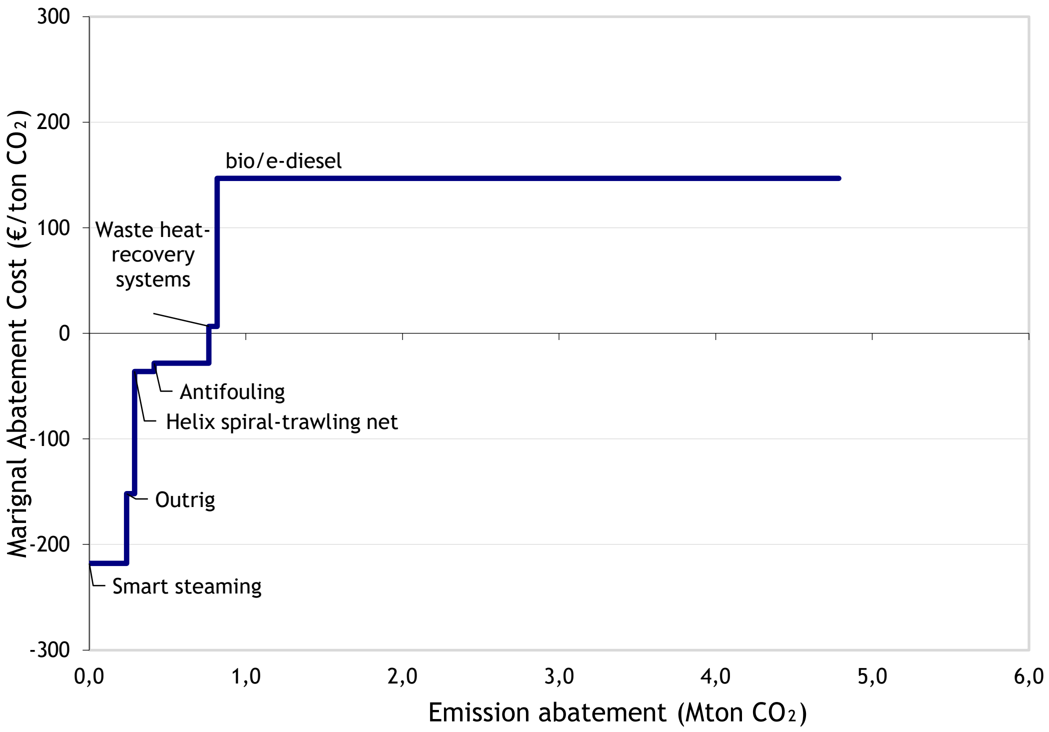
In Figure 3.1 and Figure 3.2 below, the short term and long-term marginal abatement cost curves are presented. In both figures, the horizontal axis tells how much CO_2 (in Mton) can be abated by implementing the consecutive measures. The vertical axis gives the respective marginal abatement cost (i.e., in €/ton CO_2) per measure: this is the cost-efficiency of the measure. The measures are sorted from low-cost efficiency to high-cost efficiency. In other words, each subsequent measure is more expensive in gaining more CO_2 reduction. Some measures, such as smart steaming, have a negative cost-efficiency. This means the measure provides a net saving. This is due to the fuel cost savings, caused by less fuel use or more efficient fuel use. In summary, from left to right the figures show possible emissions abatement and from bottom to top how expensive it is to realise those emissions.

Figure 3.1 Short term marginal abatement cost curve for the total European fisheries fleet



Source: project specific version of CE-Ship model.

Figure 3.2 Long term marginal abatement cost curve for the total European fisheries fleet



Source: project specific version of CE-Ship model.

3.2.2 Results

The total emissions in 2021 of the considered fleet were approaching 5 megatons CO_2e. Both figures indicate that measures with a negative cost efficiency only can already account for an abatement of just over 0.5 megatons CO_2e each year. Furthermore, the measure with the highest abatement potential is the implementation of bio- and e-diesel. This measure has the lowest cost of the measures with positive cost efficiency. Because it is applicable to all types of ships and suitable for existing as well as newbuilt ships, the abatement potential of biodiesel is by far the largest of all measures.

Note that it has been assumed here that these alternative diesel fuels are produced with green electricity, such that it can achieve a theoretical CO_2e-emission reduction of 95%. Due to the expected limited availability until 2030, we assume a maximum uptake of 50% on the short term, while we assume on the long term 100% uptake is possible. Therefore, on the short term, additional less cost-efficient measures are necessary for abatement past 3 megatons CO_2e. Over the long term, uptake of biodiesel is the most cost-efficient measure to account for the largest part of emission abatement.

3.2.3 Total costs of abatement

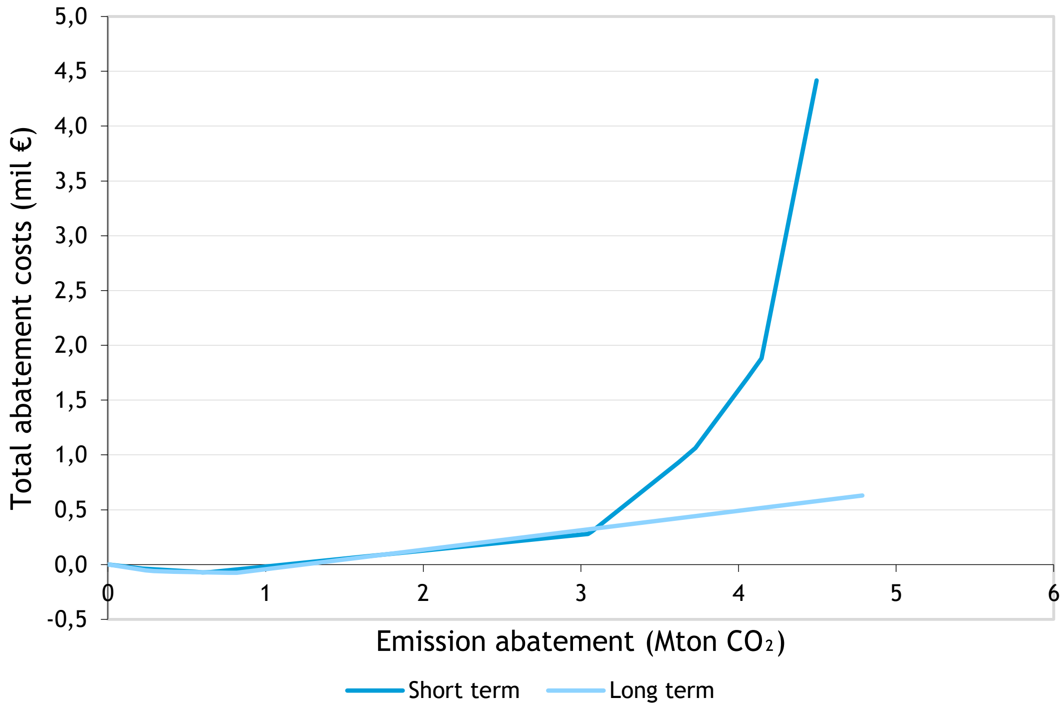
From the calculations of the marginal abatement costs, one can calculate the total costs of a given amount of abatement as well as the cost effectiveness of each individual measure.

The *total costs* are given for the short term (until 2030) and the long term (until 2050) in the figure below. Here, in the model it is assumed that measures are taken ordered by their cost efficiency, that is, the most cost-efficient measures are given priority (and considering TRL).

As a result, the findings indicate that under 1 $MtCO_2$e can be abated with zero net cost. After that, the costs increase linearly with the uptake of biodiesel. According to the MACC calculation, the total costs for abatement up to 3 $MtCO_2$e are not significantly lower on the long term, compared to the short term. However, it should be noted that potential reductions in investment costs/ prices (associated with established technology maturity processes) are not part of this calculation.

In the short term, biodiesel will not be available in enough quantities to fuel the entire fleet. This means abatement past 3 megatons will require other, less cost-efficient measures. When biodiesel is sufficiently available over the long term, this renders all less cost-efficient measures unnecessary, looking specifically from a cost efficiency standpoint.

Figure 3.3 Short- and long-term total abatement costs for the total European fisheries fleet



Source: project specific version of CE-Ship model.

3.2.4 Cost efficiency per individual measure

In the marginal abatement costs calculations, a cost efficiency per measure is calculated. This is the cost in euros per abated ton CO_2e. This cost efficiency can also be negative: this occurs when the gains from fuel use reduction outweigh the costs of the measure. Due to changing fuel costs and fuel use, the cost efficiency of the measures varies over time.

In the table below, the cost efficiencies of measures are given for short term (around 2030) and long term (before 2050). Only for measures with substantial reliable data on costs and energy/emission reduction, the cost efficiency is calculated.

The table includes several measures that are not included in the MACCs above. This is because measures that exclude each other cannot both occur in the MACC. The cost efficiency of the measures as listed below is independent from all other measures.

Table 3-9 Cost efficiency of individual innovations to abate GHG emissions on the short term (until 2030) and the long term (until 2050) of the European fishing fleet.

Measure nr	Measure	Short term cost efficiency (€/tCO_2e)	Long term cost efficiency (€/tCO_2e)
Category A: Technological Measures			
2	Frequency converters	638	637
3	Waste heat-recovery systems	-61	-108
6	Larger Propellor, Nozzle and Optimised Stern	1114	1067
7	Antifouling: hull and propellor	-73	-120
8	Use pre-and post swirl fins and stators	3366	3319
10	Propeller-rudder upgrade	1488	1441
Category B: Vessel Design and Operation			
11	Improved hull design	3233	3186
13	Energy efficient lighting systems	281	235
Category C: Alternative Propulsion			
15	Diesel-electric	3532	3532
16	Biodiesel: HVO, FAME, FT, DME	114	114
18	Methanol (bio/e-)	614	552
20	Ammonia (bio/e-)	-	321
22	Hydrogen (bio/e-)	-	5329
Category D: Wind assisted propulsion			
23	Kites	-	1070
24	Suction wings	503	365
25	Sails	2184	1858
26	Wind turbine	-	131
Category E: Fishing Gear			
28	Using a Sumwing (trawlers)	-93	-140
29	Outrig (instead of trawling)	-138	-191
30	Twinrig (instead of trawling)	230	72
34	Helix spiral-trawling net	47	-20
Category G: Facilitating Measures			
40	Smart steaming	-158	-205
42	Route-planning systems	727	732

3.3 Financial Indicators

The financial assessment of the different solutions for decarbonisation is based on a series of indicators that allow for the comparison of alternatives and to produce a ranking for them. The analysis is made in two parts, per vessel size and for each potential solution (divided into groups of solutions):

1. A *cashflow* based on EU-27 aggregate energy consumption data, from which a simple payback period (PBP), net present value (NPV), internal rate of return (IRR) and equivalent annual annuity (EAA) are calculated. In cases where there is no payback ([74]) or the payback exceeds the expected lifetime of the solution, the financial gap to reach payback is calculated.

2. A comparison of the investment results with the yearly balance sheet of a vessel from a representative Member State, i.e., a *typical vessel*. The yearly investment result is compared with the yearly revenues and with the yearly net profits. ([75]) This provides a picture of the level impact (size) of the investment on a typical balance sheet.

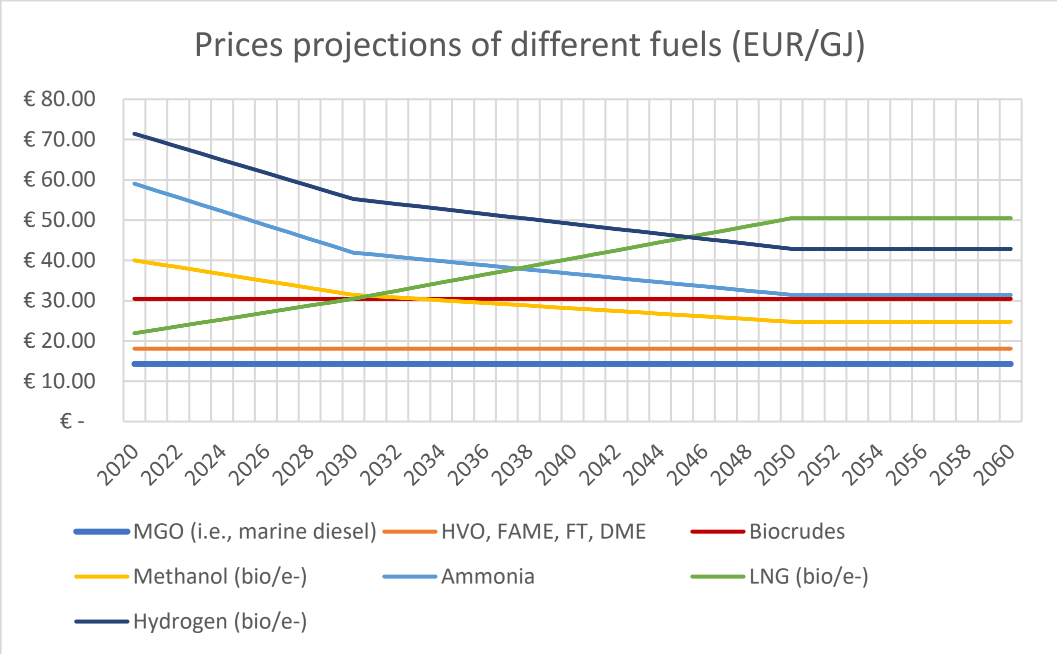
Both parts produce valuable information that will allow to rank the solutions and to assess how feasible would it be for fishers to actually invest in them. The data source for this is the latest STECF fleet segments economic performance dataset, which contains suitable data for the EU fishing fleet from 2008 to 2021, from where variables such as energy use or gross value of landings per individual fleet segment have been taken and then, averages per vessel have been calculated per Member State or as an EU27 aggregate, as needed. More information on the data used and the calculation of the indicators can be found in Annex G.

In addition, key variables for each of the solutions such as their readiness, expected lifetime, associated CAPEX and OPEX and the energy savings are consistent with the factsheets that were elaborated. For details on specific sources for this information see the fact sheets in Annex C.

The change in energy costs (energy savings) obtained for each of the possible solutions depends on the price of this energy. Because of this, we have made projections of these prices until 2050 based on literature to be used in the calculation of the indicators. In some cases, the economic lifetime of a solution exceeds the year 2050 and thus it has been assumed that prices remain constant after that point to be able to provide indicators that are comparable between the technologies. A visualisation of these projections can be seen in Figure 3.4 below.

([74]) Because the solution increases the costs of the vessel, either because it increases the yearly costs for fuel or energy, or because energy costs savings are not larger than the initial investment (CAPEX) and other operational costs (OPEX).
([75]) The definitions for the elements that conform revenues and expenses are in line with the definitions laid out by the STECF in the AER.

Figure 3.4 Price projections of marine diesel and alternative fuels



Source: Consortium elaboration based on Faber et al (2020) and ABS (2022).

The indicators for the first part have been calculated for each of the solutions and presented in the tables below (per solution category). In reality, the value of the indicators will vary on a vessel-by-vessel basis, (76) but we have provided an estimate for representative vessels. These representative vessels have been selected are mostly defined as an average vessel of every size category. For simplicity, it has been assumed that the vessel will still be in service during the economic lifetime of the technology.

For the second part of the analysis, EU27 aggregate values are not suitable as some elements of the balance sheets can vary significantly between Member States and thus Member State-specific values have been used. To select which Member States to use, the most representative Member State per type category has been chosen on the basis of the largest total vessel tonnage. The results of this analysis are summarised also in the tables below, for each of the solution categories.

3.3.1 Engine and propulsion

In this category of solutions, we have estimated the indicators for frequency converters, waste heat recovery system, larger propeller, nozzle and optimised stern; antifouling, the use of pre and post swirl fin stators and a propeller-rudder upgrade. It is worth noting that frequency converters are not applicable for SSCF vessels and waste heat recovery systems are also not viable for SSCF and DWF. Notably, electric onboard consumers, oil filtration systems, shore power and anti-roll systems have been omitted, the first due to its application being very case specific depending on the equipment of a specific vessel and the rest due to uncertain or limited information being currently available. More details and information about each solution can be found in the factsheets on Annex C.

(76) They could remain relatively similar for vessels on the same fleet segment (same size category and same gear), but there are still other factors that influence, for example, specific conditions on a Member State, or a basin.

Table 3-10 Financial indicators of the proposed solution in engine and propulsion for vessels of varied sizes, first part

# [77]	Technology	Vessel type	Payback period (years)	NPV (2023 EUR)	Internal Rate of Return (IRR)	Equivalent Annual Annuity (EAA)	Financial gap for payback within lifetime (if any)
2	Frequency converters	LSF	-	-€ 141,625.27	-	-€ 9,065.71	€ 180,464.29
		DWF	-	-€ 223,785.29	-5%	-€ 14,324.94	€ 168,278.46
3	Waste heat recovery systems	LSF	11.00	€ 4,175.79	10%	€ 267.30	€ 0.00
6	Larger Propeller, Nozzle and Optimised Stern	SSCF	-	-€ 189,868.16	-	-€ 19,014.11	€ 196,824.05
		LSF	-	-€ 372,035.74	-21%	-€ 37,257.05	€ 371,033.13
		DWF	10.00	€ 83,710.36	6%	€ 8,383.07	€ 0.00
7	Antifouling: hull and propellor	SSCF	-	-€ 7,180.04	-53%	-€ 1,369.68	€ 7,413.67
		LSF	5.00	€ 4,682.55	18%	€ 893.25	€ 0.00
		DWF	2.00	€ 171,065.38	184%	€ 32,632.76	€ 0.00
8	Use pre-and post-swirl fins and stators	SSCF	-	-€ 369,781.74	-	-€ 61,609.19	€ 384,521.17
		LSF	-	-€ 408,060.79	-56%	-€ 67,986.85	€ 423,094.23
		DWF	-	-€ 353,402.63	-28%	-€ 58,880.28	€ 351,456.50
10	Propeller-rudder upgrade	SSCF	-	-€ 90,124.86	-21%	-€ 5,769.07	€ 93,045.57
		LSF	-	-€ 84,102.67	-6%	-€ 5,383.58	€ 70,452.62
		DWF	24.00	-€ 170,583.87	1%	-€ 10,919.41	N/A

Sources: consortium elaboration based on data collected from the STECF dataset, factsheets and alternative fuels model (CE-Ship) results. Dashes are put to mark cases where the indicator could not be estimated due to a variety of reasons. For example, in the case of the payback period, it is possible that the sum of OPEX and fuel costs (savings) results in a net cost, or in other words, the cashflow is negative because the fuel costs savings do not offset the operational expenditure, so there cannot be any payback. Alternatively, the investment does not generate enough savings to cover all the expenses before the end of the economic lifetime of the solution, therefore a payback is also unrealistic. In the case of the IRR, it cannot be calculated where there are only positive or only negative cashflows since a discount rate that would make the NPV equal to zero cannot exist in this case. It can also be that the calculation of the IRR does not mathematically have a unique solution. ([78])

For the set of solutions in the table above, a set of indicators related to the performance of a (representative) vessel that incorporates the solution have also been estimated and can be found in the table below.

([77]) The numbering system corresponds with the factsheets and given that the indicators cannot be estimated for all the possible solutions, some numbers may be missing from these tables.
([78]) Mugeraya, Srinivasa (2004). Solutions to the deficiencies of IRR and NPV, including multiple IRRs (December 15, 2004). Available from: http://dx.doi.org/10.2139/ssrn.4483819

Table 3-11 Financial indicators of the proposed solution in engine and propulsion for vessels of varied sizes on specific Member States, second part

# (79)	Technology	Vessel type	Representative member state chosen	Ratio of investment results to total revenue	Ratio of investment results to profits
2	Frequency converters	LSF	Spain	-3.17%	-198.82%
		DWF	Spain	-0.18%	-1.28%
3	Waste heat recovery systems	LSF	Spain	0.07%	1.44%
6	Larger Propeller, Nozzle and Optimised Stern	SSCF	Greece	-99.96%	-
		LSF	Spain	-14.00%	-
		DWF	Spain	-1.13%	-8.63%
7	Antifouling	SSCF	Greece	-7.76%	-
		LSF	Spain	-0.06%	-1.28%
		DWF	Spain	0.77%	5.16%
8	Use pre-and post-swirl fins and stators	SSCF	Greece	-357.55%	-
		LSF	Spain	-24.97%	-
		DWF	Spain	-1.24%	-9.55%
10	Propeller-rudder upgrade	SSCF	Greece	-24.01%	-
		LSF	Spain	-1.43%	-43.05%
		DWF	Spain	0.01%	0.07%

Sources: consortium elaboration based on data collected from the STECF dataset, factsheets and alternative fuels model (CE-Ship) results. Dashes are put to mark cases where the indicator could not be estimated, particularly in the case of the ratio of investment results to profits when the vessels do not turn a profit with the investment. Negative ratios indicate that the investment decreases the profitability of the vessel and positive ratios indicate an improvement of profitability. It is possible that the investment increases revenues but not to a degree where a vessel which is slightly loss-making (according to the definitions of revenues and costs used by the STECF) turns a profit.

3.3.2 Vessel design and operations

In this category of solutions, we have estimated the indicators for an improved hull design and energy-efficient lighting systems. It is worth noting that energy efficient lighting systems are not relevant for SSCF vessels and thus this case has not been estimated. Additionally, air cavity lubrication systems have been deemed not relevant for the fisheries context as it is applicable only on ships with large and flat bottoms. More details and information about each solution can be found in the factsheets on Annex C.

(79) The numbering system corresponds with the factsheets and given that the indicators cannot be estimated for all the possible solutions, some numbers may be missing from these tables.

Table 3-12 Financial indicators of the proposed solution in vessel design and operations for vessels of varied sizes, first part

# ([80])	Technology	Vessel type	Payback period (years)	NPV (2023 EUR)	Internal Rate of Return (IRR)	Equivalent Annual Annuity (EAA)	Financial gap for payback within lifetime (if any)
11	Improved hull design	SSCF	-	-€ 335,011.85	-	-€ 21,444.77	€ 347,556.96
		LSF	-	-€ 423,832.61	-11%	-€ 27,130.36	€ 408,884.38
		DWF	22.00	-€ 251,163.43	1%	-€ 16,077.46	€ 0.00
13	Energy efficient lighting systems	LSF	-	-€ 80,970.75	-9%	-€ 5,183.10	€ 75,702.50
		DWF	9.00	€ 186,558.99	13%	€ 11,942.01	€ 0.00

Sources: consortium elaboration based on data collected from the STECF dataset, factsheets and alternative fuels model (CE-Ship) results. Dashes are put to mark cases where the indicator could not be estimated due to a variety of reasons. For example, in the case of the payback period, it is possible that the sum of OPEX and fuel costs (savings) results in a net cost, or in other words, the cashflow is negative because the fuel costs savings do not offset the operational expenditure, so there cannot be any payback. Alternatively, the investment does not generate enough savings to cover all the expenses before the end of the economic lifetime of the solution, therefore a payback is also unrealistic. In the case of the IRR, it cannot be calculated where there are only positive or only negative cashflows since a discount rate that would make the NPV equal to zero cannot exist in this case. It can also be that the calculation of the IRR does not mathematically have a unique solution.

For the set of solutions in the table above, a set of indicators related to the performance of a (representative) vessel that incorporates the solution have also been estimated and can be found in the table below.

Table 3-13 Financial indicators of the proposed solution in vessel design and operations for vessels of varied sizes on specific Member States, second part

# ([81])	Technology	Vessel type	Representative member state chosen	Ratio of investment results to total revenue	Ratio of investment results to profits
11	Improved hull design	SSCF	Greece	-90.25%	-
		LSF	Spain	-7.22%	-
		DWF	Spain	0.09%	0.61%
13	Energy efficient lighting systems	LSF	Spain	-1.38%	-40.73%
		DWF	Spain	0.37%	2.53%

Sources: consortium elaboration based on data collected from the STECF dataset, factsheets and alternative fuels model (CE-Ship) results. Dashes are put to mark cases where the indicator could not be estimated, particularly in the case of the ratio of investment results to profits when the vessels do not turn a profit with the investment. Negative ratios indicate that the investment decreases the profitability of the vessel and positive ratios indicate an improvement of profitability. It is possible that the investment increases revenues but not to a degree where a vessel which is slightly loss-making (according to the definitions of revenues and costs used by the STECF) turns a profit.

([80]) The numbering system corresponds with the factsheets and given that the indicators cannot be estimated for all the possible solutions, some numbers may be missing from these tables.
([81]) The numbering system corresponds with the factsheets and given that the indicators cannot be estimated for all the possible solutions, some numbers may be missing from these tables.

3.3.3 Alternative propulsion

In this category of solutions, we have estimated the indicators for diesel-electric propulsion, biodiesel, biocrudes, methanol, ammonia, LNG and hydrogen. It is worth noting that full electrification and ethanol have been excluded due to several uncertainties, for example, in the readiness and development in the technology. In the case of ethanol, it is worth noting that this is hardly considered an option in the maritime sector. More details and information about each solution can be found in the factsheets on Annex C.

Table 3-14 Financial indicators of the proposed solution in alternative propulsion for vessels of varied sizes, first part

# ([82])	Technology	Vessel type	Payback period (years)	NPV (2023 EUR)	Internal Rate of Return (IRR)	Equivalent Annual Annuity (EAA)	Financial gap for payback within lifetime (if any)
15	Diesel-electric	SSCF	-	-€ 477,716.01	-	-€ 30,579.54	€ 495,113.93
		LSF	-	-€ 645,238.35	-11%	-€ 41,302.97	€ 628,512.50
		DWF	17.00	-€ 14,371.75	4%	-€ 919.96	€ 0.00
16	Biodiesel: HVO, FAME, FT, DME	SSCF	-	-€ 13,175.33	-	-€ 843.38	€ 21,269.44
		LSF	-	-€ 222,698.68	-	-€ 14,255.38	€ 357,128.91
		DWF	-	-€ 2,719,766.17	-	-€ 174,097.57	€ 4,359,568.00
17	Biocrudes: SVO, PO, HTL, SO	SSCF	-	-€ 39,636.61	-	-€ 2,537.22	€ 63,615.40
		LSF	-	-€ 880,632.99	-	-€ 56,371.05	€ 1,410,020.57
		DWF	-	-€ 10,928,546.06	-	-€ 699,557.68	€ 17,496,070.88
18	Methanol (bio/e-)	SSCF	-	-€ 54,728.80	-	-€ 3,503.30	€ 98,812.04
		LSF	-	-€ 694,712.81	-	-€ 44,469.93	€ 1,346,307.38
		DWF	-	-€ 8,011,235.67	-	-€ 512,814.92	€ 15,867,969.33
20	Ammonia (bio/e-)	SSCF	-	-€ 92,780.17	-	-€ 5,939.04	€ 140,084.87
		LSF	-	-€ 1,482,027.55	-	-€ 94,867.49	€ 2,357,140.80
		DWF	-	-€ 17,453,338.11	-	-€ 1,117,222.43	€ 28,455,149.58
21	LNG (bio/e-)	SSCF	-	-€ 89,419.07	-	-€ 5,723.89	€ 132,161.39
		LSF	-	-€ 1,213,406.99	-	-€ 77,672.56	€ 2,072,111.61
		DWF	-	-€ 15,312,185.44	-	-€ 980,163.04	€ 26,128,987.14
22	Hydrogen (bio/e-)	SSCF	-	-€ 88,792.09	-	-€ 5,683.76	€ 195,873.25
		LSF	-	-€ 1,269,611.89	-	-€ 81,270.35	€ 3,064,758.37
		DWF	-	-€ 15,537,171.84	-	-€ 994,564.87	€ 38,301,140.20

Sources: consortium elaboration based on data collected from the STECF dataset, factsheets and alternative fuels model (CE-Ship) results. Dashes are put to mark cases where the indicator could not be estimated due to a variety of reasons. For example, in the case of the payback period, it is possible that the sum of OPEX and fuel costs (savings) results in a net cost, or in other words, the cashflow is negative because the fuel costs savings do not offset the operational expenditure, so there cannot be any payback. Alternatively, the investment does not generate enough savings to cover all the expenses before the end of the economic lifetime of the solution, therefore a payback is also unrealistic. In the case of the IRR, it cannot be calculated where there are only positive or only negative cashflows since a discount rate that would make the NPV equal to zero cannot exist in this case. It can also be that the calculation of the IRR does not mathematically have a unique solution.

For the set of solutions in the table above, a set of indicators related to the performance of a (representative) vessel that incorporates the solution have also been estimated and can be found in the table below.

([82]) The numbering system corresponds with the factsheets and given that the indicators cannot be estimated for all the possible solutions, some numbers may be missing from these tables.

Table 3-15 Financial indicators of the proposed solution in alternative propulsion for vessels of varied sizes on specific Member States, second part

# ([83])	Technology	Vessel type	Representative member state chosen	Ratio of investment results to total revenue	Ratio of investment results to profits
15	Diesel-electric	SSCF	Greece	-128.40%	-
		LSF	Spain	-10.99%	-
		DWF	Spain	0.44%	3.00%
16	Biodiesel: HVO, FAME, FT, DME	SSCF	Greece	-7.18%	-
		LSF	Spain	-3.99%	-511.12%
		DWF	Spain	-4.08%	-40.24%
17	Biocrudes: SVO, PO, HTL, SO	SSCF	Greece	-23.27%	-
		LSF	Spain	-15.11%	-
		DWF	Spain	-16.31%	-
18	Methanol (bio/e-)	SSCF	Greece	-44.50%	-
		LSF	Spain	-24.79%	-
		DWF	Spain	-24.91%	-
20	Ammonia (bio/e-)	SSCF	Greece	-66.95%	-
		LSF	Spain	-40.99%	-
		DWF	Spain	-42.21%	-
21	LNG (bio/e-)	SSCF	Greece	-28.03%	-
		LSF	Spain	-12.09%	-
		DWF	Spain	-12.51%	-727.99%
22	Hydrogen (bio/e-)	SSCF	Greece	-91.54%	-
		LSF	Spain	-53.87%	-
		DWF	Spain	-56.86%	-

Sources: consortium elaboration based on data collected from the STECF dataset, factsheets and alternative fuels model (CE-Ship) results. Dashes are put to mark cases where the indicator could not be estimated, particularly in the case of the ratio of investment results to profits when the vessels do not turn a profit with the investment. Negative ratios indicate that the investment decreases the profitability of the vessel and positive ratios indicate an improvement of profitability. It is possible that the investment increases revenues but not to a degree where a vessel which is slightly loss-making (according to the definitions of revenues and costs used by the STECF) turns a profit.

3.3.4 Assisted propulsion: Wind

In this category of solutions we have estimated the indicators for kites, suction wings, sails and wind turbines. It is worth noting that the first three are not applicable on SSCF vessels due to factors such as space onboard, vessel stability and proximity to the coast. Notably, flettner rotors have been omitted on account of the large space needed onboard, which is not typically available on fishing vessels. More details and information about each solution can be found in the factsheets on Annex C.

([83]) The numbering system corresponds with the factsheets and given that the indicators cannot be estimated for all the possible solutions, some numbers may be missing from these tables.

Table 3-16 Financial indicators of the proposed solution in assisted propulsion for vessels of varied sizes, first part

# [84]	Technology	Vessel type	Payback period (years)	NPV (2023 EUR)	Internal Rate of Return (IRR)	Equivalent Annual Annuity (EAA)	Financial gap for payback within lifetime (if any)
23	Kites	LSF	-	-€ 748,266.47	-	-€ 47,898.01	€ 1,039,256.25
		DWF	-	-€ 555,467.28	-5%	-€ 35,556.55	€ 444,250.00
24	Suction wings	LSF	-	-€ 468,136.18	-	-€ 29,966.32	€ 611,776.88
		DWF	-	-€ 620,479.48	-	-€ 39,718.11	€ 762,637.50
25	Sails	LSF	-	-€ 945,592.38	-	-€ 60,529.22	€ 1,122,637.50
		DWF	-	-€ 1,381,708.85	-	-€ 88,445.90	€ 1,699,335.73
26	Wind turbines	SSCF	-	-€ 9,813.62	-13%	-€ 628.19	€ 9,778.48
		LSF	19.00	-€ 2,174.97	3%	-€ 139.22	€ 0.00
		DWF	3.00	€ 205,060.91	85%	€ 13,126.35	€ 0.00

Sources: consortium elaboration based on data collected from the STECF dataset, factsheets and alternative fuels model (CE-Ship) results. Dashes are put to mark cases where the indicator could not be estimated due to a variety of reasons. For example, in the case of the payback period, it is possible that the sum of OPEX and fuel costs (savings) results in a net cost, or in other words, the cashflow is negative because the fuel costs savings do not offset the operational expenditure, so there cannot be any payback. Alternatively, the investment does not generate enough savings to cover all the expenses before the end of the economic lifetime of the solution, therefore a payback is also unrealistic. In the case of the IRR, it cannot be calculated where there are only positive or only negative cashflows since a discount rate that would make the NPV equal to zero cannot exist in this case. It can also be that the calculation of the IRR does not mathematically have a unique solution.

For the set of solutions in the table above, a set of indicators related to the performance of a (representative) vessel that incorporates the solution have also been estimated and can be found in the table below.

Table 3-17 Financial indicators of the proposed solution in assisted propulsion for vessels of varied sizes on specific Member States, second part

# [85]	Technology	Vessel type	Representative member state chosen	Ratio of investment results to total revenue	Ratio of investment results to profits
23	Kites	LSF	Spain	-17.77%	-
		DWF	Spain	-0.53%	-3.88%
24	Suction wings	LSF	Spain	-10.36%	-
		DWF	Spain	-0.77%	-5.73%
25	Sails	LSF	Spain	-22.31%	-
		DWF	Spain	-1.97%	-16.10%
26	Wind turbines	SSCF	Greece	-2.40%	-
		LSF	Spain	-0.04%	-0.83%
		DWF	Spain	0.32%	2.20%

Sources: consortium elaboration based on data collected from the STECF dataset, factsheets and alternative fuels model (CE-Ship) results. Dashes are put to mark cases where the indicator could not be estimated, particularly in the case of the ratio of investment results to profits when the vessels do not turn a profit with the investment. Negative ratios indicate that the investment decreases the profitability of the vessel and positive ratios indicate an improvement of profitability. It is possible that the investment increases revenues but not to a degree where a vessel which is slightly loss-making (according to the definitions of revenues and costs used by the STECF) turns a profit.

(84) The numbering system corresponds with the factsheets and given that the indicators cannot be estimated for all the possible solutions, some numbers may be missing from these tables.
(85) The numbering system corresponds with the factsheets and given that the indicators cannot be estimated for all the possible solutions, some numbers may be missing from these tables.

3.3.5 Fishing gear

In this category of solutions, we have estimated the indicators for sumwings, outrigs, twinrigs and helix spiral trawling nets, although none of these are applicable to SSCF vessels as they do not typically use trawling techniques. Additionally, outrigs and twinrigs are not typically applied on DWF vessels either. The use of helix spiral-trawling on these vessels is also uncertain. Notably, the use of lighter trawl doors, lighter nets, or alternative netting designs, as well as a change from active to passive gears have not been considered in this analysis as their performance would be case-specific (depending on the gear previously installed and the operational conditions and target species, for example). The use of sledges has also been omitted due to uncertainties in the data. More details and information about each solution can be found in the factsheets on Annex C.

Table 3-18 Financial indicators of the proposed solution in fishing gear for vessels of varied sizes, first part

# ([86])	Technology	Vessel type	Payback period (years)	NPV (2023 EUR)	Internal Rate of Return (IRR)	Equivalent Annual Annuity (EAA)	Financial gap for payback within lifetime (if any)
28	Using a Sumwing (trawlers)	LSF	8.00	€ 49,221.29	14%	€ 3,150.75	€ 0.00
		DWF	1.00	€ 1,126,266.08	-	€ 72,094.50	€ 0.00
29	Outrig (instead of trawling)	LSF	1.00	€ 75,147.39	-	€ 9,264.99	€ 0.00
30	Twinrig (instead of trawling)	LSF	-	-€ 382,530.56	-12%	-€ 24,486.53	€ 374,857.25
34	Helix spiral-trawling net	LSF	-	-€ 195,573.89	-	-€ 12,519.07	€ 341,281.25

Sources: consortium elaboration based on data collected from the STECF dataset, factsheets and alternative fuels model (CE-Ship) results. Dashes are put to mark cases where the indicator could not be estimated due to a variety of reasons. For example, in the case of the payback period, it is possible that the sum of OPEX and fuel costs (savings) results in a net cost, or in other words, the cashflow is negative because the fuel costs savings do not offset the operational expenditure, so there cannot be any payback. Alternatively, the investment does not generate enough savings to cover all the expenses before the end of the economic lifetime of the solution, therefore a payback is also unrealistic. In the case of the IRR, it cannot be calculated where there are only positive or only negative cashflows since a discount rate that would make the NPV equal to zero cannot exist in this case. It can also be that the calculation of the IRR does not mathematically have a unique solution.

For the set of solutions in the table above, a set of indicators related to the performance of a (representative) vessel that incorporates the solution have also been estimated and can be found in the table below.

([86]) The numbering system corresponds with the factsheets and given that the indicators cannot be estimated for all the possible solutions, some numbers may be missing from these tables.

Table 3-19 Financial indicators of the proposed solution in fishing gear for vessels of varied sizes on specific Member States, second part

# ([87])	Technology	Vessel type	Representative member state chosen	Ratio of investment results to total revenue	Ratio of investment results to profits
28	Using a Sumwing (trawlers)	LSF	Spain	0.83%	14.78%
		DWF	Spain	1.71%	10.70%
29	Outrig (instead of trawling)	LSF	Spain	-0.66%	-16.07%
30	Twinrig (instead of trawling)	LSF	Spain	-8.05%	-
34	Helix spiral-trawling net	LSF	Spain	-7.76%	-

Sources: consortium elaboration based on data collected from the STECF dataset, factsheets and alternative fuels model (CE-Ship) results. Dashes are put to mark cases where the indicator could not be estimated, particularly in the case of the ratio of investment results to profits when the vessels do not turn a profit with the investment. Negative ratios indicate that the investment decreases the profitability of the vessel and positive ratios indicate an improvement of profitability. It is possible that the investment increases revenues but not to a degree where a vessel which is slightly loss-making (according to the definitions of revenues and costs used by the STECF) turns a profit.

3.3.6 On-board processing operations

Generally speaking, this group of technologies is relevant for vessels that process fish onboard (so not relevant for SSCF vessels) and it includes technologies such as multistage mono-block ice pumps, cogged (instead of flat) V-belts in cooling systems and the use of natural refrigerants for freezing. There are, however, significant uncertainties regarding the use of these technologies on fishing vessels and its results in terms of decarbonisation and thus it was not possible to reasonably estimate any indicators for them.

3.3.7 Facilitating practices

In this category of solutions, we have estimated the indicators for smart steaming, route optimisation devices, energy audits and BlueBox. It is worth noting that smart steaming has not been deemed relevant for SSCF vessel due to potential limited benefits. Notably, slow steaming has been omitted as its benefits can vary highly across the fleet, but also given that it may be that estimates given in literature are too high for the case where this is a behavioural measure (as opposed to, for example, derating engines, which is very costly). Additionally, onboard monitoring systems have also been omitted due to being case specific. More details and information about each solution can be found in the factsheets on Annex C.

([87]) The numbering system corresponds with the factsheets and given that the indicators cannot be estimated for all the possible solutions, some numbers may be missing from these tables.

Table 3-20 Financial indicators of the proposed solution in facilitating practices for vessels of varied sizes, first part

# ([88])	Technology	Vessel type	Payback period (years)	NPV (2023 EUR)	Internal Rate of Return (IRR)	Equivalent Annual Annuity (EAA)	Financial gap for payback within lifetime (if any)
41	Smart steaming	LSF	1.00	€ 39,676.81	-	€ 2,429.75	€ 0.00
		DWF	1.00	€ 495,031.39	-	€ 30,315.00	€ 0.00
42	Route optimisation: route planning system devices	SSCF	-	-€ 24,557.75	-	-€ 1,571.99	€ 49,834.18
		LSF	-	-€ 9,263.82	-	-€ 593.00	€ 16,353.75
		DWF	1.00	€ 184,385.64	-	€ 11,802.89	€ 0.00
43	Energy audits	SSCF	-	-€ 1,395.33	-	-€ 1,451.14	€ 1,451.14
		LSF	-	-€ 995.31	-	-€ 1,035.12	€ 1,035.13
		DWF	1.00	€ 11,689.90	-	€ 12,157.50	€ 0.00
45	BlueBox	SSCF	-	-€ 22,175.15	-	-€ 1,631.69	€ 28,068.36
		LSF	8.00	€ 17,672.09	15%	€ 1,300.34	€ 0.00
		DWF	1.00	€ 576,511.17	-	€ 42,420.70	€ 0.00

Sources: consortium elaboration based on data collected from the STECF dataset, factsheets and alternative fuels model (CE-Ship) results.
Dashes are put to mark cases where the indicator could not be estimated due to a variety of reasons. For example, in the case of the payback period, it is possible that the sum of OPEX and fuel costs (savings) results in a net cost, or in other words, the cashflow is negative because the fuel costs savings do not offset the operational expenditure, so there cannot be any payback. Alternatively, the investment does not generate enough savings to cover all the expenses before the end of the economic lifetime of the solution, therefore a payback is also unrealistic. In the case of the IRR, it cannot be calculated where there are only positive or only negative cashflows since a discount rate that would make the NPV equal to zero cannot exist in this case. It can also be that the calculation of the IRR does not mathematically have a unique solution.

For the set of solutions in the table above, a set of indicators related to the performance of a (representative) vessel that incorporates the solution have also been estimated and can be found in the table below.

Table 3-21 Financial indicators of the proposed solution in facilitating practices for vessels of varied sizes on specific Member States, second part

# ([89])	Technology	Vessel type	Representative member state chosen	Ratio of investment results to total revenue	Ratio of investment results to profits
41	Smart steaming	LSF	Spain	0.64%	11.86%
		DWF	Spain	0.71%	4.72%
42	Route planning system devices	SSCF	Greece	-20.17%	-
		LSF	Spain	-0.71%	-17.45%
		DWF	Spain	0.63%	4.21%
43	Energy audits	SSCF	Greece	-9.31%	-
		LSF	Spain	-0.60%	-14.39%
		DWF	Spain	0.28%	1.93%
45	BlueBox	SSCF	Greece	-9.03%	-
		LSF	Spain	0.14%	2.94%
		DWF	Spain	1.00%	6.55%

([88]) The numbering system corresponds with the factsheets and given that the indicators cannot be estimated for all the possible solutions, some numbers may be missing from these tables.
([89]) The numbering system corresponds with the factsheets and given that the indicators cannot be estimated for all the possible solutions, some numbers may be missing from these tables.

Sources: consortium elaboration based on data collected from the STECF dataset, factsheets and alternative fuels model (CE-Ship) results. Dashes are put to mark cases where the indicator could not be estimated, particularly in the case of the ratio of investment results to profits when the vessels do not turn a profit with the investment. Negative ratios indicate that the investment decreases the profitability of the vessel and positive ratios indicate an improvement of profitability. It is possible that the investment increases revenues but not to a degree where a vessel which is slightly loss-making (according to the definitions of revenues and costs used by the STECF) turns a profit.

From the tables above it can be seen that most of the practical solutions are readily available from a technological standpoint, with most of the solutions that are not yet available being related to alternative propulsion. Some solutions are not deemed applicable to SSCF vessels, either because they are not technically feasible (e.g., due to space limitations onboard) or because they are not relevant (e.g. onboard processing solutions, given that SSCF vessels do not process fish onboard). Once again, more details about these issues can be found in the factsheets in Annex C.

Onboard processing solutions have also been deemed not applicable given their little impact on fuel consumption and emissions compared to their alternatives. Also, solutions on netting design are too case-specific to provide an estimate, as the nets currently in use and their alternative designs will depend on the context in which the vessel operates (e.g., country and target species).

Similarly, changing the use of active gears to passive gears have a similar context specificity, but more importantly is that these changes require major investments to change the equipment of a vessel to handle the different gear, so they are not feasible for retrofitting and are better suited to newly constructed vessels. In this case, a change from active fishing to passive fishing may need to be a broader strategic move for the fleet than an individual choice from a fisher or vessel owner.

For other solutions it is important to note that payback is only reached if the investments on the solutions result in net savings every year. Conversely, if the solutions result in even more costs every year, then no payback will be possible and the payback period is indeterminate. The latter case can also happen if, for example, an innovation or solution produces fuel costs savings, but its additional operational expense requirements are larger than the fuel costs saved. For a concrete example, this is the case of applying frequency converters (solution number 2) on large scale (LSF) vessels, where the deficit to produce a payback by the end of the expected lifetime of the solution is estimated to be of EUR 180,464 for one vessel.

Another scenario in which a payback would not be realistic is when the payback period is larger than the economic lifetime. In these cases, the innovation or solution has a positive cashflow and thus results in yearly savings, but the number of years needed for those savings to cover the cost of the initial investment is larger than the lifetime of the innovation or solution (for example, before needed to replace it by making a new investment). For a concrete example, this is the case of installing larger propellers (solution number 6) for small scale (SSCF) and large scale (LSF) vessels, since the economic lifetime of the solution is between 10 and 15 years, which is not enough to produce sufficient savings.

4 AQUACULTURE – TECHNO-ECONOMIC ANALYSIS OF THE INNOVATIVE LOW-CARBON SOLUTIONS

This Chapter presents techno-economic analysis of innovative, low-carbon solutions and innovations aiming to reduce the emissions from the sector based on the hot spots identified in Table 2-28 in Chapter 2. In order to analyse these innovations, a case study approach is proposed. This approach allows us to analyse the solutions and innovations identified representing different scenarios across Member States, production sizes focused on the main segments and representative farm conditions. This approach better reflects the diversity of the aquaculture sector and the specific technical and socio-economic aspects of each aquaculture typology, which translates to segment-specific solutions and innovations. Therefore, this Chapter will present a technical and economical assessment of innovations and solutions that best fit each aquaculture typology identified in Chapter 2 underrepresenting farming conditions across EU. The Chapter is structured as follows:

- Section 4.1 gives an overview of actions for improving energy and feeding efficiency which could be applied across segments.
- Section 4.2 presents the rationale for selecting a few representative case studies and the methodology used for conducting the techno-economic analysis.
- Section 4.3 presents the results of the case studies, which are focused on short-term and long-term innovation in energy sources and husbandry practices.
- Section 4.4 provides some estimates of the reduction of CO_2e emissions achievable for EU aquaculture, based on the results of section 4.3.

Figure 4 presents all the potential pathways for greenhouse gas emissions in the aquaculture sector from fed production to depuration and processing of products produced at farms. Innovations and solutions analysed in this chapter covered GHG emission hotspots identified along the whole aquaculture value chain. This approach highlights the importance of circularity and the LCA approach when assessing the impact of solutions and innovations aiming to reduce GHG emissions.

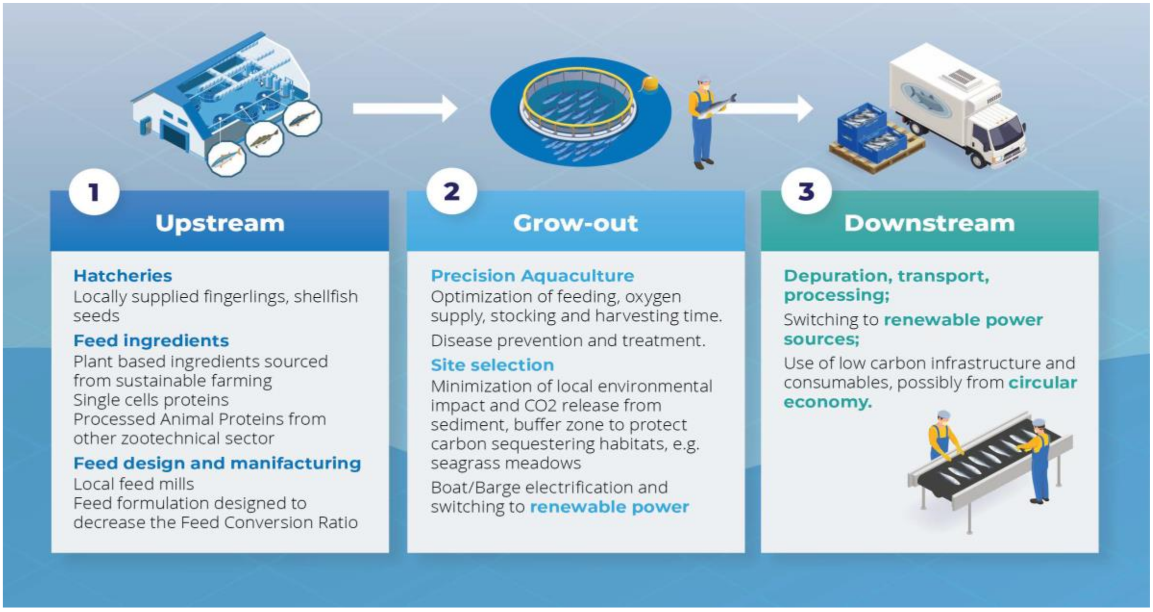


Figure 4. ***Potential pathways for greenhouse gas emissions reductions from fed finfish mariculture, for upstream, downstream and at the farm site.***

4.1 Increasing energy and feeding efficiency

In this section, an overview of actions for improving energy and feeding efficiency which could be applied across segments is analysed. In this section, we will analyse the following solutions to increase energy and feeding efficiency:

- Energy management and audit
- Precision fish farming
- Novel feed formulations

Energy management and audit

Not until recently, energy efficiency has drawn attention when analysing improvements in the aquaculture sector. The lack of stability in the energy price has stressed the need to establish energy costs as a priority together with feed. The first step towards increasing energy efficiency is including energy management as a routine practice in the management of aquafarms.

Energy management includes the identification of energy-consuming units and factors influencing energy demand, energy auditing (i.e., systematic review of the current energy flows of a company or production plant) and definition of energy indicators. Furthermore, energy management includes the development of energy-related goals and increased competence**.**

Energy management would be very important for recirculation systems, RAS, for which, according to research by Badiola and coauthors in 2012, a better understanding of key factors affecting energy use in relation to water quality and fish requirements could be more important than technical improvements. ([90]) The introduction of energy management could lead to a reduction in total energy use by 2-10%. ([91])

Despite the opportunities for aquafarms, energy efficiency is not a priority for aquafarms, as feed is regarded as the main operational cost item historically due to the mostly stable price of energy and the reduced energy input needed for aquaculture exploitations, e.g., the most energy-demanding processes in aquaculture occur upstream and downstream, namely feed production, hatchery, depuration, etc. As a result, energy analysis and energy efficiency modelling are new and unexplored topics in the aquaculture sector, compared, for example, to the building sector. However, this situation is changing, as a consequence of Russia’s unprovoked act of aggression against Ukraine, energy costs and price of raw materials strongly depending on energy use, i.e., liquid oxygen, have rapidly increased: therefore, farm owners have only recently realised the importance of optimising energy use.

([90]) Badiola, M., Mendiola, D., Bostock, J., 11 2012. Recirculating Aquaculture Systems (RAS) analysis: Main issues on management and future challenges. Aquacultural Engineering 51, 26–35.
([91]) Nistad, A., A., 2020. Current and future energy use for Atlantic Salmon farming in recirculating aquaculture systems in Norway. NTNU Master Thesis. ttps://www.ntnu.no/bridge/en/project/current-and-future-energy-use-atlantic-salmon-farming-recirculating-aquaculture-systems

Implementing Precision Fish Farming approaches (Segments 1.2 and 2)

Precision Fish Farming is an innovative approach to fish farm management which extends and adapts to aquaculture Precision Livestock Farming, is a conceptual framework introduced in terrestrial farming about 20 years ago ([92]). The general scope of PFF is to support farmer decisions concerning the management of fish farms by improving accuracy, precision and repeatability in farming operations; thus, leading to improvements in both animal welfare and productivity. These goals can be achieved by designing and implementing a control system, based on the integration of real-time data and models. A PFF system is made up of a real-time observation component, a dynamic model and a "control" component, which provides support for decisions and may also implement decisions: this could be done through IoT (Internet of Things). The observation component provides real-time data on a set of variables related to the fish's behaviour and physiological state, e.g., fish weight and environmental variables, e.g. water temperature, dissolved oxygen concentration and pH, which can affect fish welfare and feed demand. The dynamic model is the core of a PFF system: the model predicts how some key physiological variables could change, based on management decisions. For example, feed demand can be predicted based on fish size, water temperature and oxygen concentration: in a land-based system, the latter can be controlled by supplying oxygen but, on the other hand, fish size and water temperature also affect fish oxygen demand. Using a dynamic model, it is possible to predict fish oxygen demand and, in turn, suggest the optimal level of oxygen supply required to keep the oxygen concentration above a threshold which ensures the most efficient utilization of the feed ration. ([93])

Management systems based on PFF are being implemented in both marine and land-based aquaculture but at different paces, with carp farming probably lagging behind the other sub-segment: at present, the main limitation is the availability and affordability of devices for the on-line non-invasive monitoring of fish size/weight distribution, fish position in cages and fish welfare-related indicators, e.g., wounds. Devices based on pattern recognition and AI, however, are being prototyped and produced and should be affordable also for medium size farms. In the context of this study, the adoption of PFF could lead in the next few years. The adoption of PFF could lead to 1) optimise the feed rations, thus leading to a decrease in the Feed Conversion Ratio (FCR), which is the overall ratio between feed delivered and fish biomass yield; 2) optimise oxygen supply in land-based farms. At present, FCR is around 1 in land-based trout farming but is still around 2 in seabass/seabream farming. Therefore, a larger scope for increasing feeding efficiency appears in Segment 1.2. On the other hand, liquid oxygen production and aerators are energy demanding due to the increase in energy costs, the optimisation of oxygen supply has become a relevant issue in land-based farming. The potential reduction in CO_2e emissions from seabream farming in relation to a decrease in FCR was investigated by Garcia and coauthors in 2016, who estimated that a 15% decrease in FCR would lead to an 11% decrease in CO_2e emissions. ([94]) Results obtained in the

([92]) Føre, M., Frank, K., Norton, T., Svendsen, E., Alfredsen, J. A., Dempster, T., Eguiraun, H., Watson, W., Stahl, A., Sunde, L. M., Schellewald, C., Skøien, K. R., Alver, M. O., & Berckmans, D. (2018). Precision fish farming: A new framework to improve production in aquaculture. *Biosystems Engineering*, *173*, 176–193. https://doi.org/10.1016/j.biosystemseng.2017.10.014.

([93]) Royer, E., & Pastres, R. (2023). Data assimilation as a key step towards the implementation of an efficient management of dissolved oxygen in land-based aquaculture. *Aquaculture International*, *31*(3), 1287-1301.

([94]) García B.G.; Jiménez C.R.; Aguado-Giménez F.; García J.G., 2016 Life cycle assessment of gilthead seabream (*Sparus aurata*) production in offshore fish farms. Sustainability. 8, 1228; doi:10.3390/su8121228

ongoing EU-funded project NewTechAqua ([95]) suggests that a 10% decrease in liquid oxygen and FCR could be achieved by implementing PFF in a land-based seabass/seabream farm ([96]). The potential role of PFF in reducing CO_2e emissions will be further investigated using the model portfolio developed in Chapter 2.

Decreasing upstream CO_2e emissions: novel feed formulations

The aquafeed industry is facing several challenges, due to 1) constraints on the availability and cost of raw materials; 2) pressure from the aquafarm sector and consumers to formulate more sustainable feeds, in order to lower both the pressure on fish stocks and the environmental footprint of farmed fish. In perspective, the second factor may become even more compelling, should the Product Environmental Footprint be introduced, on a voluntary basis, in the EU as a tool for intercomparing the environmental performance of products and services.

In this rapidly evolving sector, it is difficult to identify clear trends. According to the recent literature ([97]), ([98]), ([99]), the environmental and economic sustainability of feeds for carnivorous fish could be enhanced by substituting, to a different extent, Fish Meal (FM) and Fish Oil (FO) from captured fish with 1) emerging ingredients, e.g. insects, single cells; 2) proteins from fisheries or other zootechnical sector by-products, in accordance with the principles of the circular economy. A shortage ranging from 0.4 to 1.23 million tonnes of FM can be estimated. ([100]) Emerging ingredients, in the mid/long term, could play a key role in supporting aquaculture productions but further research and, in particular, scale-up of production is required. Furthermore, the CO_2e emissions of novel feeds based on emerging ingredients, due also to the still low production volumes, still seem markedly higher, compared with those of current commercial feeds. An interesting comparison is presented by Maiolo and coauthors in their 2020 research in which LCA was applied to four novel ingredients, i.e. two microalgae species, *Tetraselmis suecica, DMB_Tetra and Tysocrisis lutea,* an insect species, Black soldier Fly and Poultry By-product meal. ([101]) The results are summarised in Table 4-1, which presents the ranges estimated in 6 scenarios of production, two for each of the first three ingredients and two allocation scenarios for the poultry by-product meal.

([95]) https://www.newtechaqua.eu/
([96]) Royer, E., & Pastres, R. (2023). Data assimilation as a key step towards the implementation of an efficient management of dissolved oxygen in land-based aquaculture. *Aquaculture International*, *31*(3), 1287-1301.
([97]) Maulu S.; Langi S.; Hasimuna O.J.; Missinhoun D.; Munganga B.P.; Hampuwo B.M.; Gabriel N.N.; Elsabagh M.; Van Doan H.; Abdul Kari Z.; Dawood M.A.O., 2022. Recent advances in the utilization of insects as an ingredient in aquafeeds: A review. Animal nutrition. Doi10.1016/j.aninu.2022.07.013
([98]) Jones S.W.; Karpol A.; Friedman S.; Maru B.T.; Tracy B.P., 2020. Recent advances in single cell protein use as a feed ingredient in aquaculture. Current Opinion in Biotechnology. doi10.1016/j.copbio.2019.12.026.
([99]) Porcino N.; Genovese L., 2022. Review on alternative meals for gilthead seabream, *Sparus aurata*. Aquaculture Research. doi10.1111/are.15770.
([100]) Jones S.W.; Karpol A.; Friedman S.; Maru B.T.; Tracy B.P., 2020. Recent advances in single cell protein use as a feed ingredient in aquaculture. Current Opinion in Biotechnology. doi10.1016/j.copbio.2019.12.026.
([101]) Maiolo S., G. Parisi, Biondi, N., Lunelli F., Tibaldi E., R. Pastres (2020). Fishmeal partial substitution within aquafeed formulations: life cycle assessment of four alternative protein sources. *The International Journal of Life Cycle Assessment* (2020) 25:1455–1471. https://doi.org/10.1007/s11367-020-01759-z

Table 4-1 Estimated CO_2e emissions for three novel ingredients (FU = 1 kg of protein).

FM substitute	GWP [CO_2e / kg of protein]
Dry microalgae meal	38.4 – 66.1
Insect Meal	2.0 – 4.9
Poultry By-product meal	0.7 – 5.4

The results presented in Table 4-1 suggest that the inclusion of even small amounts of microalgae in fish feed, at present, would markedly increase their carbon footprint. The emission intensities of meals based on insects and by-products of the poultry sector are about 10 times lower: the lower values, 0.7 kgCO_2e/kg of protein, was estimated using an "economic allocation", i.e., allocating to the by-product a fraction of the impact of broiler production based on the respective economic value of the edible part and of the by-products. Therefore, the second approach, i.e., reusing by-products from other agrifood sectors, seems a "low-hanging fruit," as the current trend towards the commercialisation of processed food generates a large amount of biomass as by-products. As a result, "0-waste" feeds were investigated also in a number of recent EU-funded projects, e.g., H2020 GAIN ([102]) and NewTechAqua ([103]).

4.2 Case studies: rationale and methodology

The results presented in Chapter 2 and the "hot spot" analysis summarised in Table 2-28 indicate that:

- Upstream processes, namely **feed production**, account for a large fraction of the CO_2e emissions of products from fish farming.
- Grow-out: on-site **energy use in marine segments**, both shellfish, S1.1 and fish S1.2, is related to the **use of fuel in serving vessels**.
- Grow-out: on-site **energy use in land-based** trout farming is due to **electricity** use.

Therefore, the energy transition pathway should be based on the following three pillars:

- decarbonising the serving vessels used in marine aquaculture.
- reducing the CO_2e emissions related to fish feed production and optimizing feed use.
- switching from grid electricity to local production from RESs in land-based farms.

Based on that and considering the large within-segment variability of CO_2e emissions, four case studies were investigated, analysing in detail how high TRL innovations related to each of the three pillars could lead to a marked decrease of CO_2e and estimating the related CAPEX and OPEX. As the results will show, in some instances, the investments required for reducing CO_2e emissions are also economically viable and, in the long term, could lead to increased aquafarming profitability.

4.2.1 Selection of case studies

Segment 1: Marine aquaculture

The marine aquaculture segment includes two different farming typologies, namely finfish farming, segment 1.1 and shellfish farming, segment 1.2. In both cases, fossil

([102]) DOI: 10.3030/773330 https://cordis.europa.eu/project/id/773330
([103]) DOI: 10.3030/862658 https://cordis.europa.eu/project/id/862658

fuels used for the propulsion of serving vessels account for a large fraction of on-site energy use, as shown in Chapter 2. Vessels are used for different purposes: in most Mediterranean seabass/seabream farms, feed is delivered by purposely equipped boats on a daily basis and mussel and oyster stock management also requires frequent visits to farms. In general, travelled distances are short and predictable, which means that it is possible to estimate more precisely, compared to fisheries, the fuel use and power engine required and therefore, on this basis, identify the most suitable alternative powering system. The results of a thorough search on web sources led to the identification of the main features of boat typologies used in Segment 1 in the EU: the results are summarised in Table 4-2. We also looked at examples of decarbonised vessels in Europe: the results are summarised in below.

The comparison of the two Tables suggests that switching to hybrid and/or fully electric vessels seems the pattern for their decarbonisation: this was confirmed by targeted interviews. Therefore, the electrification of serving vessels is one of the main steps towards the reduction of CO_2e emissions from marine aquaculture and, is likely to be the only effective measure to decrease the emissions from long-line mussel and suspended oyster farming.

The results of the mapping, however, highlighted that upstream seed production accounts for approximately 50% of the CO_2e emissions related to calm farming and, likely also for a significant contribution to that of oyster farming.

Therefore, we focused on three case studies:

- Shellfish farming – upstream: switching from grid electricity to local production from RESs in clam hatcheries.
- Shellfish farming – grow-out: electrification of serving vessels used in long-line mussel farming.
- Finfish farming – grow-out: electrification of serving vessels used in finfish farming and feeding optimisation through barges.

In addition to the results presented in this chapter, Annex J presents a sensibility analysis performed for each case study considering energy price variations of +/-25%.

Table 4-2 Examples of serving vessels propelled by fossil fuel currently operating.

Segment and farm typology	Length Over All [m]	Beam [m]	Speed range [kn]	Propulsion	Fuel capacity [L]	Engine power [kW]	Source
S1.1 Long-line mussel and oyster farming	16	5.5	11.5 - 35	Diesel	6,000	370	https://shipmar.com/products/aquaculture/
S1.2 Cage farming	9.9	3.26	9-10	Diesel	640	134	https://www.adaq.it/cantiere-nautico/Feeder-33/

Table 4-3 Examples of two fully electric serving vessels for shellfish and finfish aquaculture

Segment and farm typology	Length Over All [m]	Beam [m]	Speed range [kn]	Propulsion	Battery capacity [kWh]	Engine power [kW]	Source
S1.1 Oyster culture - Barge	11.9	3.7	-	Fully electric	80 (2 batteries)	70	https://lemarin.ouest-france.fr/secteurs-activites/peche/44219-mise-leau-dune-barge-electrique-pour-les-ostreiculteurs-bretons
S1.2 Cage farming	13.9	7.6	-	Fully electric	340	-	https://corvusenergy.com/projects/astrid-helene/

Segment 2: Freshwater aquaculture

According to the results of the mapping, Chapter 1, rainbow trout farming accounts for 30% of the CO_2e EU emissions from aquaculture. The emission intensity from the two main production typologies, i.e., Flow Through System (FTS) and RAS (Recirculation Aquaculture System) is quite different, due to the large difference in the on-site electricity use. More than 90% of the EU production comes from FTS: as one can see in Table 4-4, the on-site energy shows large variations across the EU, but the electricity use accounts for, at least 50%, of the total energy consumption. In most cases, the electricity is taken from the grid: even though the CO_2e emission intensities of the grid electricity are decreasing in most EU MS, still the EU average is 0.265 $KgCO_2e$/kWh (https://www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1), well above the emission intensity of electricity from RESs, i.e. about 0.06/0.07 for PV and 0.016 $KgCO_2e$/kWh for wind energy (small wind farm < 1 MW installed power), estimated in accordance with an LCA-approach (see also Annex B). Therefore, in accordance with the research of Wind and coauthors, switching to locally produced electricity would lead to marked decreases in the CO_2e emissions of trout farming, the actual extent of the reduction depending on the grid emission intensity of each EU MS. ([104])

Table 4-4 Total on-site energy use and electricity use in FTS trout farming (FU = 1 tonne of rainbow trout live weight at farm gate).

Source	Location	Production volume [tonne]	On-site total energy use [kWh/FU]	On-site Electricity use/FU [kWh/FU]	Total Electricity use [MWh]
Maiolo&al., 2021	Trento District (Italy)	60	606	300 (49%)	18
Maiolo&al. 2021	Trento District (Italy)	300	1806	1500 (83%	450
Sanchez-Matos&al., 2023	Galicia (Spain)	1700	1095	892 (81%)	1516

On this basis, we investigated a fourth case study:

- Rainbow trout farming – grow out: switching from grid electricity to local production from RESs.

([104]) Wind,T., M. Schumann, S. Hofer, C. Schulz, A. Brinker, 2022. Life cycle assessment of rainbow trout farming in the temperate climate zone based on the typical farm concept. Journal of Cleaner Production doi10.1016/j.jclepro.2022.134851.

Overall, the selected case studies cover **83% of the EU aquaculture production**, which, based on the results presented in Chapter 2, **accounts for 78% of the CO_2e emissions**.

4.2.2 Methodology

The **technical analysis** was performed using the purposely developed portfolio of LCA models used also for checking the consistency of the results presented in the peer-reviewed papers considered for mapping the aquaculture CO_2e emissions for the year 2019 (see Chapter 2). The model inputs, i.e., the inventories, were based, as far as possible, on those published in these papers. The models, the main sources used for the inventories and the characterisation methods used for estimating the CO_2e emissions are summarised in Table 4 5

The models were developed using the Software SimaPro, widely used in LCA aquaculture studies. In the case studies, the model portfolio was used for:

- Estimating CO_2e emissions for benchmarks.
- Estimating decreases in CO_2e emissions due to the implementation of the innovation: this was accomplished by changing some key inputs, as described in detail in each case study.

Table 4-5 Model portfolio used for the technical analysis.

LCA Model	Inventory sources	Characterization method for estimating CO_2e emissions
Clam seed production in hatchery	Martini et al, 2023, Turolla et al., 2020 ([105])	Recipe 2016 Midpoint (E)
Longline mussel farming	Martini et al. 2022 ([106])	Recipe 2016 Midpoint (E)
Fish feed production	Garcia et al., 2016 ([107])	Recipe 2016 Midpoint (E)
Seabass/seabream grow-out in cages	Garcia et al., 2016 ([108])	Recipe 2016 Midpoint (E)
Rainbow trout grow-out in FTS	Sanchez-Matos et al., 2023 ([109])	Recipe 2016 Midpoint (E)

Data concerning CAPEX, see below, related to case studies 1 and 4 were estimated assuming that a given percentage of the current electricity use would be covered by locally installed Photovoltaic panels. The surface to be covered with standard solar panels available on the market (monocrystalline, 0.490 kWp) was estimated by calculating the required installed power, which depends on the site-specific solar irradiation. Those

([105]) Martini, A., L. Aguiari, Capoccioni, F., Martinoli M., Napolitano, R., Pirlo, G., Tonachella, N., Pulcini, D., 2023. Is manila clam farming environmentally sustainable? A Life Cycle Assessment (LCA) approach applied to an Italian Ruditapes philippinarum hatchery. Sustainability, 15, 3237. https://doi.org/10.3390/su15043237.

([106]) Martini A.; Calì M.; Capoccioni F.; Martinoli M.; Pulcini D.; Buttazzoni L.; Moranduzzo T.; Pirlo G. 2022. Environmental performance and shell formation-related carbon flows for mussel farming systems. Sci. of the Total Environment, 831 (2022) 154891.

([107]) García B.G.; Jiménez C.R.; Aguado-Giménez F.; García J.G., 2016 Life cycle assessment of gilthead seabream (Sparus aurata) production in offshore fish farms. Sustainability. 8, 1228; doi:10.3390/su8121228.

([108]) García B.G.; Jiménez C.R.; Aguado-Giménez F.; García J.G., 2016 Life cycle assessment of gilthead seabream (Sparus aurata) production in offshore fish farms. Sustainability. 8, 1228; doi:10.3390/su8121228.

([109]) Sanchez-Matos, J. Regueiro L., González-García S. Vázquez-Rowe, I., 2023. Environmental performance of rainbow trout (Oncorhynchus mykiss) production in Galicia-Spain: A Life Cycle Assessment approach. Science of the Total Environment 856 – 159049.

estimates were conducted using two free software tools, namely Global Solar Atlas (110) and PVGIS (111). The monthly irradiance was estimated based on the Global Solar Atlas and then processed using PVGIS to estimate the annual energy requirements. On this basis, the total surface and then the number of panels were calculated. Other infrastructural costs related to cabling and inverters were subsequently added.

Other infrastructural costs related to cabling and inverters were then added. The reductions in CO_2e emissions for each scenario were estimated using the model portfolio developed in Chapter 2. For each case study, we developed a "benchmark," representative of the current situation, based on the inventory published in the reference paper. Then, we perturbed the benchmark, by substituting the electricity from the grid with that produced by PV, thus obtaining an estimated CO_2e emissions for each scenario.

The **financial assessment** of the different solutions for decarbonisation is based on a series of indicators for the main segments of EU aquaculture. The analysis is made using case studies that represent to the extent possible aquaculture exploitations occurring in the EU. A cashflow based on energy consumption data, which was obtained using LCA model portfolio for each aquaculture segment, from which a simple payback period (PBP), net present value (NPV) and internal rate of return (IRR) are calculated when possible. In cases where there is no payback (112) or the payback exceeds the expected lifetime of the solution, the financial gap to reach payback is calculated.

Data used

Obtaining the cashflows and financial indicators for decarbonisation solutions requires data on the energy used for each type of aquaculture segment and on its balance sheets. The data sources for this were peer-reviewed papers and targeted interviews, these data were then validated in a workshop with main actors in the Aquaculture sector. Depending on the case study and consequently on the innovation analysed the energy used varies between marine fuel and electricity.

The data used for the calculations is based on historic electricity prices of Eurostat (113) and future electricity price predictions for the EU27 (114), both including taxes. The projections for Italian electricity prices rely on the mean discrepancy between EU prices and country-specific rates documented from 2008 to 2023. This established ratio is subsequently extrapolated to project Italian electricity prices until 2050. The methodology entails computing the average difference between Italian and European electricity prices and applying this ratio to forecasting Italian electricity prices up to the year 2050.

Projections for fuel prices have also been elaborated based on the fuel scenarios from Faber et al (2020) and supplemented with projections from ABS et al. (2022), in the absence of more reliable and detailed projections, for example, from the EU Reference Scenario.

(110) https://globalsolaratlas.info/map
(111) https://re.jrx.ec.europa/pvg_tools
(112) Because the solution increases the costs of the vessel, either because it increases the yearly costs for fuel or energy, or because energy costs savings are not larger than the initial investment (CAPEX) and other operational costs (OPEX).
(113) https://ec.europa.eu/eurostat/databrowser/view/NRG_PC_205__custom_7796867/default/table?lang=en
(114) https://energy.ec.europa.eu/system/files/2014-10/trends_to_2050_update_2013_0.pdf

The parameters for the different technologies (i.e., expected lifetime, year when the solution will be available in the market, CAPEX, OPEX and electricity consumption reduction) are directly extracted from a combination of sources such as scientific and grey literature and stakeholder input to validate and fill gaps. Finally, a discount rate of 4% has been used when discounted cashflows are necessary (calculation of NPV and IRR).

The cashflows are built on the basis of the revenues and expenses that are a direct consequence of the investment or solution and consist of three components: **CAPEX** (always an expenditure), **OPEX** excluding energy costs (always an expense, or zero) and **change in energy costs** (can be savings).

While the CAPEX and OPEX are directly extracted from the literature, the change in energy costs is calculated on the basis of the energy consumption (in GJ) and the price of the marine fuel projected as explained in 0 (in EUR/GJ). For electricity, we use the change in electricity use from the grid - auto consumption.

The addition of these three values for every year forms the yearly (undiscounted) cashflow and the sum of the yearly cashflows up to a given year forms the cumulative (undiscounted) cashflow. The addition of the same three values but then discounted to 2023 (present) values using the discount rate forms the yearly discounted cashflow and the sum of these up to a given year forms the cumulative discounted cashflow.

The payback period is defined as the number of periods after which the undiscounted cashflows pay back the initial investment. In other words, the number of years counted from the beginning of the investment until the first year where the cumulative (undiscounted) cashflow is equal to or greater than zero.

It is possible for an investment that increases costs instead of saving them to never reach a payback (indeterminate payback period), or for the calculated payback to be larger than the expected lifetime (payback not realistic). The financial gap to reach payback is then equal in magnitude to the cumulative (undiscounted) cashflow at the end of the investment lifetime.

The NPV represents the total present value of the investment, or in other words, the cumulative discounted cashflow at the end of the expected lifetime. The IRR is linked to NPV and is defined as the value that the discount rate would need to be for the NPV to become equal to zero. The IRR calculation then requires both inflows and outflows in the yearly cashflows, as it would be impossible to equal zero with only inflows or only outflows. The higher the NPV and the IRR, the better the investment.

NPV and IRR have a limitation when comparing investments with different lifetimes. For example, if one were to consider two different investments that would have the same NPV, but one of them had a shorter lifetime, then that would be a better investment since it provides that value in a shorter time period, but this is not captured by the aforementioned indicators.

4.3 Case studies analysis

4.3.1 Case study 1: Shellfish hatchery

Opposite to mussel farming, oyster and clam culture relies, to a significant extent, on seeds produced in hatcheries. Seed production is energy-demanding, as it involves the production of shellfish food, i.e., phytoplanktonic cells, which is usually conducted in photobioreactors. The results presented and summarised in Chapter 2 highlight that seed production accounts for about 75% of the CO_2e emissions from clam farming, which is the third shellfish commercial species in volume produced in the EU. The on-site use of electricity in a hatchery is presented in Table 4-6: according to Martini and coauthors electricity contributed to 94% of the total emissions, 24.7 out of 26.3 CO_2e/kg of 6 mm spat. ([115]) Therefore, installing PV seems to be the most straightforward and, as we are going to see, also a financially viable solution for markedly reducing the CO_2e emissions of clam farming. The total energy use given in Table 4-6 was used for calculating the area required for installing a PV system which would provide 100% of the electricity requirements and related costs, which are given in Table 4-7. The decrease of CO_2e emissions in a scenario in which all grid electricity would be substituted from PV was estimated using the model portfolio: this would reduce the emission of a kg of spat produced by the hatchery from **22.8 to 3.125 kgCO_2/kg of 6mm spat**.

Table 4-8 presents the decrease in the total emission of clam farming, assuming that 1 kg of 6 mm spat would yield a biomass of 120 kg of commercial-size harvestable clams and the results from Turolla and coauthors 2020 research for estimating emissions from the grow-out phase. ([116])

Table 4-6 Total electricity use in a clam hatchery (FU = 1 kg of 6mm spat at farm gate).

Source	Location	Production volume [kg 6mm spat]	On-site Electricity use/FU [kWh/FU]	Total Electricity use [MWh/year]
Martini et al., 2023 ([117])	Goro (Italy)	5300	55	291.5

Table 4-7 Results of the technical analysis of PV installation at a clam hatchery in Northern Italy: production volume 5300 kg of 6 mm spat/year, on-site electricity use: 291.5 MWh/year.

% of electricity requirement.	Area required	Cost of material [Eurox1000]	Total Cost [Eurox1000]	Cost per FU [Euro/FU]	Area per FU [m^2/kg spat]
100%	906	162.8	295.5	55.7	0.17

([115]) Marchi, A., Bonaldo A., Di Biase, A., Cerri R., Scicchitano D., Nanetti, E., Candela, M., Picone, G., Capozzi, F., Dondi, F., Gatta, P., Parma, L. 2023. Towards a free wild-caught fishmeal, fish oil and soy protein in European sea bass diet using by-products from fishery and aquaculture. Aquaculture 573 (2023) 739571. https://doi.org/10.1016/j.aquaculture.2023.739571.

([116]) Turolla, E., Castaldelli, G:, Fano, E.A, Tamburini E., 2020. Life Cycle Assessment (LCA) Proves that manila clam farming (Ruditapes Philippinarum) is a fully sustainable aquaculture practice and a carbon sink. Sustainability, 12, 5252; doi:10.3390/su12135252.

([117]) Martini, A., L. Aguiari, Capoccioni, F., Martinoli M., Napolitano, R., Pirlo, G., Tonachella, N., Pulcini, D., 2023. Is manila clam farming environmentally sustainable? A Life Cycle Assessment (LCA) approach applied to an Italian Ruditapes philippinarum hatchery. Sustainability, 15, 3237. https://doi.org/10.3390/su15043237.

Table 4-8 Comparison between the CO_2e emissions of the benchmark model and those estimated in the scenario of grid electricity substitution with locally installed PV for hatchery production (FU = 1 tonne of clam harvested at farm gate).

Case study: hatchery in Goro (Italy)	Grow-out emissions [tonne CO_2e /FU]	Emissions from on-site electricity use in hatchery [tonne CO_2e /FU]	Total emissions from hatchery [tonne CO_2e /FU]	Total emissions from clam farming [tonne CO_2e/FU]
Benchmark from Martini et al., (2023) ([118]) and Turolla et al., (2020) ([119])	0.076	0.176	0.190	0.266
100% of hatchery electricity demand is covered by PV	0.076	0.032	0.046	0.122

Table 4-9 summarizes the input parameters used for calculating the cashflows for the installations of PV in a representative hatchery. In order to perform the financial assessment, a number of assumptions were made to build this case study as follows:

The photovoltaic panels were assumed to start operating just after their installation, they will immediately start functioning, leading to corresponding savings in electricity costs since the first year.

In this scenario, the yearly variable costs (OPEX) for maintenance, etc. were not considered.

Incentives (e.g., 50% of the cost is reimbursed over 10 years) were not included.

The cashflow consists of the capital expenditure (CAPEX) or initial investment, the additional operational expenditure (OPEX) associated with operating the innovation without including electricity use and electricity cost savings.

([118]) Martini, A., L. Aguiari, Capoccioni, F., Martinoli M., Napolitano, R., Pirlo, G., Tonachella, N., Pulcini, D., 2023. Is manila clam farming environmentally sustainable? A Life Cycle Assessment (LCA) approach applied to an Italian Ruditapes philippinarum hatchery. Sustainability, 15, 3237. https://doi.org/10.3390/su15043237.

([119]) Turolla, E., Castaldelli, G:, Fano, E.A, Tamburini E., 2020. Life Cycle Assessment (LCA) Proves that manila clam farming (Ruditapes Philippinarum) is a fully sustainable aquaculture practice and a carbon sink. Sustainability, 12, 5252; doi:10.3390/su12135252.

Table 4-9 Input parameters for calculating the cash flows of the hatchery production.

Variable	Value
Technological Readiness Level (TRL) in 2023	9
Expected year when TRL 9 could be reached	2023
Year of implementation	2024
Economic lifetime	25-30
CAPEX *Consists of costs for solar panels and their installation*	€ 295,482
Yearly additional cost with PV (OPEX)	N/A
Yearly electricity cost savings	The difference in the price of electricity per year
Electricity Auto consumption with PV	70%

Table 4-10 Table: average electricity price for the hatchery production

Average electricity price	
Net Present Value (NPV)	€ 501,275
Payback period	6
Year for payback	2029
Internal Rate of Return (IRR)	22%

Discussion

The results presented indicate that using the current technology, it would be possible to achieve a 53% reduction in CO_2e emissions from clam farming by switching from grid electricity to locally sourced RESs, namely PV, in hatcheries: this would lead to 75% decrease in hatchery emissions. In absolute terms, such a decrease, 0.143 tonne CO_2e/tonne clam live weight, is higher than the emissions estimated for the whole grow-out phase: this confirms that, for the aquaculture sector, the cost-effectiveness of measures to achieve the energy transition should consider the whole value chain. In this case, reducing the emissions upstream would have a far better effect than, for example, switching to electric boats for managing the grow-out phase. The results presented in Table 4-10 show that the investment required to achieve this goal is financially feasible with a payback period of 6 years. In addition, considering the expected trend of increasing demand for photovoltaic energy in the EU and therefore the increase in price of this equipment, the solution presented here is recommended to be implemented in the short term. ([120])

([120]) Zsiboracs, H., Hegedűsné Baranyai, N., Zentko, L., Morocz, A., Pocs, I., Mate, K., & Pinter, G. (2020). Electricity market challenges of photovoltaic and energy storage technologies in the European Union: Regulatory challenges and responses. *Applied sciences*, *10*(4), 1472.

Overall, the results of this case indicate that, besides being technically feasible, powering hatcheries using PV is also financially viable: this finding could be relevant also for the oyster farming sector.

4.3.2 Case study 2: Longline mussels

Long-line mussel farming is currently practised in many EU MSs, along the Mediterranean coast. The recruitment is based on wild seeds, which are often recovered from buoys and cords of farm infrastructure. Usually, a farm needs one boat, which is used for conducting husbandry practices, e.g., restocking mussels as they grow and harvesting: as mussels farmed in Class A waters can be commercialized after harvest, sorting and packaging can also be conducted on board. The results presented and summarised in Chapter 2 highlight that fuel use accounts for 79% of the CO_2e emissions related to mussel grow-out phase. As long-line farms are usually located close to the shore (1-6 nm), electrification of boats seems the most straightforward solution for achieving a marked reduction of CO_2e emissions through energy transition.

The decrease of CO_2e emissions in a scenario in which the fuel use would be replaced by the electricity sourced by local RESs, i.e., PV, was estimated based using the model portfolio and on the ratio between thermal and electric engine efficiencies and PV emission intensity presented in Annex B**.**

Table 4-11 Total fuel use in a long-line farm (FU = 1 tonne of mussel live weight at farm gate).

Source	Location	Production volume [tonne /year]	On-site fuel use/FU [MWh/FU]	Total on-site fuel use [MWh/year]
Martini et al., (2022) (121)	(Italy) 6 nm offshore.	290	1	290

Table 4-12 Results of the technical analysis of boat electrification: volume 290 tonne of mussel live weight, ready to be commercialized. FU: 1 tonne of fresh mussels, ready to be commercialized.

	On-site energy use [kWh/FU]	Total CO_2e emission [tonne /FU]	CO_2e emission due to on-site energy use [tonne/FU]	CO_2e Emission from other processes [tonne/FU]
Benchmark from Martini et al., (2022) (122)	1000	0.407	0.371	0.036
Electric boats sourced PV	413	0.065	0.029	0.036

(121) Martini A.; Calì M.; Capoccioni F.; Martinoli M.; Pulcini D.; Buttazzoni L.; Moranduzzo T.; Pirlo G. 2022. Environmental performance and shell formation-related carbon flows for mussel farming systems. Sci. of the Total Environment, 831 (2022) 154891.

(122) Martini A.; Calì M.; Capoccioni F.; Martinoli M.; Pulcini D.; Buttazzoni L.; Moranduzzo T.; Pirlo G. 2022. Environmental performance and shell formation-related carbon flows for mussel farming systems. Sci. of the Total Environment, 831 (2022) 154891.

Discussion

The results presented in this case study indicate that the electrification of serving vessels in long-line mussel farming would lead to an 84% reduction in CO_2 emissions, due to a 92% decrease in the emissions of serving vessels. In absolute terms, this change would bring mussel emissions down to about 0.065-gram CO_2e/kg of mussel, which would be lower than the total one of clam and very similar clam emissions related to the grow-out phase.

However, achieving this goal would require some improvement in the current technology for electric boats, which may lead also to lower investment.

4.3.3 Case study 3: Seabass-seabream

European seabass and gilthead seabream are often farmed in cages using the same infrastructure. The feed and Feed Conversion Ratio, or FCR, are also similar (see Annex B). Therefore, in this case, study, we assumed that both species are farmed in two representative farms, representative of seabass/seabream farm conditions in the two main EU-producing countries, i.e., Greece (55% of the EU production) and Spain (21% of the EU production). The results presented in Chapter 2 indicate that feed accounts for 50-70% of the CO_2e emissions and fuel for serving vessels is the most relevant source of CO_2e emissions related to the grow-out phase. Therefore, two innovations were investigated:

- Electrification of serving vessels.
- Changing in feeding practices, by switching from i) feed delivered using boats equipped with cannon to ii) barges.

Feeding is one of the most important husbandry practices, to ensure fish welfare and optimize biomass yield. Fish needs to be regularly fed, at least once a day, whenever the weather conditions allow it. In most seabass/seabream farms, feed is still delivered daily using boats, equipped with a cannon, i.e., a device for launching the feed pellets to a cage. As an alternative, feed can be stored in floating barges and distributed using pumps (see Annex B for more details). In this way, the number of journeys required to deliver feed is reduced, as the barge is recharged every two weeks and feeding can be controlled, for example, using video cameras and thus optimized, based on fish response. Based on information provided by barge producers and operators, a 5% reduction in feed consumption is expected. Further reductions, about 2%, could be achieved by implementing monitoring systems and software for Precision Fish Farming.

Switching from feeding boats with cannons to barges could lead to a decrease in CO_2e emissions and also provide an economic return but three factors should be carefully considered:

- OPEX: a barge must be powered, the potential reduction of opex depends on the production volume.
- CAPEX: the investment is large and may not be affordable by a SMEs
- Surge storms frequency: surge storms can severely damage a barge, therefore the risk of surge storms must be carefully factored in.

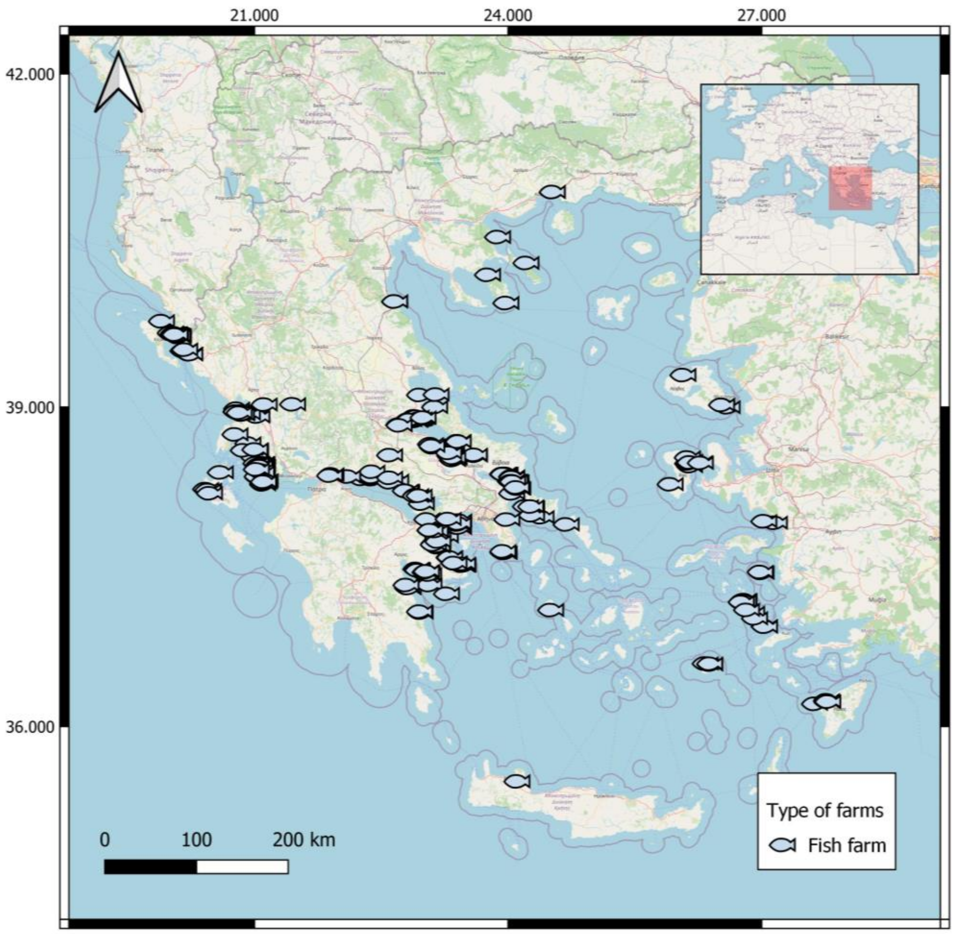
Therefore, the investment in barges volume and also in the meteorological and marine prevailing conditions seems viable for large farms located in sheltered areas.

As the production volume is an important economic variable for both CAPEX and OPEX, in accordance with the literature used for mapping the CO_2e emissions, two Representative Farms, RF were considered:

- RF 1): seabass/seabream farm in Greece producing 2,000 tons/year ([123])
- RF 2) seabass/seabream farm in Spain producing 500 tons/year ([124])

RF1 is representative of a large farm, located near the shore (1 km) and RF2 of a small-medium farm located off-shore (6 km). A pictorial distribution of fish farms in Greece and Spain is shown in Figure 4.1.

Figure 4.1 Spatial distribution of seabass/seabream farm in Greece (left) and Spain (right).



In both RFs, CO_2e emissions were estimated using the LCA model portfolio and the efficiencies of thermal and electric engines given in Annex B. To highlight the role of the innovations, the feed composition and the Feed Conversion Ratio (FCR) were standardized and, for each RF analysis two benchmark models were developed for investigating four different scenarios (S1, S2, S3 and S4):

- Benchmark model, based on desk research.
  - i) S1: The fuel used was substituted by electricity use, assuming the serving vessels would be electrified, the electricity being sourced by RESs, i.e., PV.

([123]) Kallitsis E.; Korre A.; Mousamas D.; Avramidis P. 2020. Environmental life cycle assessment of mediterranean sea bass and sea bream. Sustainability, 12, 9617; doi:10.3390/su12229617.

([124]) García B.G.; Jiménez C.R.; Aguado-Giménez F.; García J.G., 2016 Life cycle assessment of gilthead seabream (*Sparus aurata*) production in offshore fish farms. Sustainability. 8, 1228; doi:10.3390/su8121228

- B) Benchmark model, focused on the feeding process, based on data collected from operators.
  - ii) S2: Feed is delivered using: i) a diesel barge; diesel boats.
  - iii) S3: Feed is delivered using: i) a hybrid barge, ii) diesel boats;
  - iv) S4: Feed is delivered using: i) a hybrid barge; ii) fully electric boats.

The fuel use for benchmark A/S1 was taken from the literature, while the fuel use used for analysis in benchmark B/S2, S3 and S4 were estimated based on data provided by operators, which were verified during the stakeholder consultation.

To deal with the three B scenarios (S2, S3 and S4), the LCA models were focused on the estimation of the CO_2e emissions due to: 1) feed; and 2) feeding practices which, however, are, by far, the two most important emission sources in cage farming.

Reference Farm (RF) 1: seabass/seabream farm in Greece producing 2,000 tons/year.
In this case study we considered a large farm located in Greece, at a distance of 1 km from the shore. The production volume, the onsite energy use due to fuel and electricity and the total one are listed in Table 4-13 The LCA model inventory was complemented with the data listed by Garcia and coauthors in 2016. ([125]) To obtain the first scenario, S1, this benchmark model was perturbed by assuming that all serving vessels are electrified and that the power comes from RESs, i.e. PV. The results are presented in Table 4-16 Table 4-14, which shows, from left to right, with reference to a tonne of seabass/seabream: i) the CO_2e emissions due to feed use; ii) the on-site energy use; iii) the CO_2e emissions related to energy use; iv), the CO_2e emissions due to other processes; v) the total CO_2e emissions.

Table 4-13 Results of the technical analysis of boat electrification. FU: 1 tonne of seabass/seabream, at farm gate.

Source	Location	Production volume [tonne]	Upstream: Feed use [tonne]	On-site diesel use/FU [kWh/FU]	On-site electricity use/FU	On-site total energy use/FU [kWh/FU]
Garcia et al., 2016, Kallitsis et al., 2020	Greece	2000	4000	522	740	1262

Table 4-14 Results of the technical analysis of boat electrification. FU: 1 ton of seabass/seabream, at farm gate.

	CO_2e emission from feed use [ton/FU]	On-site energy use [kWh/FU]	Total CO_2e emission [tonne /FU]	CO_2e emission due to on-site energy use [tonne/FU]	CO_2e emission due to other processes [tonne/FU]	On-site energy use [kWh/FU]
Benchmark A	3.382	1263	4.606	0.836	0.388	1263

([125]) García B.G.; Jiménez C.R.; Aguado-Giménez F.; García J.G., 2016 Life cycle assessment of gilthead seabream (*Sparus aurata*) production in offshore fish farms. Sustainability. 8, 1228; doi:10.3390/su8121228

	CO_2e emission from feed use [ton/FU]	On-site energy use [kWh/FU]	Total CO_2e emission [tonne /FU]	CO_2e emission due to on-site energy use [tonne/FU]	CO_2e emission due to other processes [tonne/FU]	On-site energy use [kWh/FU]
S1: Electric boats sourced by PV	3.382	955	3.827	0.057	0.388	955

The “B” scenarios (S2, S3 and S4) concern the comparison between costs and CO_2e emissions related to changes in feeding practices. Therefore, only the energy use related to feeding and on-feed use were considered as input of the LCA models. Data concerning the fuel used by boats which transport and deliver feed using a cannon and by a barge were collected during interviews with operators.

The ”B” scenarios concern the comparison between costs and CO_2e emissions related to changes in feeding practices. Therefore, only the energy use related to feeding and on-feed use were considered as input of the LCA models. Data concerning the fuel used by boats which transport and deliver feed using a cannon and by a barge were collected during interviews with operators. The fuel and electricity used as inputs in the inventory of the LCA model were estimated as described in Annex B.

In scenarios S2, S3 and S4 the electricity was assumed to be provided by RESs, i.e., PV. The electricity use was estimated assuming a 0.35 efficiency of a thermal engine and a 0.85 efficiency of an electric one (see Annex B). The results are presented in Table 4-15, which presents, from left to right: i) the energy use, due to fuel combustion and electricity use; ii) the CO_2e emissions related to these energy uses; iii) the CO_2e emissions related to feed use: these decrease when using a barge as FCR is assumed to be 5% lower. iv) the CO_2e emissions related to feeding, i.e., feed production and delivery.

Table 4-15 Results of the technical analysis concerning the use of feeding barge, powered by diesel or hybrid and electrified boats. FU: 1 ton of seabass/seabream, live weight at farm gate.

	CO_2e emission from feed use [ton/FU]	On-site fuel use [kWh/FU]	On-site electricity use [kWh/FU]	CO_2e emission from fuel use [tonne/FU]	CO_2e emission from electricity use [ton/FU]	Total CO_2e emission due to feeding. [ton/FU]
Benchmark B	3.382	603	0	0.211	0	3.593
S2: Diesel Barge & diesel boats.	3.213	534	0	0.187	0	3.400
S3: Hybrid barge and diesel boats.	3.213	336	82	0.118	0.005	3.336
S4: Hybrid barge and electric boats.		243	122	0.085	0.007	3.306

Reference Farm 2: seabass/seabream farm in Spain producing 500 ton/year.
In this case study, we considered a medium farm located in Spain, about 6 km offshore. The production volume, the onsite energy uses due to fuel, electricity and the total one is listed in Table 4-16. The LCA model inventory was complemented with the data listed in (Garcia&al., 2016) ([126]). This paper does not consider electricity use for refrigerators: out of the precautionary principle and also for comparing the two case studies, we assumed the same electricity used for case study 1, based on Kallitsis et al., (2020) ([127]). To obtain the first scenario, S1, this benchmark model was perturbed by assuming that all serving vessels are electrified and that the power comes from RESs, i.e., PV. The results are presented in Table 4-17.

Table 4-16 Total on-site energy use and electricity use in seabass/seabream farming (FU = 1 tonne of seabass/seabream live weight at farm gate).

Source	Location	Production volume [tonne]	Upstream: Feed use [tonne]	On-site diesel use/FU [kWh/FU]	On-site electricity use /FU	On-site total energy use/FU [kWh/FU]
Garcia&al., 2016, Kallitsis&al., 2020	Spain	500	1000	5332	740	6072

Table 4-17 Results of the technical analysis of boat electrification. FU: 1 tonne of seabass/seabream, live weight at farm gate.

	CO_2e emission from feed use [ton/FU]	On-site energy use [kWh/FU]	CO_2e emission due to on-site energy use [ton/FU]	CO_2e emission due to other processes [ton/FU]	Total CO_2e emission [ton /FU]
Benchmark A	3.382	6072	2.113	0.388	5.883
S1: Electric boats sourced by PV	3.382	2935	0.221	0.388	3.991

Data concerning the fuel used by boats which transport and deliver feed using a cannon and by a barge were collected during interviews with operators. The fuel and electricity used as inputs in the inventory of the LCA model were estimated as described in Annex B.

([126]) García B.G.; Jiménez C.R.; Aguado-Giménez F.; García J.G., 2016 Life cycle assessment of gilthead seabream (*Sparus aurata*) production in offshore fish farms. Sustainability. 8, 1228; doi:10.3390/su8121228
([127]) Kallitsis E.; Korre A.; Mousamas D.; Avramidis P. 2020. Environmental life cycle assessment of mediterranean sea bass and sea bream. Sustainability, 12, 9617; doi:10.3390/su12229617.

Table 4-18 Results of the technical analysis concerning the use of feeding barge, powered by diesel or hybrid and electrified boats. FU: 1 tonne of seabass/seabream, at farm gate.

	CO_2e emission from feed use [ton/FU]	On-site fuel use [kWh/FU]	On-site electricity use [kWh/FU]	CO_2e emission from fuel use [tonne/FU]	CO_2e emission from electricity use [tone/FU]	Total CO_2e emission due to feeding [tonne /FU]
Benchmark B	3.382	1734	0	0.607	0	3.989
S2: Diesel Barge & diesel boats.	3.213	1395	0	0.487	0	3.670
S3: Hybrid barge and diesel boats.	3.213	830	233	0.291	0.014	3.517
S4: Hybrid barge and electric boats.	3.213	690	290	0.242	0.017	3.471

Discussion

In this case study, two alternative ways of reducing the CO_2e emissions were investigated, in relation to two Reference Farms, characterised by a different distance from the shore and production volume. In principle both innovations (electrification of boats and implementation of barges) are technically feasible: the first one is the electrification of serving vessels, which, however, should be powered by RESs, e.g., PV, in order to reduce the CO_2e. The second innovation may integrate the use of feeding barges, powered either by diesel or hybrid with electric vessels. Concerning the first option, the results presented in Table 4-17, Table 4-14, Table 4-18 and Table 4-17 indicate that the distance from the landing point is a key variable in determining its cost-effectiveness. In fact, energy use accounts for 18% of the total CO_2e emissions for RF1, 1 km from the shore and 36% for RF2, 6 km from the shore. Therefore, the electrification of all serving vessels and the provision of electricity for all other uses from PV would bring down the emissions by, respectively, 17% and 33%. In absolute terms, vessel electrification and all electricity supplied by PV would lead to a decrease in the CO_2e emissions by 0.78 CO_2e tonne/tonne of fish live weight for RF1 and a remarkable 1.89 CO_2e tonne/tonne of fish lw for RF2. This would also lead to close estimates of the total missions, which would be about 4 CO_2e tonne/tonne of fish, of which, on average 86% is due to feed.

The implementation of barges is more complex. In the first place, we would like to underline that Benchmark B and scenarios S2, S3 and S4 are based on data collected from operators and concern only vessels and barges used for feeding. The data presented in Table 4-17 and Table 2-20 highlight that the adoption of barges powered by diesel leads to reduced fuel use, due to the number of journeys from the landing point to the farms, even though not as much as indicated in Garciaal2016) ([128]), in which the fuel used for operating the barge was not taken into account. However, the most relevant reduction in CO_2e emissions is not related to the fuel saving but to the feed saved by switching from cannon on boats to barges. The use of hybrid barges seems to be the best option leading to a reduction in the CO_2 emissions related to feeding by 42% for

([128]) García B.G.; Jiménez C.R.; Aguado-Giménez F.; García J.G., 2016 Life cycle assessment of gilthead seabream (*Sparus aurata*) production in offshore fish farms. Sustainability. 8, 1228; doi:10.3390/su8121228.

FR1 and 49% for RF2. This option, however, may have both technical barriers, due to the risk involved in the barge being damaged by adverse weather events and economic one, due to the high investments, which may not be affordable by medium farms. In conclusion: 1) serving vessel electrification seems to be the most viable option for small/medium farms.

4.3.4 Case study 4: Rainbow trout

Rainbow trout is the most important fish species farmed in the EU in volume, see Chapter 2. More than 90% of it is currently produced in raceway systems, with production in RAS being conducted in Denmark. Therefore, in this case study, we focused on raceway farms. Four reference farms (RFs) were selected for this analysis in order to represent different conditions across the main EU rainbow trout producers, including different production sizes and different irradiance conditions. Table 4-19 summarises the results of recent LCA studies, in which farms located in different EU countries and characterized by different production volumes were investigated. As one can see, this sector is characterised by large variability in energy use during the grow-out phase, which, however, is due to electricity use.

Table 4-19. Results from LCA studies summarizing the input for the case studies for Trout production.

Source	Location	Production volume [tonne]	On-site total energy use [kWh/FU]	On-site Electricity use/FU [kWh/FU]	On-site liquid oxygen use [tonne/tonne FU]	Total Electricity use [MWh]
Maioloal., 2021	Trento District (Italy)	60	606	300 (49%)	0	18
Maioloal. 2021	Trento District (Italy)	300	1806	1500 (83%)	1.5	450
Windal. 2022	Baden-Wuerttemberg (Germany)	500	283	160	0.67	80
Sanchez-Matosal., 2023	Galicia (Spain)	1700	1095	892 (81%)	0.5	1516

1. Reference Farm 1: A small size farm in Northern Italy.
2. Reference Farrm 2: A medium-sized farm in Northern Italy.
3. Reference Farm 3: A medium-sized farm in Germany.
4. Reference Farm 4: A large size farm in Spain.

The first RF is representative of small farms, characterised by limited, high quality and low environmental impact production volumes, which use as influent decent quality river water, keep low stocking densities and, therefore, do not need to supply oxygen using either aerator or liquid oxygen or do it only occasionally. The second RF concerns an Italian medium-sized farm which uses influent groundwater, which needs more energy for pumping and more oxygen, as the oxygen concentration in groundwater is low. The third RF is representative of a medium-sized farm in Germany, which uses influent river water and is characterised by lower energy demand, as it exploits natural hydraulic gradients. The fourth RF is representative of a large farm in Spain, using river water as an influent.

As one can see from the literature, medium-large farms use either liquid oxygen or an aerator: as the cost of liquid oxygen has doubled since 2023, several companies are now investing in on-site oxygen production. This can be achieved in two ways: 1) by using an "oxygen generator" which uses air as input and produces as output a 95% oxygen gas mixture at ambient pressure; 2) by water electrolysis: in this case one also obtains hydrogen, which could be used to store energy, to be re-converted into electricity in fuel-cells.

Both processes are at TRL 9, but the first solution is, at present, more appealing for farmers as the investment cost is lower and the management of the generator is easier. Furthermore the "hydrogen economy" is not still fully developed. In fact, in perspective, the second solution would be interesting for the development of EU aquaculture once hydrogen districts, sometimes called "hydrogen valleys" will be fully implemented. The availability of substantial amounts of cheap and "green" oxygen, which is a by-product of hydrogen production, could promote investment in large-scale fish farms, as an example of industrial symbiosis. Such symbiosis seems particularly appealing for RAS technology, which can be deployed also in urban and industrial areas.

Therefore, the following scenarios were considered:

- Two scenarios for each case study, in which we assumed that 50% and 100% of the electricity demand would be covered by PV.
- A third scenario for case studies 2-4, in which we assumed that the oxygen requirement would be covered using on-site production from oxygen generators.

For each case study, the results of the technical analysis are summarised in two Tables. The first one lists:

- The area required to deploy the solar panel.
- The cost of material.
- The cost of installation.
- The cost and area normalised per tonne of trout at farm gate.

The second Table gives the results of the LCA mode for the benchmark and the scenarios, The model outputs were aggregated in order to provide:

- The total CO_2e emissions:
- The emissions related to on-site electricity use.
- The emissions related to fish feed.
- The emissions related to the use of liquid oxygen.

Given the significant variability in on-site energy due to diverse segments and varying regulatory settings across different countries, our study focuses on specific case studies. To assess the effectiveness of identified innovations and measures in cash flow calculations, to comprehensively assess the benefits, we evaluated each innovation separately, resulting in distinct cashflows for the farm — one for PV installation and the other for the oxygen generator.

The cash flow consists of the capital expenditure (CAPEX) or initial investment, the additional operational expenditure (OPEX) associated with operating the innovation without including electricity use and electricity cost savings. However, in this scenario, we do not factor in any yearly variable costs (OPEX) related to maintenance or other annual expenses for the oxygenator or the PV system due to a lack of available data or relevant literature on breakdowns or stoppages.

Solar Photovoltaic Panels (PV)

When determining the costs for solar panels and their installation, we considered the average purchasing price of these panels in the specific country. For all other expenses related to the structure, we considered a ground-based system to power the entire setup.

In order of assumptions, we are assuming that in the same year, we install the photovoltaic panels, they will immediately start functioning, leading to corresponding savings in electricity costs in the very same year. Furthermore, it's important to note that in this scenario, we haven't factored in annual variable costs (OPEX) on maintenance or other related costs. In terms of taxation, our assessment accounts for both local levies and indirect taxes like VAT.

Oxygen generator

When determining the cost of an oxygen generator and its installation, we consider the expense associated with installing a standard generator capable of providing 36 cubic meters of oxygen per hour. The quantity of generators is adjusted based on the oxygen consumption per tonne.

In order of assumptions, we are assuming that in the same year, we install the oxygen generator, it will immediately start functioning, leading to corresponding savings in the very same year. Furthermore, it's important to note that in this scenario, we haven't factored in annual variable costs (OPEX) on maintenance or other related costs. In terms of taxation, our assessment accounts for both local levies and indirect taxes like VAT. In addition, we are assuming that the PV supplies at least 50% of the electricity needed for the farm with the Oxygenator installed, however, the financial assessment only considers the costs of installing and running the oxygenator, meaning that the installation of PV would enhance the performance and benefits of installing the oxygenator.

Data were verified and, whenever necessary, corrected by interviewing operators.

Reference Farm 1: A small size farm in Northern Italy

This case study is representative of a small farm, which does not regularly supply oxygen and uses decent quality river water as an influent.

Table 4-20 Results of the technical analysis of PV installation at a small farm in Northern Italy: production volume 60 tonne/year, on-site electricity use: 18 MWh/year.

% of electricity requirement.	Area required	Cost of material [Eurox1000]	Cost of installation [Eurox1000]	Cost per FU [Euro/tonne]	Area per FU [m^2/tonne]
50%	33	5.920	10.745	179	0.55
100%	62	11.100	20.147	335.8	1.02

Table 4-21 Comparison between the CO_2e emissions of the benchmark model and those estimated in two scenarios of grid electricity substitution with locally installed PV (FU = 1 tonne of trout live weight at farm gate).

Medium farm, Italy	Total emissions [CO_2e /tonne]	Feed emissions [CO_2e /tonne]	Electricity emissions [CO_2e /tonne]	Oxygen use emissions [CO_2e /tonne]	Emissions from other processes [CO_2e /tonne]
Benchmark	1.321	1.128	0.114	0	0.078
S1: 50% of electricity covered by PV	1.273	1.128	67	0	0.078
S2: 100% electricity covered by PV	1.226	1.128	20	0	0.078

Table 4-22 Input parameters for calculating the cash flows – small-sized Italian trout farm

Variable	Value
Technological Readiness Level (TRL) in 2023	9
Expected year when TRL 9 could be reached	2023
Year of implementation	2024
Economic lifetime	25-30
CAPEX *Consists of costs for solar panels and their installation*	€ 20,147
Yearly additional cost with PV (OPEX)	N/A
Yearly electricity cost savings	Difference in price of electricity per year
Electricity estimated Auto consumption with PV	50%

Table 4-23 Summary Table: average electricity price for the small-sized Italian trout farm

Average electricity price	
Net Present Value (NPV)	€ 18,974.57
Payback period	8.00
Year for payback	2031
Internal Rate of Return (IRR)	14%

Reference Farm 2: A medium-sized farm in Northern Italy

This case study concerns a medium-sized fish farm located in Northern Italy which uses influent groundwater. The data presented in here were verified with local farmers, who indicated that the current on-site energy use is around 960 kWh per tonne of trout. Therefore, we used this in the benchmark scenarios. The third scenario assumed that one oxygen generator producing 36 m^3 oxygen/hour, i.e., 1.35 [kg of oxygen/hour] could satisfy the oxygen demand of the stocked fish. i.e., about 450 [tonne oxygen/year].

Table 4-24 Results of the technical analysis of PV installation at a medium-sized farm in Northern Italy: production volume 300 tonne/year, on-site electricity use: 450 MWh/year.

% of electricity requirement	Area required	Cost of material [Eurox1000]	Cost of installation [Eurox1000]	Cost per FU [Euro/tonne]	Area per FU [m^2/tonne]
50%	741	133.200	241.758	805.8	2.5
100%	1122	199.800	362.637	1208.8	3.7
100% + oxygen generator	1482	266.400	483.516	1611.7	4.9

Table 4-25 Comparison between the CO_2e emissions of the benchmark model and those estimated in two scenarios of grid electricity substitution with locally installed PV (FU = 1 tonne of trout live weight at farm gate).

Medium farm, Italy	Total emissions [CO_2e /tonne]	Feed emissions [CO_2e /tonne]	Electricity emissions [CO_2e /tonne]	Oxygen use emissions [CO_2e /tonne]	Emissions from other processes [CO_2e /tonne]
Benchmark	2.420	1.128	0.364	841	0.087
S1: 50% of electricity covered by PV	2.271	1.128	0.215	841	0.087
S2: 100% electricity covered by PV	2.122	1.128	0.065	841	0.087
S3: oxygen generator: 100% electricity covered by PV	1.317	1.128	0.0102	0	0.087

1) Installing solar photovoltaic panels

Table 4-26 Input parameters for calculating the cash flows – solar PV at medium sized Italian trout farm

Variable	Value
Technological Readiness Level (TRL) in 2023	9
Expected year when TRL 9 could be reached	2023
Year of implementation	2024
Economic lifetime	25-30
CAPEX *Consists of costs for solar panels and their installation*	€ 362.637
Yearly additional cost with PV (OPEX)	N/A
Yearly electricity cost savings	Difference in price of electricity per year
Electricity Auto consumption with PV	

2) Installing an oxygen generator

Table 4-26 Input parameters for calculating the cash flows – oxygen generator at medium sized Italian trout farm

Variable	Value
Technological Readiness Level (TRL) in 2023	9
Expected year when TRL 9 could be reached	2023
Year of implementation	2024
Economic lifetime	10 to 15
CAPEX *Consists of costs for solar panels and their installation*	€ 162.837.00
Yearly additional cost with PV (OPEX)	N/A
Yearly electricity cost savings	Difference in price of electricity per year

Table 4-27 Summary Table: average electricity price for the medium sized Italian trout farm - oxygen generator

Average electricity price	
Net Present Value (NPV)	€ 39.325,37
Payback period	11
Year for payback	2034
Internal Rate of Return (IRR)	7%

Reference Farm 3: A medium-sized farm in Germany

This case study concerns a medium-sized farm located in Germany, which uses river water as an influent and is characterised by a lower energy demand, as it exploits natural hydraulic gradients. In this case, given the yield of the oxygen generator of about 0.37 [kg Oxygen/kWh] and the oxygen demand of 0.67 [tonne oxygen/tonne trout] an extra 124 MWh/year would be needed to power the oxygen generator.

Table 4-28 Results of the technical analysis of PV installation at a medium-sized farm in Germany: production volume 500 tonne/year, on-site electricity use: 80 MWh/year

% of electricity requirement.	Area required	Cost of material [Eurox1000]	[Cost of installation [Eurox1000]	Cost per FU [Euro/tonne]	Area per FU [m²/tonne]
50%	152	27380	49695	99	0.3
100%	305	54760	99390	198	0.6
100% + oxygen generator	777	139494	253183	506	1.6

Table 4-29 Comparison between the CO_2e emissions of the benchmark model and those estimated in two scenarios of grid electricity substitution with locally installed PV (FU = 1 tonne of trout live weight at farm gate).

Medium farm, Germany	Total emissions [CO_2e /tonne]	Feed emissions [CO_2e /tonne]	Electricity emissions [CO_2e /tonne]	Oxygen use emissions [CO_2e /tonne]	Emissions from other processes [CO_2e /tonne]
Benchmark	1.615	1.128	0.093	0.391	0.003
S1: 50% of electricity covered by PV	1.576	1.128	0.054	0.391	0.003
S2: 100% electricity covered by PV	1.537	1.128	0.015	0.391	0.003
S3: oxygen generator: 100% electricity covered by PV	1.168	1.128	0.037	0	0.003

1) Installing solar PV

Table 4-30 Input parameters for calculating the cash flows – solar PV at German trout farm

Variable	Value
Technological Readiness Level (TRL) in 2023	9
Expected year when TRL 9 could be reached	2023
Year of implementation	2024
Economic lifetime	25-30
CAPEX *Consists of costs for solar panels and their installation*	€ 96,693
Yearly additional cost with PV (OPEX)	N/A
Yearly electricity cost savings	Difference in price of electricity per year
Electricity Auto consumption with PV	50%

Table 4-31 Summary Table: average electricity price for the German trout farm – solar PV

Average electricity price	
Net Present Value (NPV)	€ 82,596.97
Payback period	9.00
Year for payback	2032
Internal Rate of Return (IRR)	13%

2) Installing an Oxygen generator

Table 4-32 Input parameters for calculating the cash flows – oxygen generator at German trout farm

Variable	Value
Technological Readiness Level (TRL) in 2023	9
Expected year when TRL 9 could be reached	2023
Year of implementation	2024
Economic lifetime	10 to 15
CAPEX *Consists of costs for solar panels and their installation*	€ 162,837.00
Yearly additional cost with PV (OPEX)	N/A
Yearly electricity cost savings	Difference in price of electricity per year

Table 4-33 Summary Table: average electricity price for the German trout farm – oxygen generator

Average electricity price	
Net Present Value (NPV)	€ 669.970,83
Payback period	3
Year for payback	2026
Internal Rate of Return (IRR)	84%

Reference Farm 4: A large size farm in Spain.

This case study concerns a large farm located in Spain, which uses river water as an influent and is characterised by an average energy demand and an oxygen demand of 0.67 [tonne oxygen/tonne catch] similar to the RF3 one. The results of the technical analysis are presented in Table 4-37 and Table 4-38.

Table 4-34 Results of the technical analysis of PV installation at a large-size farm in Spain: production volume 1700 tonne/year, on-site electricity use: 1,516 MWh/year.

% of electricity requirement.	Area required	Cost of material [Eurox1000]	Cost of installation [Eurox1000]	Cost per FU [Euro/tonne]	Area per FU [m²/tonne]
50%	2368	425.550	568.088	563.68	1.4
100%	4715	847.300	1,136,176	1127.36	2.7
100% + oxygen generator	5691	1,022.848	1,736,176	1021.88	3.3

Table 4-35 Comparison between the CO_2e emissions of the benchmark model and those estimated in two scenarios of grid electricity substitution with locally installed PV (FU = 1 tonne of trout live weight at the farm gate.

Large farm, Spain	Total emissions [CO_2e /tonne]	Feed emissions [CO_2e /tonne]	Electricity emissions [CO_2e /tonne]	Oxygen use emissions [CO_2e /tonne]	Emissions from other processes [CO_2e /tonne]
Benchmark	1.750	1.128	0.297	0.292	0.033
S1: 50% of electricity covered by PV	1.628	1.128	0.175	0.292	0.033
S2: 100% electricity covered by PV	1.506	1.128	0.053	0.292	0.033
S3: oxygen generator: 100% electricity covered by PV	1.225	1.128	0.064	0	0.033

In this scenario, the investments at stable production rates were compared, to highlight the benefits in efficiency and environmental performance.

The data used for the calculations, is based on historic electricity prices of Eurostat (2023) and future electricity price predictions for the EU27 (Capros et al. 2013), both including taxes. The Spanish electricity price projections are based on the average ratio between EU prices and Spanish prices up until now, assuming the average ratio will remain until 2050. For the electricity cost price predictions, it was moreover assumed, that the liquid oxygen cost is stable, as well as the feed-in tariff for the unused excess electricity generated with the solar PV.

A stable trout production is considered for Spain. For land-based farms, most costs and GHG emissions result from using grid electricity, for which we consider two innovative approaches 1) installing solar PV as well as 2) oxygen generator. The following technical details built the framework for the analysis:

Table 4-36 Total on-site energy use and electricity use in FTS trout farming (FU = 1 tonne of rainbow trout live weight at farm gate).

Production [tonne/year]	Liquid oxygen use [tonne]	Liquid Oxygen cost [Euro/tonne]	Electricity use [kWh/year]	Total Electricity use with oxygen concentrator [MWh/year]
1700	3400	222	1516400.0	2772771.7

1) Installing solar photovoltaic panels

In the case of solar PV utilization, operational expenses are solely tied to self-generated electricity, which is sufficient to cover 50% of the estimated production demand. We assume an initial investment in 2024, for which the initial investment cost amounts to EUR 1,136,176 for solar PV. This includes the overall material cost and the estimated costs for installation, along with applicable taxes and allowances. In terms of taxes, we have considered both local taxes ([129]) and indirect taxes (VAT). As for allowances, our calculations have solely incorporated the VAT deduction available for companies in Spain at present.
The subsidies for installing solar panels in Galicia from the Next Generation Funds are not included, as they can only be applied for until 31 December 2023. Additionally, reductions in property taxes and the Tax on Construction are not included, as these figures vary depending on the municipality.

In this context, our emphasis is on electricity cost savings, so we do not include the expense of liquid oxygen as part of the baseline cost without innovation.

([129]) Property Tax is not included, as its calculation depends on the cadastral value of the property, to which the tax rate set by each municipality must be applied.

Table 4-37 Input parameters for calculating the cash flows - solar PV at Spanish trout.

Variable	Value
Technology Readiness Level (TRL) in 2023	9
Expected year when TRL 9 could be reached	2023
Year of implementation	2024
Economic lifetime	About 25 to 30 years ([130])
Capex (EUR) *Consists of costs for solar panels and their installation.*	€ 1,136,176
Opex (EUR) *No additional costs for repairing or maintenance*	N/A
Yearly electricity cost savings	Difference in price of electricity per year

The case study demonstrates significant reductions in both costs and emissions. It indicates that the cost savings will lead to a payback period of 7 years.

Table 4-38 Summary Table: average electricity price for the Spanish trout farm – solar PV

Average electricity price	
Net Present Value (NPV)	€ 1,588,497.19
Payback period	7
Year for payback	2030
Internal Rate of Return (IRR)	19%

2) Installing an oxygen generator

We anticipate an initial investment in 2024, amounting to EUR 488.511,00 for the oxygen generator, without innovation implemented, we calculated an annual total cost of EUR 754,800 for liquid oxygen (which we assume to remain constant over the years). In this context, we factor in both the expense of liquid oxygen and the electricity cost from the grid as part of the baseline cost without innovation.

Table 4-39 Factsheet variables for oxygen generator

Variable	Value
Technology Readiness Level (TRL) in 2023	9
Expected year when TRL 9 could be reached	2023

([130]) Manbir Sodhi, Lennart Banaszek, Chris Magee, Mercedes Rivero-Hudec (2022). Economic Lifetimes of Solar Panels, available at: https://doi.org/10.1016/j.procir.2022.02.130

Variable	Value
Year of implementation	2024
Economic lifetime	About 10 to 15 years ([131])
Capex (EUR) *Consists of costs for solar panels and their installation.*	€ 488.511,00
Opex (EUR) *No additional costs for repair or maintenance*	N/A
Yearly electricity cost savings	Difference in price of electricity per year

The case study demonstrates significant reductions in both costs and emissions. It indicates that the cost savings will lead to a payback period of 2 years.

Table 4-40 Summary Table: average electricity price for the Spanish trout farm – oxygen generator

Average electricity price	
Net Present Value (NPV)	€ 5,368.303,79
Payback period	2.00
Year for payback	2025
Internal Rate of Return (IRR)	6648%

In one case, these values depend on the location and electricity use but are almost insensitive to the scale of the production. These estimates, in fact, concern the annual energy production which matches the annual energy requirement: therefore, they provide an indication of the order to magnitude of surfaces and costs. More accurate estimations could be obtained based on monthly average electricity use and daily consumption profiles. Nevertheless, the large differences between the data presented in the different production scenarios suggest that the first step towards the reduction of on-site energy use would be an energy audit and the development of an energy model for aquafarms, to be used by companies to compare their energy performances against the consolidated benchmark and to test, at low costs, the cost-effectiveness of energy efficiency interventions.

Discussion

The results presented in the case study indicate that it would be possible, from both the technical and economic point of view, to achieve using the current technology the main goal of the energy transition partnership in the trout sector, i.e. the decarbonisation of on-site energy use, by switching towards a scenario in which farmers produce their own electricity and use it for locally producing a gas mixture at 95% oxygen concentration which could replace the current liquid oxygen supply.

([131]) No literature reference available. Information obtained directly from specific providers through direct contacts.

The results presented here indicate that CO_2e emissions related to on-site energy use and liquid oxygen can be reduced by 72%, for the low-energy use medium farm, to an average of 90% for small-medium farms, with current energy use ranging from 900 to 1,000 kWh/tonne. As a result, the abatement of the grow-out CO_2e emissions which could be obtained by combining the powering of FTS rainbow trout with RESs with locally generated oxygen would range from 49% in RF1 to 91% in RF3. However, in absolute terms, the largest abatement concerns the two more intensive and energy demanding farm RF2 and RF4**, which would reduce their grow-out emissions from 1.205 to 0.102 and from 0.589 to 0.064 tonne CO_2e/tonne of fish.** Remarkably, the total emissions of all RFs would become close, **ranging from 1.225 to 1.317 tonne CO_2e/tonne fish lw**, of which 86% to 96% related to upstream impact, i.e., feed. The average specific emission of 1.234 tonne CO_2e/tonne fish lw, would be 1.261 tonnes CO_2e/tonne fish live weight (lw) slower than that estimated in Chapter 2: as trout is, in volume, the most important farmed fish species produced in the UE, the adoption of these two innovations would lead to a marked decrease in the whole sector emissions.

CAPEX and OPEX costs vary from one EU MS to another but, in general, investment costs seem affordable, this is supported by the payback period for the different scenarios across three Member States with different production sizes from small farms to large farms. Furthermore, the area to be covered by solar panels and, therefore, the material and installation costs, depend on the location and electricity use but are almost insensitive to the scale of the production, which means that the technical data here presented can be upscaled/downscaled for screening estimations of cost/benefits. It should also be noted that the 100% estimates, in fact, concern the annual energy production which matches the annual energy requirement: therefore, they provide an indication of the order to magnitude of surfaces and costs. More accurate estimations could be obtained based on monthly average electricity use and daily consumption profiles. Nevertheless, the large differences between the data presented here in the case study, suggest that the first step towards the reduction of on-site energy use would be an energy audit and the development of an energy model for aquafarms, to be used by companies to compare their energy performances against the consolidated benchmark and to test, at low costs, the cost-effectiveness of energy efficiency interventions.

4.4 Conclusions

The results presented in the previous sections indicate that the energy transition in the aquaculture sector is technically achievable based on the current technology and, in some instances, is also economically viable, with a payback period varying from 2 to 11 years for those case studies where the payback period could be calculated. The pillars of the transition are:

- S1) Marine aquaculture: electrification of serving vessels, accompanied by electricity sourced by RES.
- S2) Freshwater aquaculture: 1) switch from grid electricity to electricity sourced by PV; 2) locally generated oxygen substituting liquid oxygen, when needed.

As previously underlined, EU aquaculture is characterized by high variability of husbandry practices and energy use, which makes it challenging to draw general conclusions from the results presented in the case study section, in which we considered a set of Representative Farms.

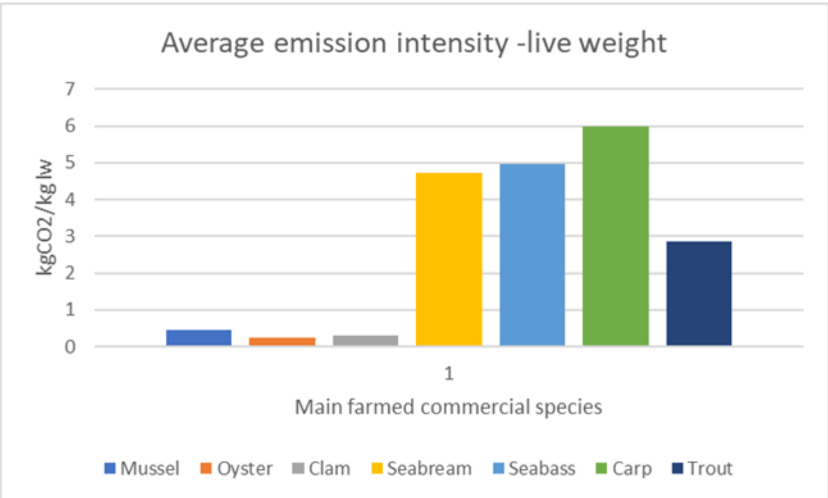
However, in this section, we will try to extrapolate from these findings and provide a preliminary assessment of the potential reduction of CO_2e emissions for the main aquaculture typologies and species considered in this chapter.

In the first place, the results of mapping presented in Chapter 2 indicate that CO_2e emissions from EU aquaculture, 2.13 million tonnes, represent 0.6% of the total emissions estimated by the EAA for the agriculture sector which in 2019 amounted to 368 million tonnes ([132]). The average emissions, expressed as $kgCO_2e/kg$ live weight at farm gate and as $kgCO_2e/kg$ edible mass, see Table 4-41, are compared in Figure 4.2.

There is a major difference between shellfish and finfish, which is less marked when normalizing the data on the edible part. In comparison with other food items, the average CO_2e emissions per kg of edible farmed fish, 10.8 $kgCO_2e$, are about 24% of those of ruminant meat, 45.5 $kgCO_2e$, while the average ones of shellfish, (0,36 live weight, 1.5 edible $kgCO_2e/kg$) are, respectively 13%, as live weight and 60%, as edible part, of those of chicken, 2.59 kgCOe/kg ([133]) (Vettera&Al., 2017). Concerning fish, we would like to recall that our approach is based on LCA and considers the whole supply chain: therefore, feed accounts for a large fraction of the emissions, in particular for marine fish, as the FCR is twice that of trout.(0,36 lw, 1.5 edible $kgCO_2e/kg$) are, respectively 13%, as lw and 60%, as edible part, of those of chicken, 2.59 kgCOe/kg ([134]) (Vettera&Al., 2017). Concerning fish, we would like to recall that our approach is based on LCA and considers the whole supply chain: therefore, feed accounts for a large fraction of the emissions, in particular for marine fish, as the FCR is twice that of trout.

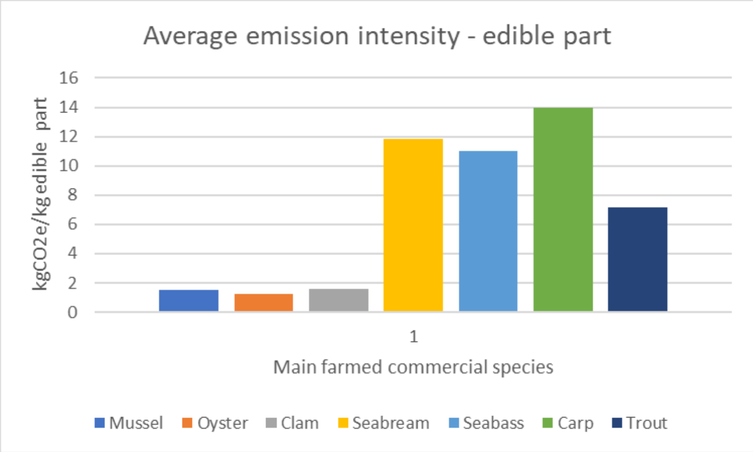
Table 4-41 Edible percentages, with reference to the live weight at farm gate

Commercial Species	% edible	Source
Mussel	30	
Oyster	20	
Clam	19	
European seabass	45.1	Marcops&al., 2021
Gilthead seabream	40.0	Marcops&al., 2021
Common carp	43.1	Marcops&al., 2021
Rainbow trout	40.0	Maringa&al., 2015



([132]) eea.europa.eu/en/datahub
([133]) Sylvia H. Vettera, Tek B. Sapkotab, Jon Hilliera, Clare M. Stirlingc, Jennie I. Macdiarmidd, Lukasz Aleksandrowicze,f, Rosemary Greene,f, Edward J.M. Joye,f, Alan D. Dangoure,f,Pete Smitha, 2017. Greenhouse gas emissions from agricultural food production to supply Indian diets: Implications for climate change mitigation. Agriculture, Ecosystems and Environment 237 (2017) 234–241.
([134]) Sylvia H. Vettera, Tek B. Sapkotab, Jon Hilliera, Clare M. Stirlingc, Jennie I. Macdiarmidd, Lukasz Aleksandrowicze,f, Rosemary Greene,f, Edward J.M. Joye,f, Alan D. Dangoure,f,Pete Smitha, 2017. Greenhouse gas emissions from agricultural food production to supply Indian diets: Implications for climate change mitigation. Agriculture, Ecosystems and Environment 237 (2017) 234–241.

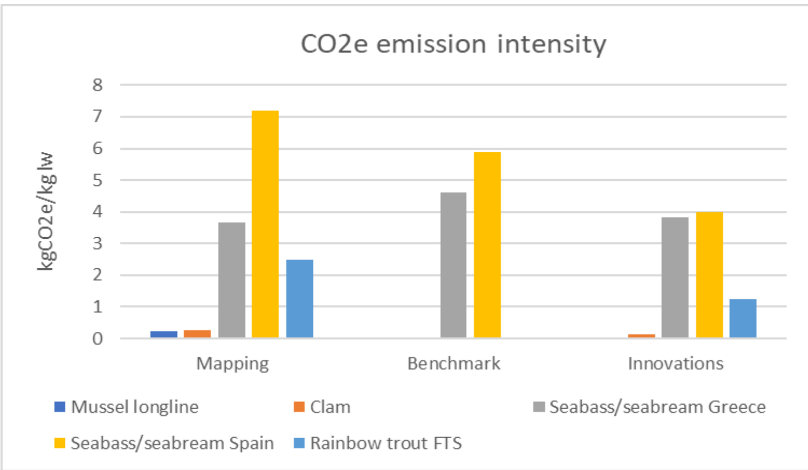
Figure 4.2 Average CO_2e emission intensities of the main species farmed in the EU



In this Chapter, we considered innovations for the energy transition for both segments but could not include in the study two relevant species, namely Pacific oysters farmed in intertidal environment and carp, as it was not possible to establish an emission baseline, due to the lack (oyster) or poor representativity (carp) of peer reviewed LCA studies and/or grey literature. Nonetheless, the species and farming typologies investigated, i.e., mussel, clam, seabass/seabream and rainbow trout cover about 82% of the EU production volume and 78% of the emissions estimated in Chapter 2. Considering that the emissions from carp are likely overestimated, the percentage of emissions covered is likely to be even higher.

The results presented in section 4.3 indicate that the emission intensities of the above species could be markedly reduced, as shown by Figure 4-3, which presents the comparison between those estimated based on the literature in Chapter 2. For seabass/seabream, we added the comparison with the benchmark developed using the model portfolio, as in this case we assumed that the representative farms would use the same feed. Emissions from long-line mussels and clam would be reduced by 80% and 55%, respectively and those from bass and bream by 17% for Greece and 32% for Spain, due to different average distances of farms from the shore, with respect to the benchmark. Rainbow trout emissions would be reduced by 50%.

Figure 4.3 Comparison between emission intensities estimated on the basis of the literature, the benchmark and the innovation scenarios, *i.e. vessel electrification for longline mussel culture and seabass/seabream farming; switch from grid electricity in clam hatchery and rainbow trout farming*



Based on these figures, the order of magnitude of the decrease in CO_2e emissions due to the above innovations can be estimated, as summarised in the Table below:

Table 4-42 Decrease in CO_2e emissions per segment and innovation

Commercial Species	Fuel emissions – mapping [tonne CO_2e/tonne lw]	Emissions electric vessel [tonne CO_2e/tonne lw]	Production Volume [tonne/year]	Total reduction [tonne CO_2e/year]
Mussel	0.154	0.015	159,989	22,238
	Hatchery emissions due to electricity use - mapping	Emissions from hatchery, all electricity from PV		
Clam	0.190	0.032	32,734	5,467
	Grow-out emissions - mapping	Emissions electric vessel, all electricity supplied by PV		
Seabass/seabream Greece	1.010	0.057	96,255	91,683
Seabass/seabream Spain	2.2	0.221	38,035	71,962
	Average emissions - mapping	Average emissions - Innovations		
Rainbow trout - FTS	2.495	1.234	180,366	227,441
Total estimated CO_2e reduction				418,792

Based on this estimate, CO_2e emissions would be reduced by 26%, with respect to the emissions of the commercial species considered in the case studies. Further significant reduction, as the rainbow trout results indicate, could be achieved only by 1) reducing the CO_2e emissions of fish feeds; and 2) optimizing the use of fish feed.

4.5 Final remarks

The results presented in the second Chapter of this study were based on a careful analysis of the LCA literature concerning the selected commercial species, which in 2019 accounted for 92% of EU aquafarming production volume. The consistency between the inventories, i.e., the input of the LCA models and the output, i.e. the estimated CO_2e emissions, were thoroughly checked by means of a purposely developed set of models. The results of the CO_2e emission mapping are, therefore, supported by and consistent with the current state-of-the-art peer-reviewed available scientific literature. However, even though the LCA methodology is standardized, the development of LCA models still involves subjective choices concerning: 1) the scope and goal; 2) the system boundaries; and 3) the methodologies selected for the impact assessment. The model output, in this case, the estimated CO_2e emission, is sensitive to these choices but is extremely difficult to quantify the related overall variability Furthermore, as shown in Chapters 2 and 4, the emission intensities depend also on site-specific factors, such as the farm distance from the landing points in marine aquaculture and the water supply and quality in trout farming. Therefore, considering these factors, it is not possible to provide confidence limits for the emission intensities estimated for each commercial species dealt with in this study. Lastly, the literature review revealed important gaps in the current literature, which should be filled in order to get a more accurate picture of EU CO_2e emissions, namely: i) the results concerning mussel raft production are based on papers published more than a decade ago; 2) pacific oyster production in France, the main EU producer, was not investigated using LCA; 3) the literature concerning carp farming in ponds, which is very important on Central European countries, is very limited and may not be representative of the current husbandry practices.

In perspective, the introduction of the PEF, Product Environmental Footprint, could be an important step for improving the accuracy of the emission intensities and monitoring the progress towards the energy transition and the decarbonisation of the aquaculture sector. On the one hand, the PEF would stimulate operators involved in the aquafarming supply chain to share their data, as the footprint of a given product is based on a farm-to-fork approach and, on the other, would provide a large publicly accessible database of environmental profiles, including the carbon footprint. In parallel, nationwide independent LCA studies, based on the PEF methodology and funded by each EU MS, could contribute to investigating the site-specific variability of CO_2e emissions from the aquaculture sector.

The targeted interviews, the validation workshop as well as informal contacts with many operators within the aquaculture supply chains, including feed producers, suggest that the aquaculture sector is, in general, acutely aware of the, often negative, effects of Climate Change on aquafarming, e.g. prolonged droughts affecting land-based farming, more frequent storm events, shellfish mass mortalities caused by heat waves and prepared to undertake adaptation and mitigation actions. The second ones, which include the energy transition towards the decarbonisation of the sector, were recently prompted by economic drivers, e.g. the sudden and marked increase in energy costs due to the “perfect storm” created by the combination of the pandemic and the unprovoked Russian aggression of Ukraine. As happened also in other economic sectors, many aquafarming companies suddenly realized that energy efficiency and the reduction of the volatility of the energy costs were two priorities for staying on the market. Therefore, in the last few years, innovations aimed at both increasing energy efficiency, for example in RAS and at decreasing the dependence on external sources of power, such as the installation of Photovoltaic panels in hatcheries, land-based farms and also in marine fish farms, to power barges, are being implemented. The panorama is therefore rapidly evolving and CO_2e emissions are likely to decrease, under the pressure of these economic drivers. The energy transition partnership could provide a framework for collecting data on the uptake of the above innovations, thus contributing to the monitoring of the progress towards a green, decarbonised EU aquaculture.

5 DECARBONISATION ALTERNATIVES FOR SHORT AND LONG TERMS (TO 2030 AND 2050)

This section provides *preliminary suggestions* for emission savings both in the *short term* and the *long term*.

5.1 Fisheries

The LSF fleet segment is responsible for a majority of the EU fishing fleet emissions (i.e., 3.71 million tonnes CO_2e, almost 73% of the total for the fishing fleet), followed by the DWF fleet (i.e. 970 thousand tonnes CO_2e, or about 19% of the total) and the SSCF fleet (i.e. 404 thousand tonnes CO_2e, or close to 8% of the total).

The fact that the LSF segment has the highest total emissions means the prioritisation of measures applicable to this segment when defining decarbonisation pathways for the sector is particularly important, even if this segment already has the lowest emissions intensity in terms of CO_2e per kilogram of fish. The DWF segment still also accounts for a significant part of the total EU fishing fleet emissions and thus could also be prioritised in the push to realise the EU's decarbonisation goals. Lastly, while the SSCF segment is only responsible for a minor fraction of the total emissions from the sector, it still has the highest emissions intensity profile and thus to meet net zero emissions goals this fleet segment will also need to be tackled.

Below, we will elaborate on the emissions reduction alternatives available for each of the fleet segments, considering among other things their financial performance and marginal abatement costs.

5.1.1 Suggested options for SSCF fleet based on financial performance and marginal abatement cost.

None of the solutions identified for the average SSCF EU vessel generate a positive payback on the investment within their expected lifetimes and thus all of them have indeterminate payback periods and are loss-making. The best performer in this case is the inclusion of wind turbines onboard the vessel, with an EAA representing an annualised loss of EUR 628 for an average SSCF vessel. After that, biodiesel, antifouling, energy audits, route optimisation and BlueBox are the next best options in financial terms, with EAAs ranging from EUR 843 to EUR 1,632 in losses. The remaining solutions have EAAs representing losses upwards of EUR 2,537 with the largest being a conversion to diesel-electric resulting in losses of around EUR 30,000 per year on average.

For these solutions to reach a payback, there are significant financial gaps to cover. ([135]) In the lowest case, for energy audits, fishers need EUR 1,451 to cover the costs of each investment in energy audits and in the most extreme case, fishers need EUR 495,114 to cover the costs of investment in diesel-electric solutions. Table 5-1 contains a summary of the available solutions for this segment, in order of their EAAs, which can serve as an initial guideline for priority setting.

([135]) Meaning the additional money fishers would need to procure for the investment to reach a payback (or net zero cumulative cashflow) by the end of the lifetime of the investment.

Table 5-1 Summary of available solutions for the SSCF segment

Technology	Payback period (years)	Financial gap for payback within lifetime (if any)	Equivalent Annual Annuity (EAA)
Technologies that do not reach a payback period within their lifetimes			
Wind turbines	Payback indeterminate	€ 9,778.48	-€ 628.19
Biodiesel: HVO, FAME, FT, DME	Payback indeterminate	€ 21,269.44	-€ 843.38
Antifouling: hull and propellor	Payback indeterminate	€ 7,413.67	-€ 1,369.68
Energy audits	Payback indeterminate	€ 1,451.14	-€ 1,451.14
Route optimisation: route planning system devices	Payback indeterminate	€ 49,834.18	-€ 1,571.99
BlueBox	Payback indeterminate	€ 28,068.36	-€ 1,631.69
Biocrudes: SVO, PO, HTL, SO	Payback indeterminate	€ 63,615.40	-€ 2,537.22
Methanol (bio/e-)	Payback indeterminate	€ 98,812.04	-€ 3,503.30
Hydrogen (bio/e-)	Payback indeterminate	€ 195,873.25	-€ 5,683.76
LNG (bio/e-)	Payback indeterminate	€ 132,161.39	-€ 5,723.89
Propeller-rudder upgrade	Payback indeterminate	€ 93,045.57	-€ 5,769.07
Ammonia (bio/e-)	Payback indeterminate	€ 140,084.87	-€ 5,939.04
Larger Propeller, Nozzle and Optimized Stern	Payback indeterminate	€ 196,824.05	-€ 19,014.11
Improved hull design	Payback indeterminate	€ 347,556.96	-€ 21,444.77
Diesel-electric	Payback indeterminate	€ 495,113.93	-€ 30,579.54
Use pre-and post swirl fins and stators	Payback indeterminate	€ 384,521.17	-€ 61,609.19

Source: consortium elaboration

Linking this with the analysis on marginal abatement cost from section 4.2, while wind turbines provide the least costs, their abatement potential is minimal and not the most suitable option for decarbonisation. In comparison antifouling has larger emissions abatement potential (i.e., around 1 Mton CO_2e in the short term but decreasing in the long term) while also being at a relatively advantageous marginal abatement costs compared to other solutions. Biodiesel has a less advantageous marginal abatement costs than the previously mentioned solutions, but it has a large abatement potential (i.e., about 3 Mton CO_2e in the short term and over 4 Mton in the long term) which makes it a promising potential solution.

The most promising option to meet decarbonisation goals for the SSCF fleet could very well be a switch to biodiesel, which in addition offers the advantage of not requiring modifications to the vessels that would warrant large upfront costs despite increasing operational costs in the short and long terms. Despite the lower abatement potential of antifouling, its lower marginal abatement costs and the possibility of combining solutions means that aiming for its application on the SSCF fleet should not be discouraged. The use of larger propellers is also an open option in the short term that could provide around 0.5 Mton of CO_2e abatement, but its installation represents a large costs for fishers and it is one that must be borne upfront which further threatens its financial viability. It is clear that in the case of the SSCF fleet, fishers will need to find additional financial resources to afford any of these solutions.

5.1.2 Suggested options for LSF fleet based on financial performance and marginal abatement cost.

The best performer for LSF is the use of outrigs and sumwings instead of trawling, with an EAA of EUR 9,265 and EUR 3,151 in returns, respectively. Following that, smart steaming, BlueBox, antifouling and waste heat recovery systems all produce positive EAAs between EUR 2,430 and EUR 267. Wind turbines on their part, while they reach a payback period, they account for a negative EAA of EUR 139 in losses due to the time value of money. Table 5-2 summarises the available solutions available, ranked by their EAA.

Table 5-2 Summary of available solutions for the LSF segment

Technology	Payback period (years)	Financial gap for payback within lifetime (if any)	Equivalent Annual Annuity (EAA)
Technologies that reach a payback period within their lifetimes			
Outrig (instead of trawling)	1	N/A	€ 9,264.99
Using a Sumwing (trawlers)	8	N/A	€ 3,150.75
Smart steaming	1	N/A	€ 2,429.75
BlueBox	8	N/A	€ 1,300.34
Antifouling: hull and propellor	5	N/A	€ 893.25
Waste heat recovery systems	11	N/A	€ 267.30
Wind turbines	19	N/A	-€ 139.22
Technologies that do not reach a payback period within their lifetimes			
Route optimisation: route planning system devices (136)	Payback indeterminate	€ 16,353.75	-€ 593.00
Energy audits	Payback indeterminate	€ 1,035.13	-€ 1,035.12
Energy efficient lighting systems	Payback indeterminate	€ 75,702.50	-€ 5,183.10
Propeller-rudder upgrade	Payback indeterminate	€ 70,452.62	-€ 5,383.58
Frequency converters	Payback indeterminate	€ 180,464.29	-€ 9,065.71
Helix spiral-trawling net (137)	Payback indeterminate	€ 341,281.25	-€ 12,519.07
Biodiesel: HVO, FAME, FT, DME	Payback indeterminate	€ 357,128.91	-€ 14,255.38
Twinrig (instead of trawling)	Payback indeterminate	€ 374,857.25	-€ 24,486.53
Improved hull design	Payback indeterminate	€ 408,884.38	-€ 27,130.36
Suction wings	Payback indeterminate	€ 611,776.88	-€ 29,966.32
Larger Propeller, Nozzle and Optimized Stern	Payback indeterminate	€ 371,033.13	-€ 37,257.05
Diesel-electric	Payback indeterminate	€ 628,512.50	-€ 41,302.97
Methanol (bio/e-)	Payback indeterminate	€ 1,346,307.38	-€ 44,469.93

(136) Available from 2027
(137) Available from 2035

Technology	Payback period (years)	Financial gap for payback within lifetime (if any)	Equivalent Annual Annuity (EAA)
Kites	Payback indeterminate	€ 1,039,256.25	-€ 47,898.01
Biocrudes: SVO, PO, HTL, SO	Payback indeterminate	€ 1,410,020.57	-€ 56,371.05
Sails	Payback indeterminate	€ 1,122,637.50	-€ 60,529.22
Use pre-and post swirl fins and stators	Payback indeterminate	€ 423,094.23	-€ 67,986.85
LNG (bio/e-)	Payback indeterminate	€ 2,072,111.61	-€ 77,672.56
Hydrogen (bio/e-) ([138])	Payback indeterminate	€ 3,064,758.37	-€ 81,270.35
Ammonia (bio/e-) ([139])	Payback indeterminate	€ 2,357,140.80	-€ 94,867.49

Source: consortium elaboration

Given that smart steaming and antifouling can be applied to a wide range of vessels, their abatement potential in the short and long term are considerable and with a negative marginal abatement costs it also comes with costs savings, making this a potential priority for this segment, especially as both solutions could be applied simultaneously. Outrigs have a limited abatement potential in aggregate for the EU as their scope is limited to trawlers, but given that they can represent monetary savings of close to EUR 200 per tonne of CO_2e reduced, they are an obvious alternative to pursue regardless. Helix spiral nets also remain an option for trawlers to abate emissions at negative costs in the longer term, so they could still be pursued as an alternative if they are compatible higher priority measures. From the solutions that do not imply cost savings, the use of biodiesel is worth mentioning again due to its large abatement potential despite the comparatively higher costs for the fleet, where fishers would need to procure finance for a gap of over EUR 350,000 per vessel to break even.

5.1.3 Suggested options for DWF fleet based on financial performance and marginal abatement cost.

The best performer for DWF is the use of sumwings instead of trawling, with an EAA of EUR 72,095 in returns. Following that, BlueBox, antifouling, smart steaming, wind turbines, energy audits, energy efficient lighting, route optimisation and using larger propellers all produce positive EAAs between EUR 42,421 and EUR 8,383. Diesel-electric propulsion, propeller-rudder upgrades and improved hull design on their part, while they reach a payback period, they account for negative EAAs between EUR 920 and EUR 16,077 in losses due to the time value of money. Table 5-3 ranks available solutions by their EAA.

Table 5-3 Summary of available solutions for the DWF segment

Technology	Payback period (years)	Financial gap for payback within lifetime (if any)	Equivalent Annual Annuity (EAA)
Technologies that reach a payback period within their lifetimes			
Using a Sumwing (trawlers)	1	N/A	€ 72,094.50
BlueBox	1	N/A	€ 42,420.70
Antifouling: hull and propellor	2	N/A	€ 32,632.76

([138]) Available from 2035
([139]) Available from 2035

Technology	Payback period (years)	Financial gap for payback within lifetime (if any)	Equivalent Annual Annuity (EAA)
Smart steaming	1	N/A	€ 30,315.00
Wind turbines	3	N/A	€ 13,126.35
Energy audits	1	N/A	€ 12,157.50
Energy efficient lighting systems	9	N/A	€ 11,942.01
Route optimisation: route planning system devices ([140])	1	N/A	€ 11,802.89
Larger Propeller, Nozzle and Optimized Stern	10	N/A	€ 8,383.07
Diesel-electric	17	N/A	-€ 919.96
Propeller-rudder upgrade	24	N/A	-€ 10,919.41
Improved hull design	22	N/A	-€ 16,077.46
Technologies that do not reach a payback period within their lifetimes			
Frequency converters	Payback indeterminate	€ 168,278.46	-€ 14,324.94
Kites ([141])	Payback indeterminate	€ 444,250.00	-€ 35,556.55
Suction wings	Payback indeterminate	€ 762,637.50	-€ 39,718.11
Use pre-and post swirl fins and stators	Payback indeterminate	€ 351,456.50	-€ 58,880.28
Sails	Payback indeterminate	€ 1,699,335.73	-€ 88,445.90
Biodiesel: HVO, FAME, FT, DME	Payback indeterminate	€ 4,359,568.00	-€ 174,097.57
Methanol (bio/e-) ([142])	Payback indeterminate	€ 15,867,969.33	-€ 512,814.92
Biocrudes: SVO, PO, HTL, SO	Payback indeterminate	€ 17,496,070.88	-€ 699,557.68
LNG (bio/e-)	Payback indeterminate	€ 26,128,987.14	-€ 980,163.04
Hydrogen (bio/e-) ([143])	Payback indeterminate	€ 38,301,140.20	-€ 994,564.87
Ammonia (bio/e-) ([144])	Payback indeterminate	€ 28,455,149.58	-€ 1,117,222.43

Source: consortium elaboration

Once again, given that antifouling can be applied to a wide range of vessels its abatement potential is large and it also comes with costs savings, it makes this a priority for this segment. Smart steaming also has large abatement potential while producing savings for this segment, so it is also one priority, especially given that DWF vessels imply operations where sailing distances are more relevant than for other segments and thus abatement of emissions during sailing become more important. Larger propellers can also provide significant abatement opportunities for this segment in the short term while also providing cost savings which makes them an attractive solution and the same applies to route optimisation, although with a much more limited abatement potential. Just like in the LSF segment, the use of outrigs instead of trawlers can also provide abatement accompanied with costs savings, although the limited scope of applicability of this solution makes their total abatement potential very limited in aggregate for the entire EU and thus only a secondary priority.

([140]) Available from 2035
([141]) Available from 2025
([142]) Available from 2030
([143]) Available from 2035
([144]) Available from 2025

5.2 Aquaculture

This section provides preliminary suggestions for emission savings in the short term for the aquaculture segments analysed in the previous chapter.

5.2.1 Suggested short-term options (to 2030) with emissions savings.

To reach the goals of a climate-neutral aquaculture sector, a variety of innovations are possible as visible in Table 5-4 below. As is visible, many innovations face high current costs in comparison with emission savings when considering the whole sector and not only the growth in the farm segment.

The costs presented here are approximated, based on the case studies analysed in Chapter 4 and can vary depending on the Member State. The costs presented here are indicative and without incentives and cover the investments assessed in the case studies.

Table 5-4 Innovations for aquaculture are categorised according to Readiness 2030-2050 and TRL including the CO_2e-potential. Wherever numbers are available, also OPEX and CAPEX (in €) are inserted

Innovation	Segment	TRL	Available in	CAPEX (EURO)	OPEX	CO_2e reduction potential in %
PV Installation	Land-based Aquaculture	9	Now	20.000 – 1.500.000	N/A	5-14%
PV Installation	Hatchery	9	Now	250.000 – 300.000	N/A	43%
O2 Generator	Land-based Aquaculture	9	Now	150.000 – 500.000	N/A	16-33%
Barge	Marine Fish Aquaculture	9	Now	1.900.000 – 2.400.000	40.000 – 90. 000	8-13%
Electrification of boats	Marine Fish Aquaculture	9	Now	1.500.000	Depends on MS and distance to the coast	20-61%
Electrification of boats	Marine Shellfish Aquaculture	9	Now	250.000 – 750.000	Depends on MS and distance to the coast	41%

The CO_2e reduction potential was estimated taking as references: 1) boat electrification in shellfish farming: the total emissions long-line mussels estimated in Chapter 2; 2) Shellfish hatchery: the total emissions of clam farming estimates in Chapter 2; 3) Marine fish and Land-based farming: the total emissions of the benchmarks for each Representative Farm, based on the results presented in Chapter 4.

Innovations regarding land aquaculture and hatcheries, which are based on reducing the energy from the electric grid by the use of renewable energy sources in-site as well as generators of oxygen are the most feasible to be successfully implemented before 2030.

Innovations regarding marine aquaculture, in particular those that require electrification of boats are according to the results presented in Chapter 4 less feasible to be implemented by 2030. This is in addition to the elevated costs, due to the need of these innovations of having support facilities at port and marinas in order to power the boats. The CO_2 reduction potential of these innovations is also highly variable when considering that the energy to power the boats should be from renewables in order to have a relevant impact on the CO_2 emission reduction by the segment.

6 IMPLEMENTATION RISKS, LIKELIHOOD, SEVERITY AND POTENTIAL SYNERGIES BY DESIGN

This section presents the outcomes of a risk analysis that builds on initial assessments focused on technological maturity, cost implications and potential emissions reductions. It also clearly identifies potential synergies between innovations in fisheries and aquaculture. The methodology for the analysis is detailed below:

Risk and synergy identification

- Technology-specific risks: For each decarbonisation technology or solution, catalogue potential risks, which may include technical malfunctions, unexpected operational costs, or unintended environmental effects.
- Cross-sectoral synergies: Pinpoint vessels and contexts where decarbonisation synergies might be realised.
- Scenario analysis: Anticipate risk scenarios for each technology, such as the risk of disrupting natural marine habitats.

Likelihood estimation:

- Likelihood scale: high (3), moderate (2), low (1).
- Estimation procedure: Evaluate the probability of each risk occurring, using desk research and expert judgement.

Severity assessment:

- Impact scale: high (3), moderate (2), low (1).
- Evaluation: Ascertain the potential impact severity of each risk.

Risk prioritisation:

- Combine the likelihood and severity scores to establish the order of priority for risks.

Each risk category was first discussed in the team to ensure a consistent understanding of the translation of the risk to each potential technology or solution. Each member of the team then assessed each risk category as high (3), moderate (2) or low (1) for every technology or solution identified. Consensus was reached in a workshop discussion, where potential synergies were also discussed.

Identified risks, likelihoods and potential severity for the fisheries sector.
For all identified decarbonisation technologies or solutions applicable the fisheries in the EU, it holds that there is a variety of risks and uncertainties that require attention beyond the financial and emissions indicators explored in previous sections. We have developed a consolidated risk assessment matrix for each set of identified technologies. The risk categories assessed were:

Applicability/ scalability risks
This category evaluates the potential for technologies or solutions to be adopted across the entire fishing fleet. Technologies scoring low in this category are universally applicable and capable of being rapidly scaled through market mechanisms, potentially reducing costs. Conversely, a high score indicates limited applicability and challenging scalability.

Reliability risks
This assesses the mechanical dependability of the solutions. A low score (1) signifies robust and reliable technology with minimal failure rates, whereas a high score (3) is assigned to solutions with a greater propensity for malfunction or fragility, indicating a higher risk of breakdowns.

External enablers
This measures the degree of dependency on external factors beyond the control of vessel owners, such as port infrastructure or investor actions. A high score (3) in this category suggests a significant requirement for enabling activities by the public sector or harbour authorities to support the technology's deployment and effectiveness.

Regulatory risks
This category identifies potential regulatory impediments specific to the adoption of recent technologies or solutions within the sector. A high score (3) indicates that the current regulatory framework poses barriers to investment and implementation, while a low score (1) suggests a conducive regulatory environment.

Political risk
This risk category gauges the potential resistance from the fishing sector or member states to the adoption of recent technologies or practices. High scores (3) reflect anticipated opposition, even in the presence of a sound financial rationale, which may impede large-scale implementation.

Additional environmental and social risks
This encompasses the potential for adverse environmental impacts not captured by carbon emissions, such as pollution, noise, or the risk of overfishing, as well as local concerns affecting vessel crew such as working conditions. A high score (3) reflects significant environmental or social concerns, while a low score (1) indicates minimal to no negative impact from the implementation of the technology or solution.

6.1 Fisheries

For the fisheries sector there are some general implementation issues, which fall into two categories.

The first category is related to **regulatory changes** identified as needed to facilitate decarbonisation in general. At least some existing decarbonisation solutions require more space on boats, which through current frameworks, the European Commission interprets as an increase in fishing capacity. Industry stakeholders are advocating for a separate measurement for decarbonisation purposes to address this issue. Additionally, some vessels (e.g. trawlers) are ineligible for national or European public funding needed for modernisation and decarbonisation. Industry stakeholders suggest the creation of a specific fund with different rules to financially support the decarbonisation of these vessels.

The second category relates to analysis assumptions and **the effect of time and place on costs and expenditures**. In particular the capital and operational costs estimated for innovations and solutions are expressed in today’s terms. We would expect that through the process of technological development and (further) commercialisation, the cost of effective solutions would become lower over time. This would be the case in particular for technologies or solutions that apply broadly to the fleet or to large segments of the fleet. A lowering of capital or operational expenditure (through the commercial development process) required for technologies or solutions could have a fundamental impact on the prioritisation/ ranking. In order to provide more certainty on prioritisation, further work would need to be done on the potential future applicability of technologies and solutions, the potential for full scale commercialisation and the impact that would have on costs.

Our analysis makes use of EU27 averages in some cases. We have attempted to minimise the impact of this on results, but it is clear that some variables are highly influenced by geographic location. This could be further explored using case studies. We have also not considered any combined effects (multipliers) that might be associated with concurrent implementation of technologies or solutions, nor that the combined effects of separate solutions in terms of emissions and cost reductions for a single vessel may be less than the sum of their individual effects due to interactions between these solutions. ([145])

In addition to emissions from fuel use, it is possible that bottom-contacting fishing gears (like trawlers and dredgers) have a larger emissions footprint by means of impacting sediments at the bottom of the ocean and releasing previously sequestered carbon into the water and subsequently the atmosphere. ([146]) The calculation of the magnitude of this additional impact is plagued by a number of scientific uncertainties; it has been estimated to be globally in the range of 15 to 20% of the total CO_2 absorbed by the ocean each year, ([147]) which is a very large amount, but it is possible that these figures are also overestimated and that some of the carbon released would make it to the atmosphere anyways. ([148]) This description of the fisheries sector focuses on energy use and thus leaves these possible additional emissions out of its scope, although they should be considered along with the aforementioned uncertainties when aiming to address all sources of emissions.

6.1.1 Assessment of risks per solution

The results of the risks, likelihood and severity assessment along with insights are summarised per technology/ solution category below. Although the technologies and solutions are used as identifiers here, more specific information can be found in Annex C.

Engine and propeller solutions

The majority of the technologies and solutions assessed are applicable, reliable and face minimal challenges in terms of external dependencies, regulatory barriers and political resistance. The environmental impacts are low, indicating that these technologies are not only viable for decarbonisation but also environmentally considerate. This suggests that the EU fishing fleet has several promising options for reducing carbon emissions while maintaining operational efficiency and compliance.

([145]) As an example of two solutions focusing on the same mechanism to reduce fuel consumption, hull design and antifouling both focus on reducing drag from water and their combined effect is not the sum of its individual contributions.

([146]) Epstein, G. et al. (2022) The impact of mobile demersal fishing on carbon storage in seabed sediments. Retrieved from: https://doi.org/10.1111/gcb.16105.

([147]) Sala, E., Mayorga, J., Bradley, D. et al. (2021) Protecting the global ocean for biodiversity, food and climate. Nature 592, 397–402. https://doi.org/10.1038/s41586-021-03371-z.

([148]) Hiddink, J.G., van de Velde, S.J., McConnaughey, R.A. et al. (2023) Quantifying the carbon benefits of ending bottom trawling. Nature 617, E1–E2. https://doi.org/10.1038/s41586-023-06014-7.

Table 6-1. Summary of risks, likelihood and severity analysis for engine and propeller solutions

#	Technology/ solution	Applicability / scalability	Relia-bility	External enablers	Regu-latory	Politi cal	Environmental (unintended)
1	Electric on-board consumers	*1*	*2*	*1*	*1*	*1*	*1*
2	Frequency converters	1	1	1	1	1	1
3	Waste heat-recovery systems	2	1	1	1	1	1
4	Oil filtration system combined with frequency driver	2	2	1	1	1	1
5	Shore power/shore supply of electricity	*2*	*1*	*3*	*1*	*1*	*1*
6	Larger Propellor, Nozzle and Optimised Stern	1	1	1	1	1	1
7	Antifouling	1	1	1	2	1	2
8	Use pre-and post-swirl fins and stators	1	2	1	1	1	1
9	Anti-roll systems/Use of stabilizer fins	2	2	1	1	1	1
10	Propeller-rudder upgrade	1	1	1	1	1	1

A description of key issues per technology or solution under this category is provided below based on the process of assessment.

1. *Electric on-board consumers*

Highly scalable and reliable, with minimal reliance on external factors, this technology aligns well with current regulations, has low political risk and minimal unintended environmental impact, making it an ideal choice for widespread adoption.

2. *Frequency converters*

Similar to electric on-board consumers, these are applicable and reliable. They face minimal regulatory, political and environmental challenges, making them a promising solution for enhancing energy efficiency.

3. *Waste heat-recovery systems*

Scalable but highly reliable. Minimally dependent on external factors and well-supported by regulatory frameworks. These systems pose low political and environmental risks, making them suitable for broader implementation.

4. *Oil filtration system combined with frequency driver.*

Moderately scalable and reliable. Like other technologies, they have low dependence on external enablers and align well with current regulations and political landscapes. Their environmental impact is minimal, making them a viable option.

5. *Shore power/ shore supply of electricity*

Moderately scalable, reliable, but more dependent on external infrastructure. Regulatory support is present, but the higher dependence on port infrastructure poses a challenge. Political and environmental risks remain low.

6. Larger propellor, nozzle and optimised stern

Applicable, reliable and independent of external factors. They align well with existing regulations, face minimal political resistance and have low unintended environmental impacts, suggesting strong potential for widespread adoption.

7. Antifouling

Highly scalable and reliable with minimal external dependencies. However, they face slightly higher regulatory challenges and have a moderate environmental impact due to potential chemical usage, which may require careful consideration.

8. Use of pre-and post-swirl fins and stators

High applicability but moderate reliability. These solutions are well-supported by regulatory frameworks and have low political and environmental risks, indicating good potential for adoption despite some reliability concerns.

9. Anti-roll systems/use of stabiliser fins

Moderately scalable and reliable. These systems are minimally dependent on external factors and align well with regulations. They pose low political and environmental risks, making them a feasible option for enhancing vessel stability.

10. Propeller-rudder upgrade

Applicable and reliable, with minimal external dependencies. Supported by existing regulations and facing minimal political resistance. Their environmental impact is low, making them an excellent option for improving propulsion efficiency.

Vessel design and operation solutions

While improved hull design and energy efficient lighting systems demonstrate high reliability and minimal challenges across all criteria, air lubrication systems face some scalability and environmental concerns. Nonetheless, these solutions collectively offer significant potential for enhancing the efficiency and environmental sustainability of vessel design and operation within the EU fishing fleet.

Table 6-2. Summary of risks, likelihood and severity analysis for vessel design and operation solutions

#	Technology/ solution	Applicability / scalability	Reli-ability	External enablers	Regula tory	Poli-tical	Environmental (unintended)
11	Improved hull design	*2*	*1*	*1*	*1*	*1*	*1*
12	Apply Air Lubrication Systems	3	2	1	1	1	2
13	Energy efficient lighting systems	1	1	1	1	1	1

A description of key issues per technology or solution under this category is provided below based on the process of assessment.

11. Improved hull design

Moderately scalable, with high reliability. These designs have minimal dependence on external factors and align well with current regulations. They also face low political risk and minimal unintended environmental impact, making them a viable option for enhancing vessel efficiency. This is however a solution that is difficult to retrofit and mostly available for new vessels.

12. Apply air lubrication systems.

Less scalable due to higher technical demands or costs, with moderate reliability. Minimal dependency on external enablers and aligns well with regulatory frameworks. Political resistance is low, but there is a moderate environmental risk due to potential impacts on marine ecosystems.

13. Energy efficient lighting systems

Highly scalable and reliable, requiring minimal external enablers. These systems are well within regulatory requirements and face minimal political challenges. They also have a low unintended environmental impact, making them an excellent choice for improving energy efficiency on vessels. This technology is not relevant for small scale vessels that are only active during daytime, however.

Alternative propulsion solutions

While alternative propulsion technologies such as biodiesel and biocrudes show high applicability and reliability as they are drop-in solutions, advanced fuels like electric, methanol, ethanol, ammonia, LNG and hydrogen face scalability challenges due to infrastructure and technology limitations. Regulatory and political risks are low across these technologies, but there are moderate concerns regarding unintended environmental impacts, particularly with advanced fuel options. This suggests a need for careful consideration of infrastructure development and environmental impact assessments in the adoption of these alternative propulsion technologies.

Table 6-3. Summary of risks, likelihood and severity analysis for alternative propulsion solutions

#	Technology/ solution	Applicability/ scalability	Relia-bility	External enablers	Regu-latory	Politi-cal	Environmental (unintended)
14	Electric	*3*	*2*	*3*	*1*	*1*	*1*
15	Diesel-electric	2	2	2	1	1	1
16	Biodiesel: HVO, FAME, FT, DME	1	1	2	1	1	2
17	Biocrudes: SVO, PO, HTL, SO	*1*	*2*	*2*	*1*	*1*	*2*
18	Methanol (bio/e-)	3	1	3	2	1	2
19	Ethanol (bio/e-)	3	1	3	1	1	2
20	Ammonia (bio/e-)	*3*	*1*	*3*	*2*	*1*	*2*
21	LNG (bio/e-)	3	1	3	1	1	2
22	Hydrogen (bio/e-)	3	1	3	1	1	2

A description of key issues per technology or solution under this category is provided below based on the process of assessment.

14. *Electric propulsion*

Less scalable due to infrastructure and technology limitations, with moderate reliability. Highly dependent on external infrastructure and moderately aligns with current regulations. Faces minimal political resistance but has a low unintended environmental impact.

15. *Diesel-electric propulsion*

Moderately scalable and reliable, with some dependency on external infrastructure. Generally, aligns well with regulatory frameworks and faces low political resistance. Its environmental impact is low.

16. *Biodiesel: HVO, FAME, FT, DME*

Applicable and reliable, with moderate dependence on fuel supply and infrastructure. Complies with current regulations and faces low political resistance. However, it carries a moderate risk of unintended environmental impacts.

17. *Biocrudes: SVO, PO, HTL, SO*

Applicable with moderate reliability and dependency on fuel supply. Aligns with regulatory requirements but carries a moderate risk of unintended environmental impacts.

18. *Methanol (bio/e-)*

Less scalable due to current technology limitations and infrastructure needs, with high reliability. Faces moderate regulatory challenges and dependency on external factors. It has a moderate unintended environmental impact.

19. *Ethanol (bio/e-)*

Similar to methanol, less scalable due to technological and infrastructure constraints, but reliable. Faces minimal regulatory challenges and has a moderate unintended environmental impact.

20. *Ammonia (bio/e-)*

Less scalable due to technological and infrastructure constraints, with high reliability. Faces moderate regulatory challenges and dependency on external infrastructure, with a moderate unintended environmental impact.

21. *LNG (bio/e-)*

Less scalable due to infrastructure requirements, but reliable. Aligns well with current regulations and faces minimal political resistance. It carries a moderate unintended environmental impact.

22. *Hydrogen (bio/e-)*

Similar to other advanced fuels like ammonia and LNG, hydrogen propulsion is less scalable due to current technological and infrastructure limitations, but it is reliable. It aligns well with current regulations and faces minimal political resistance, with a moderate unintended environmental impact.

Wind assistance solutions

Wind assistance technologies like kites, suction wings and wind turbines present high scalability and reliability with minimal challenges in terms of external dependencies, regulatory barriers and political resistance. The environmental impacts are low.

However, sails and Flettner rotors, while reliable, face scalability challenges related to practical implementation on vessels, especially on smaller vessels that have constrained space on deck to place the necessary equipment, vessel stability, or the need to train crews on their use. Despite these challenges, wind assistance solutions offer promising potential for reducing reliance on conventional propulsion methods and enhancing environmental sustainability in the EU fishing fleet.

Table 6-4. Summary of risks, likelihood and severity analysis for wind assistance solutions

#	Technology/ solution	Applicability/ scalability	Reliabil-ity	External enablers	Regula-tory	Politi-cal	Environmental (unintended)
23	Kites	*1*	*1*	*1*	*1*	*1*	*1*
24	Suction wings	2	1	1	1	1	1
25	Sails	3	1	1	1	1	1
26	Wind turbine	*1*	*1*	*1*	*1*	*1*	*1*
27	Flettner rotor	3	1	1	1	1	2

A description of key issues per technology or solution under this category is provided below based on the process of assessment.

23. Kites

Highly scalable and reliable, requiring minimal external support. These systems are well within regulatory requirements and face minimal political and environmental challenges. Their high applicability makes them an excellent choice for augmenting propulsion with wind power.

24. Suction wings

Moderately scalable with high reliability. Minimal dependency on external enablers and aligns well with regulatory frameworks. Faces low political risk and has a low unintended environmental impact, making it a viable option for wind-assisted propulsion.

25. Sails

Less scalable due to potential practical limitations on certain vessel types, but highly reliable. Requires minimal external support and aligns well with current regulations. Faces low political risk and has a low environmental impact.

26. Wind turbine

Highly scalable and reliable, with minimal dependence on external factors. These systems comply with regulatory requirements and face minimal political challenges. They also have a low unintended environmental impact, making them an excellent option for harnessing wind energy on vessels.

27. Flettner rotor

Less scalable due to potential design and operational limitations, but highly reliable. Requires minimal external support and aligns well with regulatory frameworks. Faces low political risk, although there is a moderate environmental risk due to potential impacts on bird life and other factors.

Fishing gear solutions

The assessed fishing gear technologies present moderate to high scalability and high reliability, noting that some of them are only relevant to trawlers. These solutions present minimal challenges in terms of external dependencies and political resistance. Regulatory challenges and environmental impacts vary, but overall, these technologies offer promising potential for improving fishing efficiency and sustainability. During this assessment we did not include consideration of the future (viability) of trawling practices in general since we are specifically considering the potential to decarbonise the practice. Innovations in netting and trawling equipment, along with shifts from active to passive fishing methods, can play a significant role in enhancing the environmental sustainability of the EU fishing fleet.

Table 6-5. Summary of risks, likelihood and severity analysis for fishing gear solutions

#	Technology/ solution	Applicability/ scalability	Reli-ability	External enablers	Regu-latory	Poli-tical	Environmental (unintended)
28	Using a Sumwing (trawlers)	*2*	*1*	*1*	*1*	*1*	*1*
29	Outrig (instead of trawling)	2	1	1	1	1	1
30	Twinrig (instead of trawling)	2	1	1	1	1	1
31	Lighter trawl door	*2*	*1*	*1*	*1*	*1*	*1*
32	Using sledges	2	1	1	1	1	1
33	From active to passive	*1*	*1*	*1*	*1*	*2*	*1*
34	Helix spiral-trawling net	2	1	1	1	2	1
35	Lighter nets	1	2	1	2	1	1
36	Alternative netting design	*1*	*1*	*1*	*2*	*1*	*1*

A description of key issues per technology or solution under this category is provided below based on the process of assessment.

28. Using a Sumwing (trawlers)

Moderately scalable and reliable. Requires minimal external support and aligns well with regulatory frameworks. Faces low political risk and has a low unintended environmental impact, making it a viable option for improving trawling efficiency.

29. Outrig (instead of trawling)

Moderately scalable and reliable. Minimal dependency on external enablers and aligns well with current regulations. Faces low political risk and has a low environmental impact, suggesting it's a feasible alternative to traditional trawling methods.

30. Twinrig (instead of trawling)
Moderately scalable and reliable. Requires minimal external support and complies with regulatory requirements. Low political risk and environmental impact, offering a viable alternative to conventional trawling.

31. Lighter trawl door
Moderately scalable and reliable. Minimal dependency on external factors and aligns well with regulatory frameworks. Faces low political risk and has a low environmental impact, making it an effective solution for trawling efficiency.

32. Using sledges
Moderately scalable and reliable. Minimal external support required and aligns well with current regulations. Low political and environmental risks, making it a feasible option for trawling.

33. From active to passive
Highly scalable and reliable, requiring minimal external support. Aligns well with regulatory requirements but faces moderate political resistance. Has a low unintended environmental impact, making it a promising shift in fishing practices.

34. Helix spiral-trawling net
Moderately scalable and reliable. Minimal dependency on external factors and aligns well with regulations. Faces moderate political risk, with a low environmental impact, suggesting it's a viable innovation in net design.

35. Lighter nets
Highly scalable but with moderate reliability. Minimal external dependencies but faces some regulatory challenges. Low political risk and environmental impact, indicating potential for improving trawling efficiency with material innovations.

36. Alternative netting design
Highly scalable and reliable, with minimal dependence on external factors. Faces some regulatory challenges but has low political risk and environmental impact, making it a promising area for innovation in fishing gear.

Onboard processing solutions

These onboard processing technologies face applicability challenges and in any case are not relevant for smaller scale vessels. They are reliable and face minimal challenges in terms of external dependencies, regulatory barriers and political resistance. The environmental impacts vary, with natural refrigerants presenting some concerns. Overall, these technologies offer potential improvements in onboard processing efficiency and sustainability for the EU fishing fleet, although careful consideration of environmental impacts, especially for natural refrigerants, is necessary.

Table 6-6. Summary of risks, likelihood and severity analysis for onboard processing solutions

#	Technology/ solution	Applicability/ scalability	Reli-ability	External enablers	Regu-latory	Poli tical	Environmental (unintended)
37	Multistage mono-block ice pumps	3	1	1	1	1	1
38	Cogged V-belt instead of flat V-belt in cooling system	3	1	1	1	1	1
39	Using natural refrigerants for freezing	3	1	1	1	1	2

A description of key issues per technology or solution under this category is provided below based on the process of assessment.

37. Multistage mono-block ice pumps

Less scalable due to potential technological or practical limitations, but reliable. Requires minimal external support and aligns well with current regulatory frameworks. Faces low political risk and has a low unintended environmental impact, making them suitable for onboard ice management.

38. Cogged V-belt instead of flat V-belt in cooling system

Less scalable due to specific technical requirements, but reliable. Minimal dependency on external factors and aligns well with regulatory requirements. Faces low political risk and has a low environmental impact, suggesting effectiveness in enhancing cooling system efficiency.

39. Using natural refrigerants for freezing

Less scalable due to technological and practical constraints that can include the need for new safety standards, but reliable. Requires minimal external support and complies with current regulations. Faces low political risk but carries a moderate risk of unintended environmental impacts, due to the nature of the refrigerants used.

Consumption management solutions

Consumption management solutions like slow steaming, smart steaming, route-planning systems, energy audits, on-board energy-monitoring devices and Bluebox are applicable and reliable. They face minimal challenges in terms of external dependencies, regulatory barriers and political resistance. Slow and smart steaming are likely to face some opposition or severe operational limitations in a competitive environment (i.e., the need for standardisation of practice exists, providing a high regulatory burden and probably ineffective/ varied practice from the perspective of decarbonisation, or the need to derate vessels as a means of enforcement, which comes at tremendous costs for existing vessels). Their unintended environmental impacts are low, highlighting their potential for significantly improving energy efficiency and reducing fuel consumption in the EU fishing fleet. These solutions are key to managing and optimising energy use onboard, contributing to the overall goal of decarbonisation.

Table 6-7. Summary of risks, likelihood and severity analysis for consumption management solutions

#	Technology/ solution	Applicability/ scalability	Reli-ability	External enablers	Regu-latory	Poli-tical	Environmental (unintended)
40	Slow steaming, de-rating	*1*	*1*	*1*	*2*	*2*	*1*
41	Smart steaming	1	1	1	1	1	1
42	Route-planning systems	1	1	2	1	1	1
43	Energy audits	*1*	*1*	*1*	*1*	*1*	*1*
44	On-board energy-monitoring devices and operative advice	1	1	1	1	1	1
45	Bluebox (dashboarding and performance data communication)	1	1	1	1	1	1

A description of key issues per technology or solution under this category is provided below based on the process of assessment.

40. Slow steaming, de-rating

Highly scalable and reliable, requiring minimal external support. Faces some regulatory challenges and moderate political resistance, due to operational impact on shipping schedules. Has a low unintended environmental impact, making it a viable strategy for reducing fuel consumption.

41. Smart steaming

Highly scalable and reliable, with minimal dependency on external factors. Aligns well with current regulations and faces minimal political risk. Has a low environmental impact, indicating its effectiveness in optimizing fuel efficiency.

42. Route-planning systems

Highly scalable and reliable, with some dependency on external navigational data sources. Aligns with regulatory frameworks and faces minimal political risk. Has a low environmental impact, offering a practical solution for optimising voyage planning.

43. Energy audits

Highly scalable and reliable, independent of external factors. Complies with regulatory requirements and faces minimal political challenges. Has a low environmental impact, making it an essential tool for identifying energy-saving opportunities.

44. On-board energy-monitoring devices and operative advice

Highly scalable and reliable, requiring minimal external support. Aligns well with current regulations and faces minimal political risk. Has a low environmental impact, making it an effective means for continuous monitoring and optimisation of energy consumption.

45. Bluebox (dashboarding and performance data communication)

Highly scalable and reliable, with minimal dependence on external factors. Aligns well with regulatory frameworks and faces minimal political risk. Has a low environmental impact, indicating its effectiveness in data collection and analysis for energy management.

6.1.2 *Resulting recommendations*

The resulting recommendations affect various aspects and stakeholders.

Policymaking and regulatory changes

Fleet-wide implementation of measurement practices is crucial for giving fishers insights into fuel consumption and the impact of fuel-reduction strategies. Energy audits and digital equipment, adapted to different fleet sectors (SSCF/LSF/DWF), are important initial steps, particularly beneficial for SSCF and LSF. To facilitate the use of alternative fuels, regulatory adjustments concerning tonnage and vessel length are required, as alternative fuel storage demands more space onboard. Biodiesel stands out as a viable long-term option, not necessitating engine alterations, though its current supply is limited. Financial indicators also need integrating into this evaluation. Slow steaming, cost-effective especially for LSF, is challenging to implement due to the competitive market. Local stakeholder assessments are essential, considering local customs and the necessity of timely return. Fish prices influence this; higher prices can mitigate the impact of reduced catches from slow steaming amid greater competition.

Skills development and capacity building

The transition requires new skills and a change in mindset for fishers, a challenge due to the traditional transfer of knowledge. Education programmes should cover energy transition and the required skill set and safety standards, especially for new generations and update with each innovation (e.g., methanol, ammonia, new gear types, measurement systems, wind assistance in propulsion). R&D support is vital, as many maritime sector technologies are underutilised in fisheries. Investigations into the adoption of onboard electrical consumers and biofouling treatments and R&D focusing on infrastructure for alternative fuels and wind-assisted propulsion are necessary, guided by a vision on prioritised fuels like biodiesel. Local context experimentation and understanding port infrastructure capacities for alternative fuels are important, considering geographical, cultural and socio-economic differences. Further exploration into the shift from active to passive fishing is needed. More research into fishers' incentives is essential to understand the limited uptake of certain technologies and encourage innovation acceptance, addressing related concerns.

Funding and financing

Financing individual measures is a possibility, but prohibitive costs raise doubts about fishers' willingness to invest without financial aid. Deciding between fleet renewal and retrofitting requires more research, as new builds differ significantly from retrofit measures. If retrofitting is chosen, short-term viability of technologies like waste heat recovery systems and antifouling is suggested, with biodiesel as a long-term strategy, dependent on adequate supply. Prioritising the more fuel-intensive active fleet before the passive fleet could be effective. Transforming part of the active fleet to passive fishing needs separate study and experimentation, especially given the variety of alternatives and operational conditions that can be found across the EU.

Where technological solutions provide great societal and environmental benefits, where increased costs cannot be fully passed on to consumers, fully private investments cannot be always justified, especially so for a sector which is already struggling for economic and financial viability. Market failures may emerge and these can provide a rationale for (additional) public support. For this, a wide array of EU public funding and finance schemes are already available and they have been grouped and recently published in a guide on financing the green energy transition of fisheries and aquaculture under the 2021-2027 multiannual financial framework. ([149])

Industry engagement and involvement

As preconditions for decarbonisation measures are place- and time specific, mapping local contexts for experimentation and learning, including consumer involvement, is key. Establishing working groups in each locality to discuss specific challenges and strategies can enhance stakeholder involvement and awareness. However, several conditions need addressing: a roadmap for the fisheries sector to guide decision-making on fuel-reducing innovations, a potential backlog at shipyards following subsidised innovation adoption, fair competition with non-EU fish imports, stock depletion and environmental concerns, different strategies for small-scale fisheries versus distant water vessels and the CO_2e emissions and resources needed for alternative fuel production and other innovations. Deciding between investing in old vessels or constructing new ones, especially when considering cost-intensive innovations like hull improvements, is also crucial.

6.2 Aquaculture

6.2.1 Assessment of risks per solution

The results of the assessment along with insights are presented per technology/solution:

Table 6-8. Summary of risks, likelihood and severity analysis for aquaculture solutions

Segment	Technology/ Solution	Applicability/ scalability	Reli-ability	External enablers	Regu-latory	Poli-tical	Environmental (unintended)
S1.2	PV Installation	*1*	*2*	*2*	*2*	*1*	*1*
S.1.2	Oxygenator	1	*2*	*1*	*1*	*1*	*1*
S.2.1	PV Installation (Hatcheries)	1	*2*	*2*	*2*	*1*	*1*
S.2.1	Electrification of boats	1	1	*2*	1	1	1
S.2.2	Barge	1	1	1	1	1	1
S.2.2	Electrification of boats	*2*	1	3	1	1	1
Feeding	Feeding precision	1	1	1	1	1	1

All innovations/solutions discussed in this study for the aquaculture sector have high applicability as well as scalability since most of the innovations are ready to be used at the farm level: in fact, some innovations, e.g., installation of PV and oxygen generators in trout farms, installation of PV in shellfish hatcheries, are being already implemented at the farm level. For marine finfish aquaculture, differences in the distance from the coast are the main factor that might reduce the applicability of electric boats, however, the current technologies available and the case studies presented here have demonstrated that this innovation can be implemented for most scenarios.

([149]) https://op.europa.eu/en/publication-detail/-/publication/49590638-8e76-11ee-8aa6-01aa75ed71a1

The reliability of the solutions assessed here is high with the consideration that the technologies which aim to reduce the dependency of external factors e.g., electricity and oxygen providers, for these cases, back-up solutions are to be considered to diversify the risk of malfunction. External enablers are a key factor for PV and electric boats, the last requires infrastructure at marinas or aquaculture facilities to support the charging or docking of electric boats, while the installation of PV profitability depends on the access to sell excess electricity and height of feed-in tariffs, which is regulated at Member State level ([150]). Likewise, the installation of PV is subject to prior approval, requiring the submission of a written description of the proposed installation along with a site plan. Depending on the location it may require permits and compliance with local building codes and zoning regulations ([151]). The battery charging infrastructure may also involve permitting and compliance with electrical safety standards. For selling exceeding electricity generated, there are potential grid interconnection regulations and agreements. For the rest, no regulatory issues are expected for the innovations, however, the regulation of charging and maintenance facilities at ports and marinas for electric boats would be key for the successful implementation of this solution.

The innovations presented here are not seen as politically challenging, as confirmed through the validation workshop with key stakeholders in the sector. Similarly, we do not foresee environmental issues derived from them, however, the manufacturing and disposal of PV and batteries require a regulated supply-chain framework to avoid additional environmental risks ([152]).

6.2.2 Resulting recommendations

The resulting recommendations affect various aspects and stakeholders.

Policymaking and regulatory changes

Incentivising aquaculture farmers to invest in renewable energy sources (RESs) such as photovoltaics (PV) and micro-hydroelectric systems could accelerate the energy transition. Removing legal barriers at the member state level, particularly for technologies like floating PV, is crucial. This is especially relevant for rainbow trout and carp farming. Implementing the Product Environmental Footprint (PEF) would provide accurate data on seafood impact, including CO_2e emissions, by standardising the Life Cycle Assessment (LCA) methodology across the value chain, including shellfish hatcheries and fish feed. In marine aquaculture, implementing Marine Spatial Planning (MSP) and harmonising regulations regarding the distance of marine fish farms from the coast can reduce CO_2e emissions, as confirmed by stakeholders. For freshwater aquaculture, systems like Recirculating Aquaculture Systems (RAS) and aquaponics, though currently more energy-intensive, could significantly lower CO_2e emissions if powered by RESs. Less stringent regulations on the reuse of by-products, like nitrogen and phosphorus-rich sludge in agriculture as fertiliser, are essential for reducing emissions in land-based aquaculture.

([150]) https://stats.oecd.org/Index.aspx?DataSetCode=RE_FIT
([151]) COM(2022) 221 final. EU Solar Energy Strategy.
([152]) Antonanzas, J., & Quinn, J. C. (2021). Net environmental impact of the PV industry from 2000-2025. *Journal of Cleaner Production*, *311*, 127791.

Skills development and capacity building

Incorporating energy audits and energy management into the standard practices of aquafarms, particularly SMEs, can yield immediate CO_2e and cost reductions. Advancing digitalisation and increasing access to affordable software for Precision Fish Farming and Precision Aquaculture can optimise feed and oxygen usage in land-based farming, major factors in CO_2e emissions. Research into novel feeds based on circularity and new ingredients, such as single cells, is important for identifying low CO_2e emission options, including full value chain assessments, even for ingredients produced outside the EU.

Funding and financing

In case technological solutions provide great societal and environmental benefits, but where increased costs cannot be fully passed on to consumers, fully private investments cannot be always justified, especially so for a sector which is already struggling for economic and financial viability. Market failures may emerge and these can provide a rationale for (additional) public support. Financial support should focus on transitioning from fossil-fuel-powered vessels to hybrid/electric ones, including necessary port and marina infrastructure. Financing should also support the installation of local RESs like PV, wind farms and micro-hydroelectric systems and aid in digitalising aquafarms and implementing Precision Aquaculture tools.

For this, a wide array of EU public funding and finance schemes are already available and they have been grouped and recently published in a guide on financing the green energy transition of fisheries and aquaculture under the 2021-2027 multiannual financial framework. ([153])

Industry engagement

The industry views the energy transition positively, with potential for long-term economic benefits. Current barriers include policy framework limitations and new licence challenges, such as MSP, PV installation and innovative sludge management. The main technological hurdle is the prohibitive cost of hybrid-electric vessels for SMEs in marine aquaculture. The sector recognises that achieving full energy transition in EU aquaculture requires applying innovations both upstream (e.g., in feed production) and downstream (e.g., in transport and processing), as farm-level emissions represent only a part of the sector's total emissions.

6.3 Synergies by design

The synergies between the fisheries and aquaculture sector in the context of the energy transition are significant considering the **overlap in vessel use**. Both sectors can benefit from various technological measures, alternative propulsion systems, equipment optimisations and facilitating measures like energy audits. The effectiveness of vessel-based technologies and solutions in aquaculture depends on the distance travelled from the coast as part of practices.

As shown earlier in the report, this varies across geographies and could require location-specific implementation/ incentivisation. In this case, **maritime spatial planning** (MSP) can play a vital role to help accommodate aquaculture practices closer to the shore, as it is often pushed out to more remote distant locations in case of tensions with other

([153]) https://op.europa.eu/en/publication-detail/-/publication/49590638-8e76-11ee-8aa6-01aa75ed71a1 maritime functions (e.g., tourism). MSP could also support geographic proximity between fishery and aquaculture operations, e.g., allowing for shared upstream or downstream activities (e.g. fish processing).

Both sectors use small-scale vessels that could benefit from similar technological development or upgrades. The age of aquaculture vessels and the extent to which they have adopted these technologies might vary, but there is potential for retrofitting or upgrading. Technological improvements such as antifouling, frequency converters and hull design modifications can enhance operational efficiency and reduce carbon footprints in both sectors.

Alternative propulsion systems have potential particularly for aquaculture vessels, akin to passive fishing vessels, primarily travelling to and from their operational sites. This similarity underscores the potential for using alternative propulsion systems like electric, biodiesel, or hybrid engines. In particular (as shown previously) electric propulsion may even be more applicable/ viable to aquaculture vessels than fisheries vessels due to the more certain nature of their everyday operations. These propulsion systems offer a sustainable alternative to traditional fossil fuels, reducing emissions and potentially lowering operational costs. The predictable travel patterns of aquaculture vessels may even make them ideal candidates for technologies still developing scalability, like electric propulsion.

Equipment optimisation, while specific equipment needs may differ, certain technologies have universal applicability. Adopting lighter and more efficient gear can benefit both sectors by reducing energy use and operational costs. This could include innovations in net design or the use of more sustainable materials, potentially improving overall environmental impact.

Facilitating measures such as **energy audits and digital monitoring** in both sectors can benefit from measures that identify and manage energy use. Energy audits and digital energy monitoring systems offer insights into consumption patterns and inefficiencies. Implementing these measures can lead to significant energy savings and operational optimisations. Regular energy audits can help identify areas for improvement, while onboard energy-monitoring devices can provide real-time data for immediate adjustments. The adoption of "smart" technologies like route-planning systems and smart steaming can further enhance efficiency.

In **conclusion**, the overlap in vessel use between fisheries and aquaculture presents a unique opportunity to apply decarbonisation technologies and practices across both sectors. By focusing on shared technologies like alternative propulsion, equipment optimisations and energy management tools, these sectors can collectively reduce their carbon footprint, improve operational efficiency and move towards more sustainable practices. The key is to tailor these technologies to the specific needs and characteristics of each sector while leveraging their commonalities for broader environmental benefits. Facilitating learnings and collaborations across the sectors could be a role for the public sector. Any small vessel incentivisation provided for modernising and decarbonising the fishing fleet should be assessed for applicability in aquaculture practices.

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