EU Aquaculture: Greenhouse Gas Reduction Costs and Pathways to Net Zero by 2050

Final Report

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EU Aquaculture: GHG Reduction Costs and Pathways to Net Zero by 2050

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List of Abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
ASC	Aquaculture Stewardship Council
CAPEX	Capital Expenditures
CINEA	European Climate, Infrastructure and Environment Executive Agency
CRCF	Carbon Removals and Carbon Farming
DCF	Data Collection Framework
DG MARE	Directorate-General for Maritime Affairs and Fisheries
ESR	Effort Sharing Regulation
ETP	Energy Transition Partnership
ETS	Emission Trading System
EU	European Union
EUMOFA	European Market Observatory for Fisheries and Aquaculture
FAO	Food and Agriculture Organization
FE	Feed (conversion) Efficiency
FCM	Framework Contract Manager
FCRs	Feed Conversion Ratios
GHG	Greenhouse Gas
GIS	Geographic Information System
IMTA	Integrated Multi-Trophic Aquaculture
IQR	Interquartile Range
LCA	Life Cycle Assessment
LW	Live Weight
MAC	Marginal Abatement Cost
MACC	Marginal Abatement Cost Curve
MCA	Multi-Criteria Analysis
MS	Member State
NPV	Net Present Value
OPEX	Operating Expenditures
PFF	Precision Fish Farming
RAS	Recirculating Aquaculture Systems
SCM	Specific Contract Manager
SCP	Single-Cell Protein
STECF	Scientific, Technical and Economic Committee for Fisheries
SWD	Staff Working Document
t	Metric tonne
VCS	Verified Carbon Standard

Abstract

This study develops evidence-based pathways for the EU aquaculture sector to reach carbon neutrality by 2050, focusing on emissions arising along the full farming chain: hatchery and grow-out operations, feed production and transport, on-farm energy use, vessel use for cage and non-fed systems, and related infrastructure and logistics. Emissions are quantified for five main production systems (cages, non-fed, ponds, raceways and recirculating aquaculture systems, RAS) over 2005–2024, providing the basis for assessing mitigation options and long-term transition pathways.

A harmonised EU-wide database of CO_2eq emissions was built for all aquaculture species and five main production systems for 2005–2024 using life-cycle assessment, filling data gaps with ecologically similar species and neighbouring countries and remodelling energy use with SimaPro to reflect national energy mixes.

Eight scenarios were then designed, combining different tools considered technically and economically feasible: emerging feed materials and breeding, AI-based tools, renewable energy, integrated multi trophic aquaculture, improved energy efficiency, increasing the share of non-fed aquaculture, and offsetting tools such as buying carbon credits on the voluntary market and paying for ecosystem restoration. Scenarios range from business-as-usual (no policy or technology change) and a “high non-fed growth” baseline, to alignment with EU climate targets, low-investment pathways, resilience-focused pathways, and “maximum reduction” variants with and without offsets. For scenarios emission reductions, that differ from business as usual, investment needs and marginal abatement costs (MAC) were quantified; MAC ranges from about 46–243 €/t CO_2eq in 2026–2030, 65–232 €/t CO_2eq in 2026–2040, and 69–228 €/t CO_2eq in 2026–2050, with system-specific MACs between roughly 41–72 €/t CO_2eq for cages, ponds, raceways and RAS, and higher costs (≈172–227 €/t CO_2eq) for further reductions in already low-emission non-fed systems.

Sensitivity analysis with higher carbon prices (up to around 195, 252 and 495 €/t CO_2eq in 2030, 2040 and 2050) shows a marked increase in MACs across all systems, with electric boat dependent suspended and cage systems reaching annual MACs of about 600 €/t CO_2eq by 2050.

These MACs reflect both the costs of internal abatement measures within aquaculture operations and the costs of compensating indirect upstream emissions from feed, energy, transport and hatcheries, even though—under a strict Climate Law interpretation—those upstream emissions should primarily be reduced within the respective supplying sectors rather than by aquaculture alone.

A multi-criteria analysis and SWOT assessment, informed by surveys, focus groups and interviews, evaluated economic, environmental and social trade-offs and stakeholder views on each tool and scenario, and fed into the design of reduction pathways with time-specific adoption rates per production system. Even with these pathways, the model shows that emissions in 2030, 2040 and 2050 are still above the required caps, so direct mitigation is not enough to reach carbon neutrality, especially as the sector is expected to grow; offsets are therefore essential. The need for offsets arises because residual emissions remain from energy, transport and infrastructure, and because feed-related emissions, although indirect, are attributed to aquaculture, implying that fed aquaculture can only become fully climate neutral if these supplying sectors also decarbonise or if their residual emissions are compensated through additional measures.

Scenario results excluding feed emissions show that feed is the dominant source of GHGs in fed aquaculture (raising total emissions from about 1.8 to 2.8 million t CO_2eq in 2026), that non-fed systems can approach near-zero emissions by 2050 while fed systems retain residual emissions, and that—without feed—suspended and cage systems have the highest abatement costs (peaking around 600 €/t CO_2eq by 2050) compared with lower, similar costs for ponds, raceways and RAS.

Achieving carbon neutrality in EU aquaculture by 2050 is therefore only possible through a combination of full deployment of available tools, credible offsetting, strong public policy support across the whole value chain, and parallel decarbonisation of indirect, upstream emission sources in feed, energy, transport and their related sectors.

Eight lines of recommendation are proposed: drive energy efficiency and digitalisation (e.g. audits, AI/IoT for precision feeding), support decarbonisation of feed and raw materials, accelerate the energy transition for transport and operations, support breeding for resilience and efficiency, continue support for IMTA and non-fed species, develop recognised methods and standards for carbon offsetting, stimulate markets and consumer awareness for low-carbon aquaculture products, and reinforce existing aquaculture policy and licensing frameworks to reduce dependencies on external markets for non-EU aquatic products and enable long-term low-carbon investment.

Executive Summary

This study provides evidence-based pathways for the EU aquaculture sector to reach carbon neutrality by 2050, identifying where emissions occur across production systems and along the value chain, and assessing which combinations of solutions are technically and economically feasible at scale. The analysis focuses on fed and non-fed systems, feed production and logistics, energy use and transport, and the role of indirect, upstream emissions linked to aquaculture inputs.

Emissions from aquaculture and fisheries fall under the Effort Sharing Regulation (Regulation (EU) 2023/857), which stipulates a 40% collective reduction of GHG emissions for all sectors by 2030 compared to 2005 levels. Revised national targets in 2024 aimed for a 55% emissions reduction by 2030. In February 2024, the European Commission proposed a 90% net greenhouse gas (GHG) reduction by 2040 (compared to 1990 levels) as a step toward climate neutrality by 2050.

To begin with, the study aimed to develop a harmonised database of CO_2 equivalent (CO_2eq.) emissions associated with the production of all aquaculture species, from 2005 to 2024, across five production systems (cages, non-fed, ponds, raceways and Recirculating Aquaculture Systems (RAS) systems) in EU Member States, based on life cycle assessment (LCA) data. Emissions were collected per tonne of live weight (t LW) and broken down by life cycle stage, including feed production, feed transportation, grow-out, emissions related to boat trips (for cage, freshwater and marine, and non-fed aquaculture only), using a cradle-to-gate ([1]) boundary.

Data gaps present for some species were filled using data from ecologically similar species at the same trophic level. As studies from every Member State were not available, data from countries with comparable environmental conditions and industry infrastructure were used. Emissions were modelled using SimaPro software ([2]) and these were adjusted according to the sources of energy used within individual countries. LCA data from studies in countries outside of Europe were used for certain species that are not well established within the EU (e.g. tilapia, malacostracans). When using data from studies outside of Europe the energy profiles were re-modelled and adapted to the sources of energy used in EU Member States. All assumptions and recalculations aimed to ensure consistency and comparability across countries,

([1]) Cradle-to-gate refers to a "boundary condition" in Life Cycle Assessment that assesses a product's environmental impact from raw material extraction (the "cradle") to the point it leaves the factory (the "gate").

([2]) https://simapro.com/

species, and systems, enabling a robust analysis of EU aquaculture's GHG emissions.

The study further focused on identifying the various technological, managerial and other tools to reduce GHG emissions in aquaculture in the European Union. Following the inventory of tools, eight different scenarios were formulated for achieving climate neutrality in the sector by 2050, thus:

- Scenario 1 assumes no policy or technological change.
- Scenario 1b estimates emissions in the hypothesis of a disproportionate growth of non-fed (low trophic) aquaculture from 2041 to 2050.
- Scenario 2 aligns with the EU climate targets set under the Effort Sharing Regulation (ESR) and Green Deal, assuming proportional emissions reduction in aquaculture to meet the 2030, 2040, 2050 climate goals.
- Scenario 3 prioritises low-investment tools, such as replacing conventional feed with emerging feed materials, promoting non-fed aquaculture, integrated multitrophic aquaculture (IMTA), and conducting energy audits.
- Scenario 3b prioritises low-investment tools with the inclusion of offsetting mechanisms.
- Scenario 4 focuses on building climate resilience for the sector while reducing emissions. This scenario includes, for example, use of AI-based tools to improve feeding efficiency and for the early detection of pathogens.
- Scenario 5 maximises the CO_2eq emission reduction without cost constraints by fully deploying emerging feed materials, AI tools, renewable energy, species diversification, and IMTA systems.
- Scenario 5b maximises potential for emission reductions, assuming no financial constraints and including offsetting mechanisms.

Scenario 1b extends Scenario 1 with the disproportionate growth of non-fed aquaculture. Scenarios 3b and 5b are extensions of Scenarios 3 and 5 respectively with the inclusion of compensatory tools to tackle hard-to-abate emissions.

These scenarios, further elaborated in Section 3, are based on the application of what are considered to be technologically feasible tools: emerging feed materials & breeding, AI-based tools, renewable energy, integrated multi-tropic aquaculture, improvement of energy use efficiency, increasing share of non-fed aquaculture, purchasing voluntary carbon credits, and supporting ecosystem conservation and restoration.

Overview of tools and scenarios

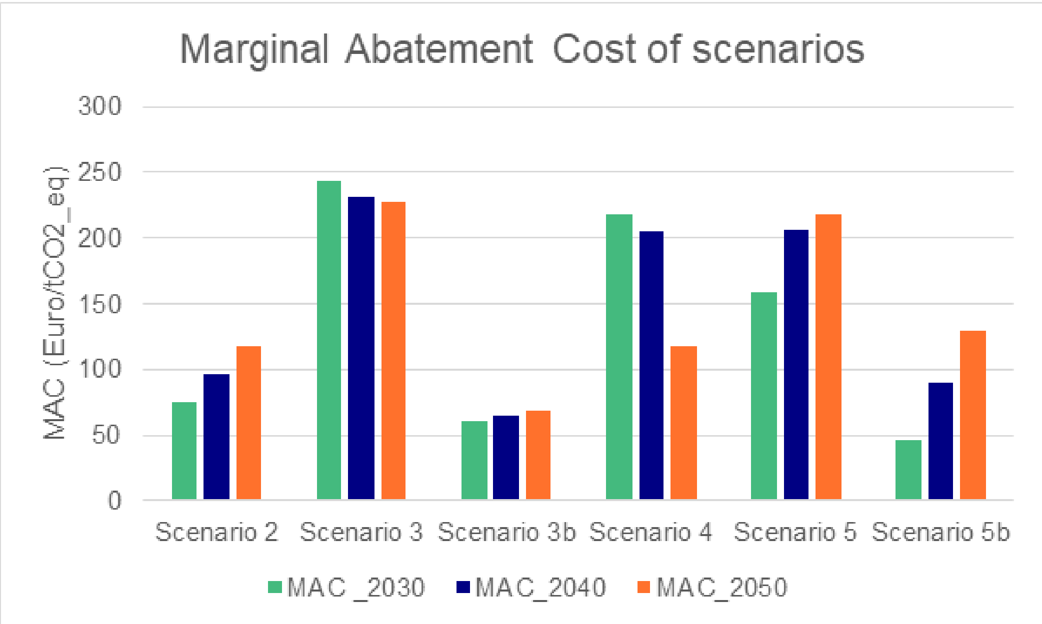
Scenario no.	Description	Emerging feed materials & breeding	AI-based tools	Renewable energy	IMTA	Improvement of energy use efficiency	Increasing share of non-fed aquaculture	Voluntary carbon credits	Support ecosystem conservation and restoration
1	Business-as-usual								
1b	Increased growth of the non-fed aquaculture industry						x		
2*	Alignment with EU Climate Targets	x	x	x	x	x			
3	Prioritisation of low investment	x			x	x			
3b	Prioritisation of low investment with the inclusion of carbon credits	x			x	x		x	
4	Prioritisation of the resilience of the sector to climate change.	x	x		x	x			
5*	Maximum potential for emission reductions, assuming no financial constraints	x	x	x	x	x			
5b	Maximum potential for emission reductions, assuming no financial constraints and including carbon credits and ecosystem restoration	x	x	x	x	x		x	x

**Scenario 2 and 5 have the same tools but differ in adoption levels.*

The study calculated emissions reductions, investments costs and the cost per tonne of CO_2eq-abated across six scenarios, from Scenario 2 to Scenario 5b (Section 4). Using these calculations, the Marginal Abatement Cost (MAC) was derived to assess the cost-effectiveness of each scenario. The values vary over the periods as follows:

- 2026-2030: ranging from 46 to 243 €/t CO_2eq
- 2026-2040: ranging from 65 to 232 €/t CO_2eq
- 2026-2050: ranging from 69 to 228 €/t CO_2eq

Marginal Abatement Cost of scenarios



The wider social-economic impacts of the tools and scenarios are also assessed (Section 5), providing input to formulation of pathways. To this end, a survey, plus focus group meetings and interviews were conducted to inform a multi-criteria and SWOT analysis. The results show the diverging views on applicability and desirability of the tools across different production types. The Multicriteria Analysis (MCA) informs the formulation of pathways in task 5, for each production type, and the SWOT analysis is used to inform the formulation of recommendations.

The last section of the study proposes and evaluates reduction pathways for the five aquaculture production systems studied. The reduction pathways consist of time-specific adoption targets for the relevant tools. Building upon the scenario analysis, it is concluded that in order to achieve carbon neutrality, all available tools need to be implemented together in combination with offsetting mechanisms.

The MCA and stakeholder consultations informed the formulation of adoption pathways per tool per aquaculture type. The calculation tools developed under

Section 6 are used to calculate emission reduction achieved for the pathways and the MACs. The MAC was evaluated for five production systems over the periods 2026–2030, 2026–2040, and 2026–2050, with the following ranges observed for each system:

- Cage: ranging from 65 to 68 €/t CO_2eq
- Non-fed: ranging from 172 to 227 €/t CO_2eq
- Pond: ranging from 60 to 62 €/t CO_2eq
- Raceways: ranging from 66 to 72 €/t CO_2eq
- RAS: ranging from 41 to 52 €/t CO_2eq

The above- assessments, in conjunction with interviews and the SWOT analysis, are the basis for the formulation of recommendations along the following eight lines:

1) Drive energy efficiency and digitalization
2) Support decarbonisation of production of feed and raw materials
3) Accelerate the Energy Transition for transport and operations
4) Support breeding programs for resilience and efficiency
5) Continue support for IMTA including non-fed species
6) Develop recognized methods for carbon offsetting
7) Continue effort to stimulate market development and consumer awareness for low-carbon footprint aquaculture products
8) Strengthen the aquaculture regulatory framework increasing clarity and specificity and streamlining licensing

The evaluation of these pathways, to assess if they can meet the GHG emission reduction targets for 2030 (55%), 2040 (90%) and 2050 (carbon neutrality), is presented in detail below. The baseline used here are the 2005 aquaculture emissions.

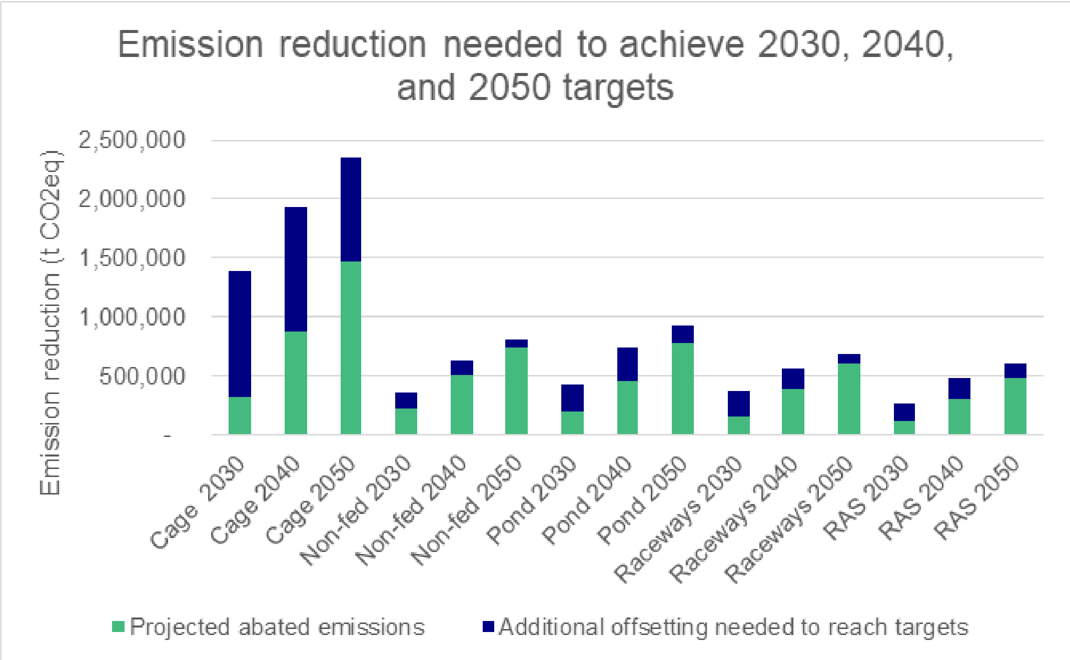
This study is based on the premise that the aquaculture sector has to abate scope 1 (direct emissions), scope 2 (purchased energy with emissions decreasing to 2050) and scope 3 emissions (feed production and feed transport). This is not to say that the costs related to reducing these emissions should be borne by the aquaculture sector alone, and indeed under the climate law ([3]) the responsibility to reduce emissions falls to the relevant sector.

It is concluded that the above measures are not sufficient to reach the target of carbon neutrality and that this can only be reached if offsetting measures are taken. There are two main reasons for this: (1) all energy production, transport and construction come with residual GHG emissions that are not offset by aquaculture practices; and (2) including feed-related emissions in the carbon

([3]) Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law') footprint of aquaculture, implies that achieving carbon neutrality in fed aquaculture requires achieving carbon neutrality in fisheries and agriculture too.

The study was explicitly designed to assess how the aquaculture sector can move towards carbon neutrality in a context where upstream agriculture remains significantly emissive. If all aquaculture feed would be carbon neutral at the point of purchase – as stipulated in the Climate Law – the analysis would yield different results.

Emission reduction needed to achieve 2030, 2040, and 2050 targets



The extent to which offsetting measures are needed to reach the climate targets differs per production type and over time. With the exception of cage production, aquaculture is expected to need more offsetting measures to reach the 2040 target, than is needed to reach the 2050 target. This is explained by the fact that various tools to reduce GHG emissions are not ready to implement at large-scale in the next years and the expected adoption rates increases largely in the period 2040-2050.

It is stressed that the baseline is set at 2005, in line with the Effort Sharing Regulation. These GHG emission reduction targets are also highly challenging to achieve in light of the expected growth of the EU aquaculture sector until 2050.

The study concludes that reduction of GHG emissions from the aquaculture sector, the need for which stems also from the Effort Sharing Regulation (Regulation (EU) 2023/857), is a highly demanding objective, which can only be achieved by strong governance support at both EU and Member State level, efforts to reduce GHG emissions in the whole aquaculture supply chain and the use of offsetting measures.

1 Introduction

1.1 Background

The European Green Deal, launched in 2019, is the European Union's (EU) growth strategy aiming to transform the EU into a climate-neutral economy by 2050. It addresses critical environmental challenges such as climate change, biodiversity loss, and environmental degradation, while fostering economic growth, innovation, and investment. The European Climate Law (Regulation (EU) 2021/1119) ([4]) enshrines this 2050 climate neutrality goal into law.

The EU aquaculture sector, contributing approximately 2 million tonnes CO_2eq in 2019 (European Commission, 2024a), faces challenges from rising energy costs, post-pandemic inflation, and geopolitical tensions. Emissions from aquaculture and fisheries fall under the Effort Sharing Regulation (Regulation (EU) 2023/857) ([5]), which accounts for nearly 60% of EU domestic emissions. Revised national targets in 2024 aim for a 55% emissions reduction by 2030, with higher-income Member States adopting more ambitious goals.

In February 2024, the European Commission proposed a 90% net greenhouse gas (GHG) reduction by 2040 (compared to 1990 levels) as a step toward 2050 climate neutrality. Similarly, the Energy Transition Communication for the EU Fisheries and Aquaculture Sector (COM(2023) 100 final) (European Commission, 2023) outlined actions to increase energy efficiency and transition to low-carbon and renewable energy, further described in Implementing the Strategic Guidelines on EU Aquaculture Energy transition in the EU aquaculture sector (SWD(2024) 280 final) (European Commission, 2024b).

Emissions of greenhouse gasses in the aquaculture industry stem from transport, electricity, feed production, and production systems. A study, *Techno-economic analysis for the energy transition* (European Commission, 2024a), highlighted key solutions: optimizing feed through Precision Fish Farming (PFF) to reduce Feed Conversion Ratios (FCRs); implementing energy audits to cut energy use; and adopting emerging feed formulations like insect-based proteins. While transitioning is feasible, challenges remain, including high costs, renewable energy needs, and port infrastructure development.

This study aimed "to develop evidence-based recommendations for actionable pathways towards climate-neutrality for the EU aquaculture sector". The report

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([4]) OJ L 243, 9.7.2021, ELI: http://data.europa.eu/eli/reg/2021/1119/oj

([5]) OJ L 111, 26.4.2023, ELI: http://data.europa.eu/eli/reg/2023/857/oj presents a summary, objectives and results per task, followed by overarching conclusions. For the detailed description of the methodologies, we refer to Annex 1.

1.2 Scope of work

Temporally this project looked at two key periods: 2005 to 2024 and 2026 to 2050. Historical data on production within the EU aquaculture sector were used to establish GHG emissions per year, Member State, production system, and species between 2005 and 2023. Whilst in the second period potential tools were explored for their emissions reduction potential with a focus on EU emissions reductions targets for years 2030, 2040, and 2050.

Geographically this project covered EU Member States only and emissions were calculated at both Member State and EU level. Pathways to net zero emissions were discussed on the EU level with attention paid at Member State level when heterogeneity was revealed.

1.3 Structure of the report

This report is structured sequentially from the establishment of the initial emissions baseline (2005 emissions calculations) through analysis of potential emissions reduction tools and scenarios and their costs before a final realistic pathway and recommendations for achieving said pathway are presented.

Table 1 - Report and Task Structure

Task No.	Task name	Objective	Corresponding chapter No.
1	Baseline definition	to update and complement existing data on GHG emissions produced by the EU aquaculture sector from 2005 to 2024, at European Member State level	2
2	GHG reduction scenario	to develop feasible and cost-effective renewable energy scenarios for the EU aquaculture sector	3
3	Scenario cost analysis	to calculate the cost-effectiveness of reducing GHG emissions through the different scenarios	4
4	Impact, limitations, gaps, and sensitivity analysis of scenarios	to assess the wider social-economic impacts of the tools and scenarios, providing input to formulation of pathways	5
5	Proposed reduction pathways	to propose recommendations for carbon neutrality by 2050	6

2 Baseline definition

2.1 Summary

This first task aimed to develop a harmonised database of CO_2 equivalent ($CO_2eq.$) emissions associated with the production of all aquaculture species, from 2005 to 2024, across five production systems (Ponds, raceways, cages, Recirculating Aquaculture Systems and non-fed aquaculture) in EU Member States, based on existing life cycle assessment (LCA) data. Emissions were collected per tonne of LW and broken down by life cycle stage, including hatchery, feed production, feed transportation, grow-out, and emissions related to boat trips (for cage and non-fed aquaculture only), using a cradle-to-gate ([6]) boundary.

Data gaps present for some species were filled using data from ecologically similar species. For missing data for specific Member States, data from neighbouring countries were used, assuming comparable environmental conditions affecting production cycles and emissions. Emissions were then modelled using SimaPro software ([7]) adjusting them for specific sources of energy used within individual countries. LCA data from studies in countries outside of Europe were used for certain species that are not well established within the EU (e.g., tilapia, malacostracans). All assumptions and recalculations aimed to ensure consistency and comparability across countries, species, and production systems, enabling a robust analysis of EU aquaculture's GHG emissions.

2.2 Objectives

The goal of this task is to update and complement existing data on GHG emissions produced by the EU aquaculture sector from 2005 to 2024 (production for 2024 estimated), at European Member State level, as outlined in the Commission Staff Working Document (SWD) "Implementing the Strategic Guidelines on EU Aquaculture Energy transition in the EU aquaculture sector" (SWD(2024)0280). This work includes the delivery of an Excel-based database to provide an overview of aquaculture-associated GHG emission per country and species per production system. The database is used in task 2, to design

([6]) Cradle-to-gate refers to a "boundary condition" in Life Cycle Assessment that assesses a product's environmental impact from raw material extraction (the "cradle") to the point it leaves the factory (the "gate").

([7]) https://simapro.com/

the baseline scenario, and in task 3 for calculation of GHG emissions reduction under various emission reduction scenarios.

Estimating CO_2eq. emissions from EU aquaculture presented several challenges due to the sector's diversity in terms of species and production systems. The methodology description in Annex 1 outlines the sequential steps required to construct the database and provides an explanation of the assumptions made throughout the research process.

In the references the emissions at farm gate (after culture phase) have been considered, excluding processing or transport.

2.3 Results

2.3.1 Structure of the database

The database is composed of a total of 33 columns for finfish and 15 columns for non-fed aquaculture, representing sorting data, calculation data and CO_2eq emissions (Table 2 and Table 3). Screenshots of the database can be found in Annex 1.

Table 2 – Detailed description of the fish database

Column	Column name	Data description	Data source
A	Species	Species grouped at family level	FishStatJ
B	Environment	Production environment (seawater, freshwater, brackish water)	FishStatJ
C	Year	Specific year included in the database (from 2005 to 2024)	
D	Production System (PS)	Categorisation of the data per 4 production systems: ponds, raceways, RAS and cages	European Commission and national databases
E	% PS Used	Percentage of systems used per production system, species and time frame retrieved	European Commission and national databases
F	Production per system (t)	Annual production for each group of species and production system	Calculated (%PS*total annual production)
G	Total production (t)	Total annual production for each group of species	FishStatJ
H	CO_2eq emissions per t of LW (t CO_2eq /t LW)	Emissions extracted from previous studies before country specific adjustments	Literature (list in Table 46)

Column	Column name	Data description	Data source
I	Total CO_2eq emissions per system (t CO_2 eq),	Emissions from production in different systems	Calculated (column H * column F)
J	Electricity use (kWh/ tLW)	Electricity used, data extracted from previous studies before country specific adjustments	Literature (list in Table 46)
K	CO_2eq emissions from all processes except electricity use (CO_2eq)	All emissions derived from sources different from electricity consumption	Calculated (% from the literature * column I/100)
L	CO_2eq emissions from electricity use per t of LW (t CO_2eq / t LW) adjusted per specific country	Emissions remodelled considering specific sources of energy used in different countries	Modelled in SimaPro (Data in column I modelled according to country-specific energy mix sourced by EUROSTAT)
M	Total CO_2eq emissions from electricity use (t CO_2eq)	Emissions due to electricity use considering country-specific sources of energy	Calculated (column L * column F)
N	Total CO_2eq emissions excluding hatchery stage (t CO_2eq)	A column added to facilitate subsequent calculations	Calculated (column M * column K)
O	Total CO_2eq emissions for feed production + transportation (t CO_2eq)	Emissions from feeding activity including feeding transportation (production and transportation will be disaggregated in subsequent columns)	Calculated (% from the literature * column N/100)
P	CO_2eq emissions from grow-out stage (electricity + materials) (t CO_2eq)	"materials" includes different sources of emissions within the grow-out stage, not uniform in different studies used (e.g. use of lime in ponds, specific equipment, etc.)	Calculated (% from the literature * column N/100)
Q	FCR	Feed Conversion Ratio, used subsequently to estimate emissions associated with feed transportation	Literature
R	Total feed consumed (t)	Feed consumed to support production indicated in column F	Calculated (column Q * column F)
S	Amount of feed transported per trip (t)	Assumed 28 t for all species, systems and countries	Assumption considering average truck size
T	Distance travelled per trip (km) (average assumed)	Distance between feed producer and fish farm, assumed 250 km	Assumed after consulting stakeholders
U	Amounts of trips required to transport total feed (units)	Based on annual feed consumption	Calculated (column R/ 28)
V	CO_2eq emissions per trip (t CO_2eq / 250 km) Calculated with SIMAPRO	Calculation for single trip with full load	Calculated using Simapro. 7000tkm imputed (250X28), represents transportation of 28t of feed for 250km (emissions from 1 trip), for calculation purpose only

Column	Column name	Data description	Data source
W	Total emissions from feed transportation	t CO_2eq for total number of trips	Calculated (Column V * column U)
X	Total CO_2eq emissions from other processes (t CO_2eq)	Emissions from other minor sources such as materials, maintenance, cleaning etc.	Calculated (column N - (column O + columnn P)
Y	Total CO_2eq emissions from hatchery stage (t CO_2eq)	10% of total emissions (assumption made)	10% extracted from literature (Table 1)
Z	Total CO_2eq emissions from boat fuel consumption (t CO_2eq)	Trips with vessels from nearest harbour to cages (only for cage aquaculture)	Calculated (column AE * column F)
AA	CO_2eq emissions for feed (transportation + production) per t of LW (t CO_2eq/t LW)	Emissions from feeding activity including feeding transportation expressed in t CO_2eq / t LW	Calculated (column O / column F)
AB	CO_2eq emissions from grow-out stage per tof LW (t CO_2eq /t LW)	Emissions for electricity and materials expressed in t CO_2eq / t LW	Calculated (column P / column F)
AC	CO_2eq emissions from hatchery stage per t of LW (t CO_2eq /t LW)	CO_2eq emissions from hatchery stage expressed in t CO_2eq /LW	Calculated (column Y / column F)
AD	CO_2eq emissions related to other stages per t of LW (t CO_2eq /t LW)	Emissions from other minor sources such as materials, maintenance, cleaning etc. expressed in t CO_2eq /LW	Calculated (column X / column F)
AE	CO_2eq emissions from fuel consumption for boat trips per t of LW (t CO_2eq /t LW)	Trips with vessels from nearest harbour to cages (only for cage aquaculture) expressed in t CO_2eq LW	Literature
AF	TOTAL CO_2eq emissions per t of LW (t CO_2eq t LW)	Emissions per LW including all processes and sources and country-specific	Calculated (AA+AB+AC+AD)
AG	Total CO_2eq emissions (t CO_2eq)	Emissions for total annual production including all processes and sources	Calculated (column N + 10% for hatchery)

Table 3 - Detailed description of the non-fed database

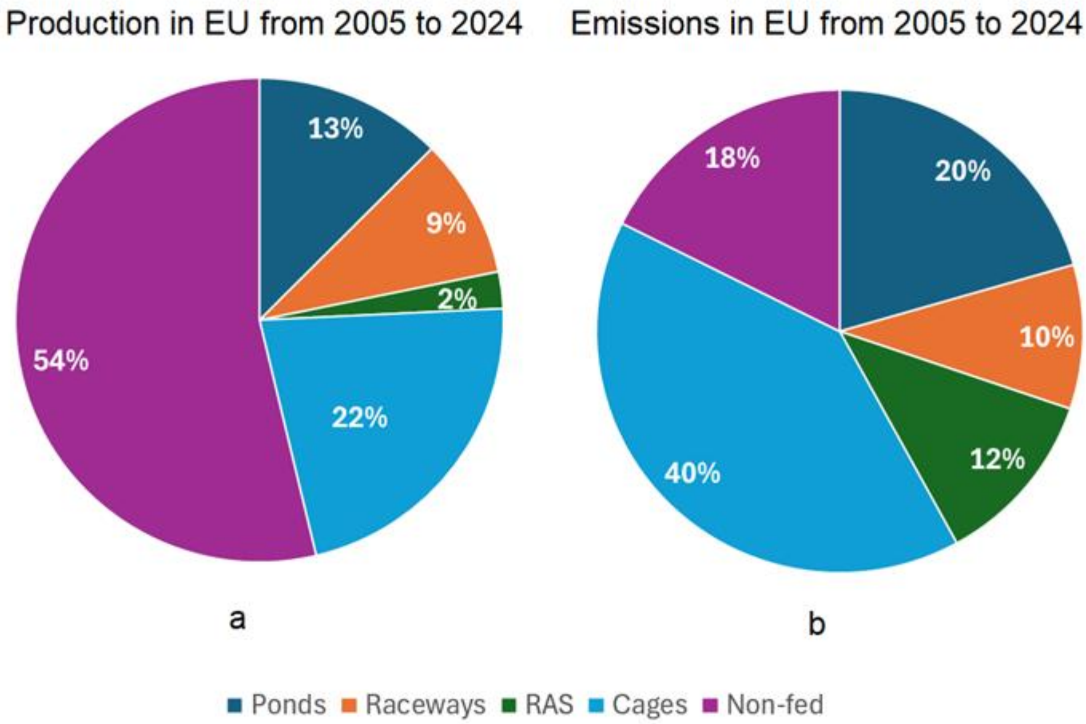
Column	Column name	Data description	Data source
A	Species	Species grouped at genus level	FishStatJ
B	Environment	Production environment (seawater, brackish water)	FishStatJ
C	Year	Specific year included in the database (from 2005 to 2024)	-
D	Production System (PS)	Categorisation of the data per 5 production systems: longlines, raft, bouchout, on bottom and off bottom)	European Commission
E	% PS Used	Percentage of systems used per system, specie and time frame retrieved	European Commission
F	Total production (t)	Total annual production for each group of species	FishStatJ
G	Production per systems (t)	Annual production for each group of species and production system	Calculated (%PS*total annual production)
H	Fuel-associated CO_2 emissions (t CO_2eq/t LW)	Emissions from vessel (when used) extracted from published studies	Literature (list in Table 46)
I	Fuel-associated CO_2 emissions (t CO_2eq)	Total Emissions from vessel (when used)	Calculated (column G * column H)
J	Hatchery-associated CO_2 emissions (t CO_2eq/t LW)	Emission due to hatchery stage when present (t CO_2eq/t LW)	Literature (list in Table 46)
K	Hatchery-associated CO_2 emissions (t CO_2eq)	Total mission due to hatchery stage when present	Calculated (column J * column G)
L	Other CO2 emissions (t CO_2eq/t LW)	Emission from other sources expressed in t CO_2eq/t LW	Literature (list in Table 46)
M	Other CO2 emissions (t CO_2eq)	Total emission from other sources	Calculated (column G * column L)
N	CO2 emissions per t of LW(t CO_2eq/t LW)	Total emissions expressed in t CO_2eq/ t LW	Literature (list in Table 46)
O	Total CO2 emissions per year (t CO_2eq)	Emissions for total annual production including all processes and sources	Calculated (column N * column G)

Due to the complexity and the important amount of data, a second “presentation” database was modelled, containing only total annual production and the CO_2eq emissions organized by life cycle phase, species, country and period, without considering the calculation columns. Screenshots of this database can be found in Annex 2.

During the same period, non-fed aquaculture represented 54% of aquaculture production in terms of LW and it was responsible for only 18% of aquaculture-associated GHG emissions (Figure 1).

Among the different systems for the fish production, the most used was cage production (22%), responsible for 40% of the emissions. The least used method was RAS production (2%) responsible for 12% of the emissions. Fish farmed in ponds and raceways represented the 13% and 9% of the production, respectively. These two systems were responsible for the 20% and 10% of the emissions (Figure 1).

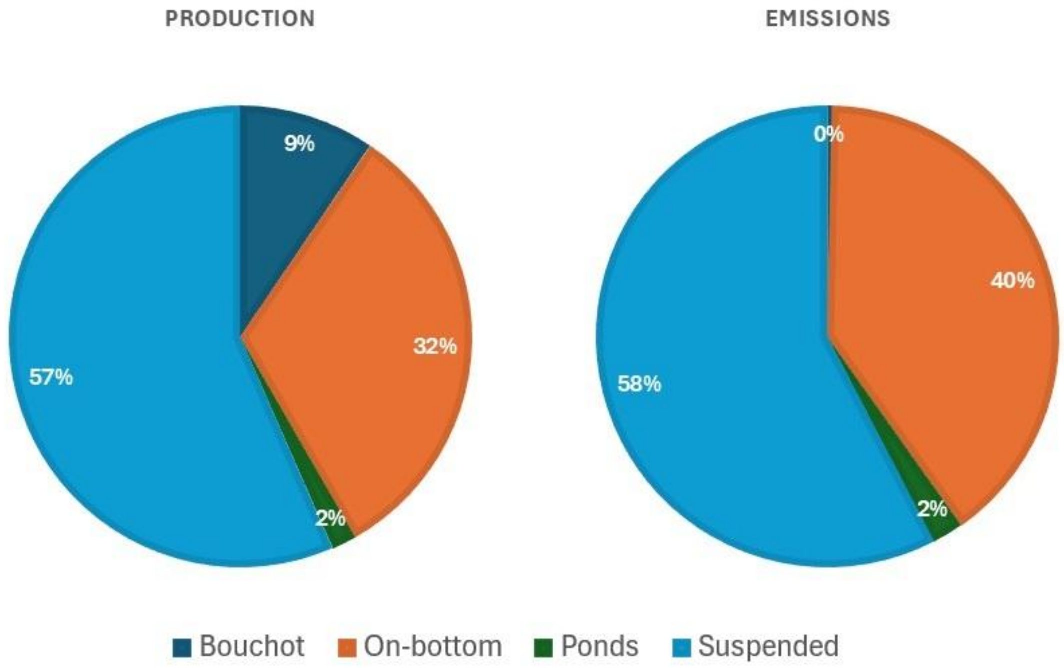
Figure 1 – Aquaculture production (a) and associated emissions (b) from different production methods in EU from 2005 to 2024



Source: Calculations based on FAO FishStatJ production volume data (a) and calculations and sources specified in the methodology (Annex 1) (b).

When the different systems used for non-fed aquaculture were analysed, non-fed aquaculture (using including longlines, rafts and vertical hanging ropes) resulted the most used method (57% of production with this method) and the method responsible for most emissions (58%) (Figure 2). The second most used method is on-bottom culture, responsible for 32% of production and 40% of emissions. Production of non-fed aquaculture in ponds and with the bouchout method are only marginal (Figure 2).

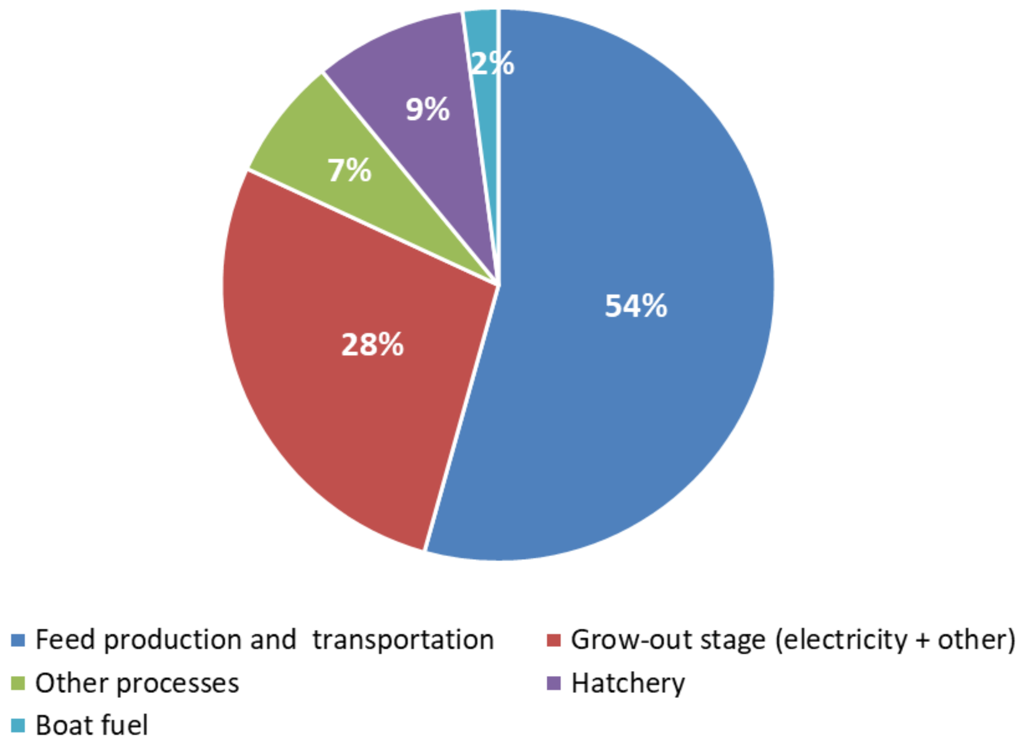
Figure 2 – Contribution to non-fed aquaculture emissions in EU Member States of different processes and stages during the last 20 years for specific production systems



Source: Calculations based on FAO FishStatJ production volume data (a) and calculations and sources specified in the methodology (annex 1) (b).

The relative impact of different stages and processes of the aquaculture production was also analysed. The production and transportation of feed was the most impactful process, contributing to 54% of aquaculture-associated emissions during the last 20 years. The second most impactful process was the grow out stage, including electricity use and other processes like use of different materials and products. Emissions from boat trips in cage aquaculture only contributed to 2% of the emissions during the same period.

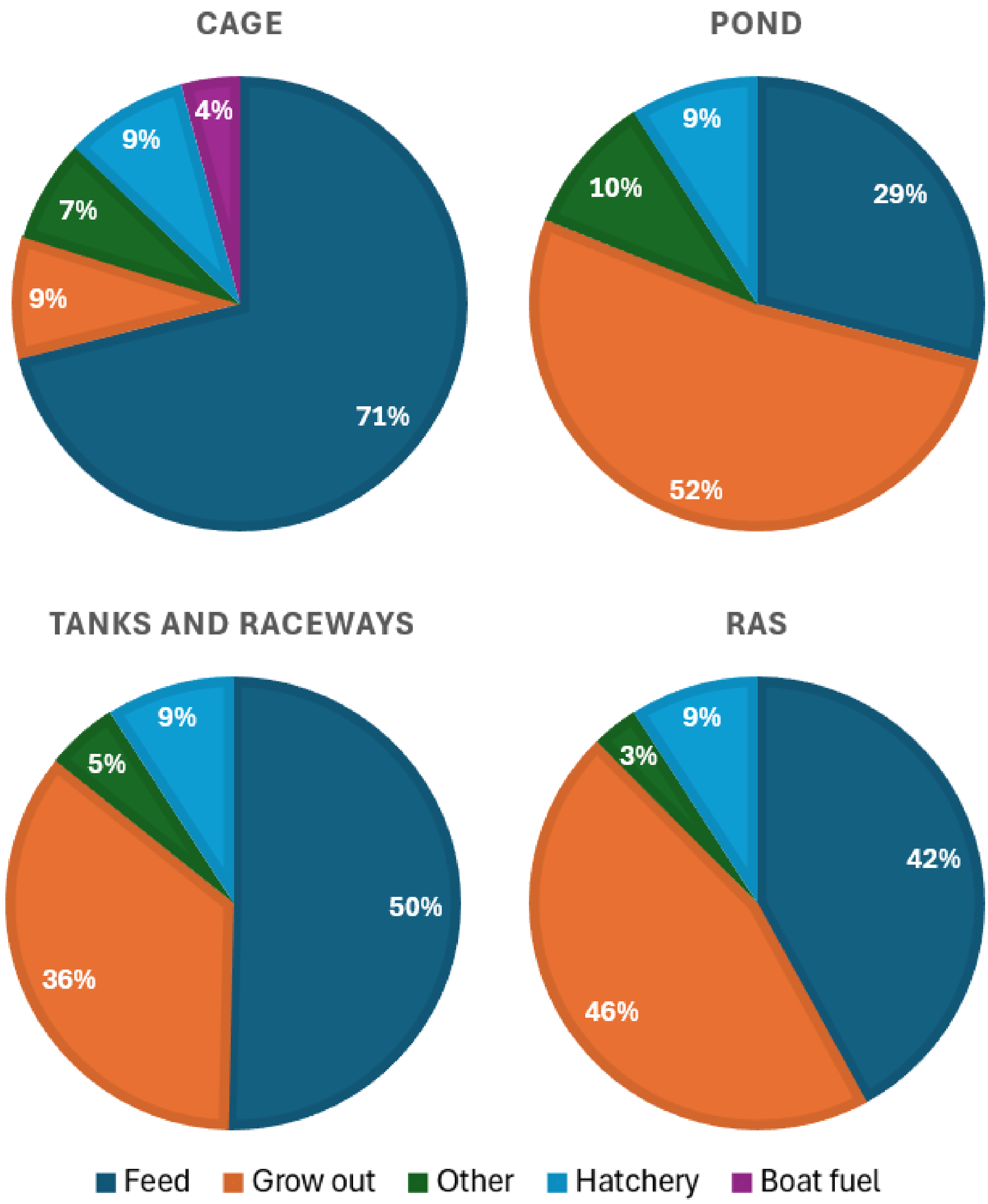
Figure 3 – Contribution to aquaculture-associated emissions in EU Member States of different processes and stages of the production system during the last 20 years (2005-2024)



Source: Own calculations

When the contribution of the different sources of emissions is analysed for separate production methods, feed production and transportation has a higher impact than other sources in cage aquaculture. This is due to the fact that the grow out stage involves minimal use of electricity. In RAS aquaculture, the feed produces a higher amount of emissions per tonne of LW, probably because these feeds contain high-quality feedmaterials with carefully balanced amino acid, energy, and fatty acid profiles to support rapid growth. However, the contribution of feed production to total emissions in RAS is only 42% because of the high amount of electricity needed to run the system.

Figure 4 - Contribution to fed aquaculture emissions in EU Member States of different processes and stages during the last 20 years (2005-2024) for specific production systems



Source: Own calculations

3 GHG reduction scenarios

3.1 Summary

This task focused on identifying the various technological, managerial and other tools to reduce GHG emissions in aquaculture in the European Union. Following the inventory of tools, 5 different scenarios were formulated for achieving climate neutrality in the sector by 2050. The scenarios represent different approaches to reduce GHG emissions in the EU Member States' aquaculture sector by 2050.

- The first scenario (Business-as-usual) assumes no policy or technological change. The aquaculture production from 2025 to 2050 is based on an estimated annual growth of 1.6%.
- The second scenario aligns with the EU climate targets set under the Effort Sharing Regulation (ESR) and Green Deal, assuming proportional emissions reduction in aquaculture to meet the 2030 (55% reduction), 2040 (90% reduction), 2050 climate goals (carbon neutrality).
- The third scenario prioritizes low-investment tools such as replacing conventional feed with emerging feed materials, promoting non-fed aquaculture, IMTA and conducting energy audits.
- The fourth scenario focuses on building climate resilience for the sector while reducing emissions. This scenario includes, for example use of AI-based tools to improve feeding efficiency and for the early detection of pathogens.
- The fifth scenario maximises the CO_2eq emission reduction without cost constraints by fully deploying emerging feed materials, AI tools, renewable energy, species diversification, and IMTA systems across the EU.
- Two extra scenarios were considered where the costs and potential of voluntary carbon credits were investigated as additional tools to apply to Scenario 3 and 5, termed 3B and 5B respectively.
- A sixth scenario (1B) was also included in order to estimate emissions in the hypothesis of a higher growth of non-fed aquaculture from 2041 to 2050

3.2 Objectives

To develop feasible and cost-effective renewable energy scenarios for the EU aquaculture sector that help in reducing fossil-fuel consumption per kg of aquaculture products and achieve climate-neutrality in the sector by 2050 with interim milestones for 2030 and 2040.

3.3 Results

3.3.1 Tools to reduce GHG emissions in aquaculture

Following the consultations with stakeholders, the list of tools to use in the different scenario was finalised.

3.3.1.1 Tool 1: Emerging feed materials and breeding programs

It is estimated that 70% of fed aquaculture associated GHG emissions are due to aquafeed production and transport. The production of aquafeeds currently involves fishing, growing and processing raw materials such as soybean meal, wheat, fishmeal and fish oil, which require significant energy inputs and generate emissions during cultivation, harvesting, processing, and transport. Moreover, synthetic fertilizers used in crop production further contribute to the GHG emissions associated with aquafeeds production. Hence, one of the most powerful tools to reduce GHG emissions generated by the aquaculture sector is the use of aquafeeds where traditional feed materials are replaced with more sustainable sources of lipids and protein.

There are many candidates to replace traditional sources. Single-cell proteins, insects, by-products of fish and terrestrial animals, microalgae, plant protein alternative to soy and other marine biomasses have been investigated as more sustainable tools to reduce GHG emissions associated with production of fish feed. A high number of different formulations have been tested, with many of them still not available on the market.

For the purposes of the present study, a literature review was carried out to select potential most promising alternative feed materials with the lowest emissions.

Five emerging feed materials were selected (Table 4) and, for each of them, another literature review was carried out to assess the percentage of inclusion of the ingredient in aquafeeds that gave the best results when tested on different species.

Table 4 – Emerging feed materials identified to reduce GHG emissions associated with aquafeeds production

Source	Ingredient	Production method	Kg CO_2eq/kg of protein	Percentage of replacement
(Bava et al., 2019)	Black Soldier Fly larvae meal (*Hermetia illucens*)	Produced using Brewer's grain as substrate	1.53	40 (average for all species)
(Modahl & Brekke, 2022)	Tenebrio molinal meal	Produced with diet based on vegetable waste food and brewery side-streams	2.37	40 (average for all species)
(Schade & Meier, 2021)	Microalgae Nannochloropsis Oceania dried biomass	Produced in tubular bioreactors, main carbon source industrial CO2	4.63	10 (Salmon and similar species)
				100 (Tilapia and other low trophic species)
				25-40 in common carp shrimp
(Campos et al., 2020)	Poultry by-products meal		1.04	10 (salmon, carp and trout), 50 (Nile tilapia and other species)
(Jean & Brown, 2024)	Single Cell Protein (SCP)	Produced via gas fermentation of carbon dioxide, oxygen, and hydrogen, using wind-powered water electrolysis to produce hydrogen and oxygen with carbon dioxide captured from corn ethanol.	0.73	40 (average for all species)

The CO_2eq. generated and the highest percentage of protein replacement for different species are also indicated in the table

Replacement of feed materials in aquafeeds can lead to decreased digestibility and increased FCR (Gasco et al., 2018), offsetting in part the reduction of the emissions. Specific breeding programs aimed at the selection of genotypes with higher capacity to assimilate and digest the emerging feed materials, should be carried out in parallel with the adoption of the emerging feed materials to avoid this negative effect and make sure to exploit the emissions reduction potential of using sustainable sources of protein. For the present study, we assume that tailored breeding programs are implemented to maximise the environmental benefits of the emerging feed materials.

3.3.1.2 Tool 2: AI-based tools

The use of artificial intelligence (AI) in aquaculture has the potential to contribute to the reduction of GHG emissions generated by this sector. AI tools can help to optimise the feeding process (Rather et al. 2024), to monitor fish health (Panda and Baral, 2023), and to manage environmental conditions such as temperature, oxygen levels and pH. AI can optimize aeration, pumping, and other energy-consuming processes based on real-time data (Capetillo-Contreras et al., 2024). Smart feeding systems can minimize the feed wasted and improve the FCR (Chen et al. 2022). AI-powered computer vision and big data analytics can also detect early signs of disease or stress by monitoring fish behaviour and physical condition. This allows timely interventions, reducing mortality, the use of antibiotics and the need for energy-intensive interventions (Fernandes and Dmello, 2025).

Conventional software currently used in aquaculture support operations without advanced automation, relaying on user-defined thresholds for alert. They focus on real-time data logging, stock management, and basic monitoring. These software programs are based on manual inputs, use of spreadsheets, and they prioritise data collection from sensors, and decision support through dashboards and notifications.

The main challenge in adopting these tools is that AI models require large, high-quality datasets for training and validation. AI can support decision-making but must be properly trained before for real-world applications. Training an AI model begins with defining the problem the AI is meant to address and collection of relevant data. The model is then developed and trained in an iterative process, followed by evaluation using unseen data to test its performance and accuracy. Continuous monitoring and updating (proper machine learning) ensure the model remains accurate and effective as new data and user feedback become available.

An example of existing AI-based tool already applied to aquaculture is the Norwegian platform AquaCloud, although its use is restricted to Norway for the moment. Over 30 Norwegian fish farmers, producing about 55% of Norway's farmed Atlantic salmon and rainbow trout biomass, share data on the AquaCloud platform and they actively use it to predict sea lice outbreaks using analytics on production data. AquaCloud was developed in 2017 and since then Norwegian fish farmers share anonymised data on biomass, temperature, oxygen, and more on a central platform. The farmers follow specific IoT-based sensor protocols, and a partner-led steering committee ensures transparency, with legal frameworks for secure, voluntary collaboration. AquaCloud facilitates AI-driven predictions, better monitoring, and cross-company insights without competitive risks, positioning it as Norway's leading aquaculture data hub.

In the present study, when we suggest adopting this tool in a scenario, we assume that at least 80% of EU aquaculture farmers adopt these three technologies:

1. smart water quality monitoring
2. automatic feeding system
3. AI-based technology for early detection of diseases

There is a lack of peer-reviewed studies assessing the reduction of emissions when AI-based tools are used. Global Seafood Alliance reports that the Japanese company Umitron achieved 20% of GHG emissions reduction when using an AI-based tool that combines the three technologies listed above ([8]). Hence, in this study we assume that the adoption of AI-based tools in aquaculture reduce emissions by 20%.

3.3.1.3 Tool 3: Renewable energy

EU Member States rely on different mixes of renewable and non-renewable energy sources to produce energy. Apart from France, which depends largely on nuclear power, most countries still rely on high-emission, non-renewable sources such as coal and oil (EUROSTAT, 2025). To achieve the required emission reduction targets, it is crucial to shift toward more sustainable energy sources, available in different countries.

This tool is suggested for Scenario 2, 4 and 5, at different intensities. As different sources of energy are available in different countries, we calculated the reduction of emissions associated with the adoption of different sources of energy using the software SimaPro.

([8]) https://www.globalseafood.org/advocate/can-carbon-mitigation-strategies-for-aquafeeds-help-cut-aquacultures-greenhouse-gas-emissions/

Different energy sources used in Member States were selected and modelled in the software. To ensure a single and consistent data source for energy related emissions per source across all Member States, European energy production was used in the software to represent average emissions by energy source in Europe.

The emissions generated from producing 1 kWh of electricity using the different sources of energy were calculated by the software and entered in a specific table (Table 5).

Table 5 – Emissions related to the use of 1 kWh of different EU energy sources calculated using SimaPro

Energy source category	Energy source	Emissions for the consumption of 1 kWh of different energy sources (kg CO_2eq)
Non-renewable	Coal	1.11
Non-renewable	Lignite	1.3
Non-renewable	Peat	1.18
Non-renewable	Oil and petroleum products	1.02
Renewable	Hydro	0.0047
Renewable	Wind	0.0166
Renewable	Solar	0.047
Renewable	Geothermal	0.0714
Renewable	Thermovalorisation of Waste (burning waste to obtain energy)	0.00533
Renewable	Biomass	0.159
Non - renewable	Uranium	0.00703

By averaging the emissions of the energy sources categories (renewable and not renewable), an estimation of the emission reduction when switching from non-renewable to renewable energy in Europe was calculated. Nuclear power was kept in a separate category as it is a non-renewable source of energy with very low carbon emissions.

Transitioning from a non-renewable to a renewable/low emissions energy source was therefore estimated to decrease emissions by 95.6%, while switching from non-renewable to nuclear energy reduces emissions by 99.4% (Table 6).

Table 6 – Energy source categorization and reduction rate estimation based on emissions modelled with Sima-Pro

Energy source category	Average emissions for the energy consumption of 1 kWh (kg CO_2eq)	Average emissions reduction rate from a high emissions energy source to a low-emissions energy source (%)
Non-renewable / High emissions	1.15	NA
Renewable / low emissions	0.05	95.6
Nuclear	0.01	99.4

3.3.1.4 Tool 4: Integrated Multitrophic Aquaculture (IMTA)

Integrated multitrophic aquaculture (IMTA) is a sustainable production method where different aquatic species from various trophic levels (such as fish, shellfish, and seaweed) are cultivated together in a way that the waste and by-products of one species serve as food or nutrients for another. This approach enhances environmental sustainability by reducing pollution, reusing nutrients, and improving ecosystem health, while also diversifying economic outputs for farmers.

IMTA helps reduce GHG emissions associated with aquaculture by minimising waste and lowering the need for chemical fertilizers. IMTA systems use organic waste and excess nutrients efficiently, which prevents eutrophication and reduces the environmental footprint. Additionally, it fosters biodiversity and promotes climate resilience by creating synergistic interactions among species. Exact percentages for emissions reduction associated with adoption of IMTA are difficult to estimate. Alam et al (2024) estimated that emissions in IMTA systems can be 15-20% lower than traditional single-species aquaculture systems, depending on the setup and species involved. This percentage was assumed in the present study.

3.3.1.5 Tool 5: Improvement of energy use efficiency

Implementing measures such as upgrading to energy-efficient equipment, conducting regular maintenance, optimizing transportation and operational practices, performing energy audits, and investing in staff training can substantially improve energy efficiency, reduce costs, and minimise environmental impact.

Energy-efficient water pumps, aerators, and lighting systems consume less power while maintaining optimal performance. Ensuring that equipment is regularly maintained keeps systems running at peak efficiency. Dirty or worn components often cause machinery to consume more energy to achieve the same output.

Transportation logistics and everyday operational procedures significantly affect energy use. By streamlining routes, consolidating shipments, and adopting fuel-efficient vehicles, aquaculture operators can reduce transportation-related energy consumption. Additionally, optimizing feeding schedules, water circulation, and harvesting routines helps minimise energy waste within production processes.

Conducting comprehensive energy audits allows aquaculture facilities to identify key areas of inefficiency. Audits provide data to implement improvements, guiding investment decisions, and tracking progress over time.

Finally, well-trained staff play a crucial role in sustaining energy efficiency efforts. Educating employees about energy-saving practices, equipment handling, and maintenance protocols fosters an energy-conscious culture. Informed staff can quickly spot inefficiencies and contribute to continuous improvement initiatives.

In the present study, when suggesting this tool for a scenario, we assume that one or more of the following actions are implemented:

- Upgrade to Energy-Efficient Equipment
- Regular maintenance
- Optimize Transportation and Operational Practices
- Energy Audits
- Staff Training

Moreover, we assume that the improvement of energy use efficiency reduces the GHG emissions associated with operational activities (pumps, monitoring system etc.) by 10% (de Vet et al., 2024).

3.3.1.6 Tool 6: Diversification of farmed species

In aquaculture, adopting different cultured species can help decrease the sector’s vulnerability to climate change by promoting the use of more climate-resilient organisms that thrive under altered environmental conditions. For instance, saline intrusion and increased storm surges may encourage the cultivation of brackish water and euryhaline species, while elevated water temperatures and higher turbidity could benefit species adapted to low dissolved oxygen levels or to pathogens more frequent at higher temperature.

For example, production of barramundi could be introduced in coastal areas with increasing salinity due to rise of sea level (Cusimano et al. 2025). Or meagre production could be increased in the Mediterranean as this species is more tolerant to the increasing sea temperature (Kružić et al., 2016).

The emission reduction associated with this tool are indirect and they are linked to the reduced mortality when production species more suitable for the climatic conditions. For this study, we do not consider diversification a tool to reduce emissions, but we included it as it is important to increase aquaculture resilience to climate change, and we believe diversification of farmed species should be implemented in EU in the next 25 years.

3.3.1.7 Tool 7: Increasing share of non-fed aquaculture

This tool was used only for one scenario (1B) for which a higher growth of non-fed aquaculture was assumed from 2041 to 2050 (2% growth vs 1% for fed aquaculture). Considering the generally low emissions associated with non-fed aquaculture, an increased production of protein with this method was considered a tool to reduce GHG emissions while increasing the production.

3.3.2 Tools to offset hard-to-abate emissions

3.3.2.1 Voluntary carbon credits

The voluntary carbon credit markets consist of various initiatives and certification schemes all based on the principle that by buying credit, an emitter financially supports the reduction or removal of the equivalent GHG emissions somewhere else. The demand for voluntary carbon credits has led to a proliferation of privately governed certification standards and purchase of these credits can be used as a method to offset hard-to-abate emissions.

One prime example of such certification is The Verified Carbon Standard (VCS) which presents itself as “the world’s most widely used GHG crediting program. It drives finance toward activities that reduce and remove emissions, improve livelihoods, and protect nature” ([9]).

Voluntary credits are generally cheaper than the compliance credits (described above). According to a 2020 report by the World Bank (World Bank, 2022), carbon prices on the VCM start at less than 1 US$/t CO_2eq and increase to 119 US$/t CO_2eq. The price for almost half of emissions is at less than 10 US$/t CO_2eq as of 2020 (World Bank, 2020). Live carbon price trackers show that the price for voluntary credits has decreased, with e.g. the price of an aviation industry offset credit now (4th August 2025) at 0.33 US$/t CO_2eq ([10]).

Concerns about double claiming and more generally, questioning the adequacy of offsetting have led various stakeholders to redefine the rules of the market to ensure its credibility and legitimacy (Kreibich 2024). The Carbon Removals and

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([9]) https://verra.org/programs/verified-carbon-standard/

([10]) https://carboncredits.com/carbon-prices-today/

Carbon Farming (CRCF) Regulation (EU/2024/3012) ([11]) is the first EU-wide voluntary framework for certifying carbon removals, carbon farming and carbon storage in products across Europe. In the coming years, it is expected that the European Commission will approve certification schemes that apply the CRCF rules.

It is important to note that the CRCF does not currently provide a specific eligibility route for most aquaculture activities (except possibly some seaweed-based activities) with the carbon removal credentials of bivalve and other low trophic forms of aquaculture not being sufficiently established or quantified. The offsetting assumptions used below in this report refer to the broader voluntary carbon market, which is evolving and where methodologies for marine and coastal projects are still under development.

3.3.2.2 Support ecosystem conservation and restoration projects of carbon-capturing marine and freshwater habitats

Under this tool, the remaining GHG emissions are offset by supporting marine ecosystem conservation and restoration projects that focus on habitats with high carbon sequestration potential. A study was carried out on the cost of ecosystem restoration in Europe, but this is not specified per type of ecosystem (Institute for Environment and Sustainability Joint Research Centre et al 2015). Another study concluded that “Marine restoration costs might span from approximately US$ 0.5–25 million per hectare for shallow-water habitats”. This is then compared to the benefits created: “Existing economic assessments of coastal-ecosystem restoration report benefit-cost ratios typically between 0.05 and 1.7 (De Groot et. al., 2013) (where 1 corresponds to 100% return on investment) reaching a value of 4 for coral reef restoration”. This includes climate benefits among others (Danovaro et al 2025).

A recently published study calculated the benefit-costs ratio for kelp restoration projects in southern Australia (Carnell et al 2025). In this study, the costs for restoration are related to the culling of sea urchins (dive time, travel) and the application of ‘green gravel’ to re-seed the kelp forest. When calculated per ha, the median estimated cost for restoration was AU$ 37 450 / €20 750 (Further AU$ values converted to Euro as of Aug 2025 ([12]), (interquartile range (IQR) €19 770 - €23 570) per ha.

These costs are held against the benefits of a restored kelp forest, i.e. water purification, wild fisheries biomass provisioning, recreational fishing and global

([11]) OJ L, 2024/3012, ELI: http://data.europa.eu/eli/reg/2024/3012/oj

([12]) Google Finance - Australian Dollar to Euro 22/08/2025 climate regulation. A large variation in the benefits was reported, from €9 480 − €68 160 per ha, with a median of €19 900 per ha. This includes all reported benefits. Zooming in on climate regulation, the estimates used GHG reduction though the use of carbon capture range from 0.01 – 1.61 t C ha^{-1} depending on the biomass estimated for each reef. The study valued these at the most recent Australian Carbon Credit unit price (18.88 AU$/t of CO_2).

On a more critical note, Tölgyesi et al (2025) concluded that there is limited carbon sequestration potential from global ecosystem restoration. This study does not include marine ecosystems, only wetlands. If we zoom in on wetlands, it states that ‘Total area predicted for wetland restoration including all freshwater and saltwater herbaceous wetlands (excluding permanent water and wooded wetlands) was 2.83 million km^2 (9.8%), concentrated in the American Midwest and Eastern Asia, where wetlands have been extensively drained for agriculture.

3.3.3 Scenarios

The five core scenarios represent different pathways to reduce GHG emissions in the EU Member States aquaculture sector by 2050. The first scenario (Business-as-usual) assumes no policy or technological change. The production is based on trends and estimations made accordingly. The second scenario aligns with the EU climate targets set under the ESR and Green Deal, assuming proportional emissions reduction in aquaculture to meet the 2030, 2040, 2050 climate goals. The third scenario prioritizes low-investment tools such as replacing conventional feed with emerging feed materials, promoting non-fed aquaculture, IMTA and conducting energy audits. The fourth scenario focuses on building a climate resilience by using AI for early pathogen detection. This scenario also includes an increased diversification of farmed species. While this tool does not influence significantly costs and emissions reduction, it has been included in this scenario because a diversified aquaculture production lowers the risks associated with climate change. Finally, the fifth scenario maximises the CO_2eq emission reduction without cost constraints by fully deploying emerging feed materials, AI tools, renewable energy, species diversification, and extensive IMTA systems across the EU. Scenarios 3b and 5b are extensions of Scenarios 3 and 5 respectively with the inclusion of additional tools to tackle hard-to-abate emissions (Table 7).

Table 7 – Overview of tools and scenarios

No.	Description	Emerging feed materials & breeding	AI-based tools	Renewable energy	IMTA	Improvement of energy use efficiency	Increasing share of non-fed aquaculture	Voluntary carbon credits	Support ecosystem conservation and restoration
1	Business-as-usual								
1b	Increased growth of the non-fed aquaculture industry						x		
2*	Alignment with EU Climate Targets	x	x	x	x	x			
3	Prioritisation of low investment	x			x	x			
3b	Prioritisation of low investment with the inclusion of carbon credits	x			x	x		x	
4	Prioritisation of the resilience of the sector to climate change.	x	x		x	x			
5*	Maximum potential for emission reductions, assuming no financial constraints	x	x	x	x	x			
5b	Maximum potential for emission reductions, assuming no financial constraints and including carbon credits and ecosystem restoration	x	x	x	x	x		x	x

* Scenario 2 and 5 have the same tools but differ in adoption level

3.3.3.1 Scenario 1: Business-as-Usual (BAU)

This scenario assumes no significant changes or additional mitigation measures are implemented in the aquaculture sector up to 2050. Projected annual production growth is based on an estimated annual rate of 1.6% The average growth rate over this period is used to forecast production volumes through to 2050.

GHG emissions in this scenario are calculated using the baseline data from task 1, which provides emission factors per unit of production. An annual increase in production of 1.6% (FAO 2024) was assumed for all countries to calculate the aquaculture emissions in 2030, 2040 and 2050.

3.3.3.2 Scenario 1b: Differentiated growth rates for non-fed aquaculture

Scenario 1b, like Scenario 1, assumes no action will be taken until 2040. However, this scenario assumes that from 2041 to 2050 non-fed aquaculture will increase at a yearly rate of 2.0%, while other aquaculture types will grow at 1.0% per year. This scenario aims to investigate the costs and reduction of emissions in a scenario where a higher portion of protein and lipids produced is provided by shellfish.

3.3.3.3 Scenario 2: Alignment with EU Climate Targets

This scenario models emission reductions consistent with the EU ESR and the European Commission’s climate targets for 2030, 2040, and 2050. These targets vary between Member States, reflecting national circumstances such as GDP, existing emissions, and potential for reduction (Table 8). The scenario lays out a 90% reduction in emissions by 2040 and a 100% reduction by 2050.

To achieve these goals, five key tools are suggested

- Renewable energy
- Emerging feed materials and selective breeding
- AI-based tools to optimise Feed Conversion Ratio (FCR), manage water and for early detection of diseases
- Integrated Multi-Trophic Aquaculture (IMTA)
- Improved equipment efficiency and durability

The first tool of this scenario is the gradual replacement of non-renewable energy sources with renewable sources. Wind, solar, geothermal and biomass energy can gradually substitute fossil fuels. The percentages of gradual replacement for different countries, indicated in Table 8, from 2025 to 2050 suggested in this scenario for different countries are indicated in Table 8.

The percentages were allocated based on the following consideration:

- Current utilisation of renewable sources: in countries where renewable sources of energy are most used, the increase in use of renewable energy is smaller. Vice versa, countries that currently use less renewable energy sources, were assigned a high renewable energy effort.

- Energy resources available in the country: specific characteristics of the country (size, location, geology and climate) were taken into consideration to estimate the capacity of each country to produce renewable energy. Countries with great unused potential, like some Mediterranean countries who do not extensively use solar power, were assigned a greater transition effort. On the contrary, small countries with limited natural resources were assigned a lower transition effort.

- Economic capacity of the country: as renewable energy requires financial investments, countries with lower funding availability were assigned a lower transition effort, at least in the first two periods of time (2025-2030 and 2031-2040).

Each tool contributes to the overall emission reduction targets of each country, but not at the same rate. Their combined effect is modelled and summarised in the following table (Table 8) which illustrates country-level progress toward the 2025-2050 climate goals, broken down into the five presented tools.

Table 8 – Scenarios and corresponding emission reduction rates goals towards 2050, according to Scenario 2

Country	Total emissions reduction goal.	Renewable energy	Emerging feed materials + breeding programs	AI-tools	IMTA	Improved efficiency of equipment
2026 - 2030						
Austria	48%	10%	25%	5%	3%	5%
Belgium	47%	10%	25%	5%	2%	5%
Bulgaria	10%	2%	5%	1%	1%	1%
Croatia	16.7%	4%	5%	2%	0.7%	5.0%
Cyprus	32%	10%	15%	1%	1%	5%
Czechia	26%	5%	14%	1%	1%	5%
Denmark	50%	15%	20%	5%	3%	7%
Estonia	24%	5%	10%	5%	2%	2%
Finland	50%	20%	20%	5%	2%	3%

Country	Total emissions reduction goal.	Renewable energy	Emerging feed materials + breeding programs	AI-tools	IMTA	Improved efficiency of equipment
France	47.5%	10%	20%	5%	5%	7.50%
Germany	50%	20%	20%	5%	3%	2%
Greece	22.7%	10%	5%	4%	1%	2.7%
Hungary	18.7%	8%	5%	3%	1%	1.7%
Ireland	42%	20%	15%	3%	2%	2%
Italy	43.7%	20%	15%	5%	2%	1.7%
Latvia	17%	5%	3%	3%	3%	3%
Lithuania	21%	5%	5%	5%	5%	1%
Malta	19%	4%	4%	4%	4%	3%
Netherlands	48%	13%	20%	5%	5%	5%
Poland	17.7%	7%	7%	1%	1%	1.7%
Portugal	28.7%	10%	10%	3%	3%	2.7%
Romania	12.7%	3%	3%	3%	3%	0.7%
Slovakia	22.7%	5%	5%	5%	5%	2.7%
Slovenia	27%	6%	6%	6%	6%	3%
Spain	37.7%	8%	8%	8%	8%	5.7%
Sweden	50%	20%	10%	10%	5%	5%
2030 – 2040						
Austria	42%	10%	20%	10%	1.00%	1%
Belgium	43%	10%	20%	10%	1.00%	2%
Bulgaria	80%	30%	30%	10%	5%	5%
Croatia	73.3%	30%	30%	5%	5%	3.3%
Cyprus	58%	30%	20%	3%	3%	2%
Czechia	64%	30%	20%	6%	6%	2%
Denmark	40%	20%	10%	5%	2%	3%
Estonia	66%	30%	20%	5%	6%	5%
Finland	40%	10%	20%	5%	2%	3%
France	42.5%	10%	20%	8%	2%	2.5%
Germany	40%	20%	10%	5%	2%	3%
Greece	67.3%	30%	30%	5%	1%	1.3%
Hungary	71.3%	30%	30%	5%	3%	3.3%
Ireland	48%	20%	20%	4%	2%	2%
Italy	46.3%	20%	20%	2%	2%	2.3%
Latvia	73%	30%	30%	10%	1%	2%
Lithuania	69%	30%	30%	3%	3%	3%
Malta	71%	30%	30%	5%	3%	3%

Country	Total emissions reduction goal.	Renewable energy	Emerging feed materials + breeding programs	AI-tools	IMTA	Improved efficiency of equipment
Netherlands	42%	20%	15%	5%	1%	1%
Poland	72.3%	30%	30%	5%	5%	2.3%
Portugal	61.3%	30%	20%	5%	5%	1.3%
Romania	77.3%	30%	30%	10%	2%	5.3%
Slovakia	67.3%	30%	30%	5%	1%	1.3%
Slovenia	63%	25%	25%	5%	3%	5%
Spain	52.30	25%	20%	5%	1%	1.3%
Sweden	40.00	20%	10%	5%	2%	3%
2040 – 2050						
Austria	10%	3%	3%	3%	0.5%	0.5%
Belgium	10%	3%	3%	3%	0.5%	0.5%
Bulgaria	10%	3%	3%	3%	0.5%	0.5%
Croatia	10%	3%	3%	3%	0.5%	0.5%
Cyprus	10%	3%	3%	3%	0.5%	0.5%
Czechia	10%	3%	3%	3%	0.5%	0.5%
Denmark	10%	3%	3%	3%	0.5%	0.5%
Estonia	10%	3%	3%	3%	0.5%	0.5%
Finland	10%	3%	3%	3%	0.5%	0.5%
France	10%	3%	3%	3%	0.5%	0.5%
Germany	10%	3%	3%	3%	0.5%	0.5%
Greece	10%	3%	3%	3%	0.5%	0.5%
Hungary	10%	3%	3%	3%	0.5%	0.5%
Ireland	10%	3%	3%	3%	0.5%	0.5%
Italy	10%	3%	3%	3%	0.5%	0.5%
Latvia	10%	3%	3%	3%	0.5%	0.5%
Lithuania	10%	3%	3%	3%	0.5%	0.5%
Malta	10%	3%	3%	3%	0.5%	0.5%
Netherlands	10%	3%	3%	3%	0.5%	0.5%
Poland	10%	3%	3%	3%	0.5%	0.5%
Portugal	10%	3%	3%	3%	0.5%	0.5%
Romania	10%	3%	3%	3%	0.5%	0.5%
Slovakia	10%	3%	3%	3%	0.5%	0.5%
Slovenia	10%	3%	3%	3%	0.5%	0.5%
Spain	10%	3%	3%	3%	0.5%	0.5%
Sweden	10%	3%	3%	3%	0.5%	0.5%

Table 9 – Adoption rate of Scenario 2 to achieve carbon neutrality by 2050

Period	Emerging feed materials + breeding programs	IMTA	Improved efficiency of equipment	Use of AI-based tools	Renewable energy
2025-2030	20% of fish produced fed with emerging feed materials	10% of fish farms integrating the system with more species	20% of farms improving efficiency of structures and equipment	10% of EU farms sharing data and adopting AI-based tools for feeding, water management and early detection of disease	20% of energy used in the sector produced with renewable sources
2030-2040	40% of fish produced fed with emerging feed materials	30% of fish farms integrating the system with more species	50% of farms improving efficiency of structures and equipment	30% of EU farms sharing data and adopting AI-based tools for feeding, water management and early detection of disease	50% of energy used in the sector produced with renewable sources
2040-2050	70% of fish produced fed with emerging feed materials	60% of fish farms integrating the system with more species	90% of farms improving efficiency of structures and equipment	60% of EU farms sharing data and adopting AI-based tools for feeding, water management and early detection of disease	90% of energy used in the sector produced with renewable sources

To achieve the target of carbon neutrality by 2050, after analysing the emissions reductions attained, it is assumed that the remaining emissions will be offset through the adoption of the voluntary carbon market.

3.3.3.4 Scenario 3: Prioritise low investment

The tools selected for this scenario are considered inexpensive action that can be taken without major investments for the fish farmers. These tools consist of:

- Replacement of conventional materials with emerging feed materials
- Integrated Multi-Trophic Aquaculture (IMTA) in existing farms
- Improved efficiency of equipment and structures

For this scenario, the tools are applied across all EU countries.

The table below show the extension of the use of the tools we suggest for the three periods focus of this study.

Table 10 – Detailing Scenario 3

Period	Emerging feed materials + breeding programs	IMTA	Improved efficiency of equipment
2026-2030	50% of fish produced fed with emerging feed materials	5% of fish farms integrating the system with more species	20% of farms improving efficiency of structures and equipment
2030-2040	80% of fish produced fed with emerging feed materials	10% of fish farms integrating the system with more species	60% of farms improving efficiency of structures and equipment
2040-2050	100% of fish produced fed with emerging feed materials	20% of fish farms integrating the system with more species	100% of farms improving efficiency of structures and equipment

For this scenario, we also assume the good practice of carrying out site pre-assessments for the new farms to avoid sensitive ecosystems will be adopted. Before expanding aquaculture facilities, GIS-based mapping or ecological screenings should be used to avoid areas like blue carbon ecosystems (seagrass beds, salt marshes) and/or carbon sinks.

These assessments are relatively inexpensive and can prevent high long-term costs associated with environmental damage, short-term, large scale carbon emissions, legal issues, and/ or restoration costs/impacts.

3.3.3.5 Scenario 4: Prioritise the resilience of the sector to climate change

To prioritise the resilience of the EU aquaculture sector to climate change, the following tools were identified:

- Replacement of conventional feed materials with emerging feed materials
- Integrated Multi-Trophic Aquaculture (IMTA) in existing farms
- Improved efficiency of equipment and structures
- Use of AI-based tools for early detection of pathogens or harmful events (such as algal blooms) due to climate warming
- Diversification of farmed species

The last point was not included in the calculations of task 3 as it was assumed that this tool does not reduce emissions but increases resilience to climate change. Different species have varying tolerances to temperature, salinity, oxygen levels, and other climate-induced stressors. By producing multiple species or genetic strains with diverse environmental tolerances, aquaculture operations can maintain productivity even if some species perform poorly under changing conditions. This approach acts as ecological and economic insurance, spreading risks and improving the system's overall adaptability to climate variability and change. Furthermore, diversification enables the implementation of IMTA.

The table below show the extension of the use of the tools we suggest for the three periods focus of this study.

Table 11 – Detailing Scenario 4

Period	Emerging feed materials + breeding programs	IMTA	Improved efficiency of equipment	Use of AI-based tools
2026-2030	30% of fish produced fed with emerging feed materials	5% of fish farms integrating the system with more species	20% of farms improving efficiency of structures and equipment	30% of EU farms sharing data and adopting AI-based tools for feeding, water management and early detection of disease
2030-2040	50% of fish produced fed with emerging feed materials	10% of fish farms integrating the system with more species	60% of farms improving efficiency of structures and equipment	50% of EU farms sharing data and adopting AI-based tools for feeding, water management and early detection of disease
2040-2050	80% of fish produced fed with emerging feed materials	20% of fish farms integrating the system with more species	100% of farms improving efficiency of structures and equipment	80% of EU farms sharing data and adopting AI-based tools for feeding, water management and early detection of disease

3.3.3.6 Scenario 5: Maximum potential for emission reductions, assuming no financial constraints.

For this scenario, we assume the adoption of all the tools, as specified in the table below.

Table 12 – Detailing Scenario 5

Period	Emerging feed materials + breeding programs	IMTA	Improved efficiency of equipment	Use of AI-based tools	Renewable energy
2026-2030	50% of fish produced fed with emerging feed materials	10% of fish farms integrating the system with more species	20% of farms improving efficiency of structures and equipment	50% of EU farms sharing data and adopting AI-based tools for feeding, water management and early detection of disease	30% of energy used in the sector produced with renewable sources
2030-2040	80% of fish produced fed with emerging feed materials	50% of fish farms integrating the system with more species	60% of farms improving efficiency of structures and equipment	80% of EU farms sharing data and adopting AI-based tools for feeding, water management and early detection of disease	60% of energy used in the sector produced with renewable sources
2040-2050	100% of fish produced fed with emerging feed materials	100% of fish farms integrating the system with more species	100% of farms improving efficiency of structures and equipment	100% of EU farms sharing data and adopting AI-based tools for feeding, water management and early detection of disease	100% of energy used in the sector produced with renewable sources

3.3.4 Hard-to-abate scenarios

3.3.4.1 Scenario 3b: Prioritizing low investments and offsetting remaining emissions on the voluntary carbon market

This scenario builds upon Scenario 3. After analysing what GHG emission reduction is achieved under Scenario 3, this Scenario 3b assumes that the remaining emissions are offset on the voluntary carbon market, in simple words: The aquaculture sector would then buy carbon credits on the voluntary market.

The reason to focus on offsetting on the voluntary carbon market only is that other tools to offset hard-to-abate emissions are more expensive.

3.3.4.2 Scenario 5b: Exploring the maximum potential for emission reduction and offsetting remaining emissions by supporting ecosystems conservation and restoration

This scenario builds upon Scenario 5. After analysing what GHG emission reduction is achieved under Scenario 5, Scenario 5b assumes that the remaining emissions are offset by supporting conservation and restoration of marine and freshwater ecosystems. In simple words: The aquaculture sector would then financially support ecosystem conservation and restoration projects to offset remaining emissions.

4 Scenarios cost analysis

4.1 Summary

Task 3 analysed emissions reductions, investment costs, and cost per tonne CO_2eq abated (Marginal Abatement Cost or MAC) across proposed scenarios using a financial accounting approach. Key findings include:

MAC generally increases over time but varies widely across six scenarios:

- 2026-2030: 46-243 €/t CO_2eq
- 2026-2040: 65-232 €/t CO_2eq
- 2026-2050: 69-228 €/t CO_2eq
- Lower MAC values (46-69 €/t CO_2eq) are competitive with current voluntary carbon credit prices (around 56 €/t CO_2eq). The alignment between MAC values and voluntary carbon credit prices indicates that these measures could be financially feasible for aquaculture producers.

Cost-effective rankings:

- 2026-2030: Scenario 5b is most cost-effective (46 €/t CO_2eq, 18.9 million tonne CO_2eq reduction).
- 2026-2040: Scenario 3b ranks best (65 €/t CO_2eq, 61.6 million tonnes CO_2eq reduction).
- 2026-2050: Scenario 3b remains the most cost-effective (69 €/t CO_2eq, 111.6 million tonnes CO_2eq reduction).

Scenario 3b heavily relies on offsetting mechanisms, as it incorporates only three tools for adoption. In contrast, Scenario 5b achieves 100% adoption of all proposed tools and integrates an offsetting approach through supporting ecosystem conservation and restoration. While Scenario 5 utilises all tools available to abate emissions, it manages to reduce only 50% of total emissions. To meet the target, as demonstrated in Scenario 5b, the remaining emissions are addressed via offsetting. However, the effectiveness of these offsetting mechanisms remains unproven and is further discussed in task 4.

In addition, task 3 also considered the impacts of changes in investment costs for tool implementation, discount rates, and emissions from feed on the MAC. Furthermore, granular analysis was conducted for Scenario 5b.

4.2 Objective

The objective of this task is to calculate the cost-effectiveness of reducing GHG emissions through the different scenarios formulated under task 2.

4.3 Results

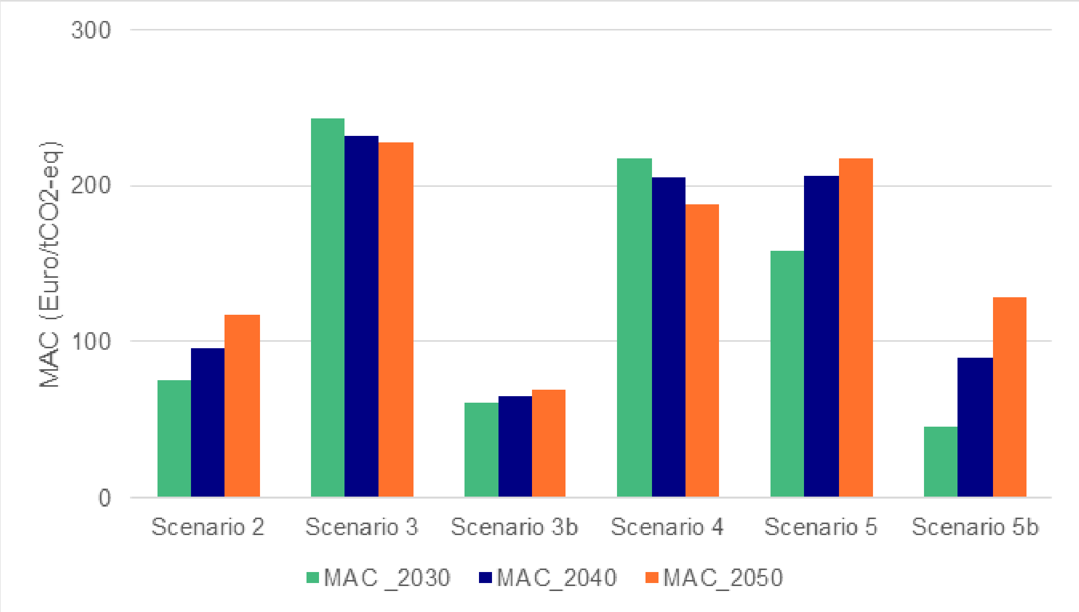
4.3.1 Scenario cost analysis

The analysis reveals that the marginal abatement cost for different scenarios generally increases overtime throughout the implementation periods. The average MAC across European countries for six scenarios is presented in the figure below. Across scenarios, MAC values show a wide range:

- 2026-2030: ranging from 46 to 243 €/t CO_2eq
- 2026-2040: ranging from 65 to 232 €/t CO_2eq
- 2026-2050: ranging from 69 to 228 €/t CO_2eq

The lower end of the MAC spectrum (46 to 69 €/t CO_2eq) presents a financially feasible for aquaculture producers, as it is competitive with current voluntary carbon credits prices, which have traded approximately 56 €/t CO_2eq in recent times (Gold Standard 2025), and are projected to increase around 100 €/t CO_2eq by 2035 (EY 2025). However, the higher end MAC values around 232 €/t CO_2eq, exceed the current spot price of voluntary carbon credits, suggesting potential financial challenges for adoption at these levels. This is due to the high costs associated with implementing innovative decarbonization tools in that specific scenario. The lower-cost scenarios, on the other hand, achieve cost-effectiveness by maintaining a certain level of adoption for tools while also incorporating offsetting mechanisms, such as the purchase of voluntary carbon credits and supporting ecosystem conservation and restoration.

Figure 5 – Marginal abatement cost for 6 scenarios



Across the six scenarios, MAC values exhibit a relatively wide range, reflecting the impact of technology adoption rates, technology costs, and their emission reduction potential. This information is summarised in the table below for further clarification.

Table 13 – Marginal abatement cost and emission reduction across scenarios

Scenario	Period	Projected abated emissions with tools (t CO_2eq)	Projected emissions offsetting (t CO_2eq)	Total projected reduced emissions (t CO_2eq)	Marginal abatement cost (€/t CO_2eq)
2	2026-2030	788 020	18 141 202	18 929 222	75
	2026-2040	6 646 276	54 961 267	61 607 542	86
	2026-2050	16 757 117	94 870 510	111 627 627	117
3	2026-2030	997 419	0	997 419	243
	2026-2040	6 876 904	0	6 876 904	232
	2026-2050	18 282 851	0	18 282 851	228
3b	2026-2030	997 419	17 931 803	18 929 222	61
	2026-2040	6 876 904	43 324 691	61 607 542	65
	2026-2050	18 282 851	93 344 776	111 627 627	69
4	2026-2030	1 295 444	0	1 295 444	218
	2026-2040	8 573 659	0	8 573 659	205
	2026-2050	23 260 579	0	23 260 579	188
5	2026-2030	3 282 967	0	3 282 967	158
	2026-2040	22 548 102	0	22 548 102	206
	2026-2050	60 455 715	0	60 455 715	218

Scenario	Period	Projected abated emissions with tools (t CO_2eq)	Projected emissions offsetting (t CO_2eq)	Total projected reduced emissions (t CO_2eq)	Marginal abatement cost (€/t CO_2eq)
5b	2026-2030	3 282 967	15 646 255	18 929 222	46
	2026-2040	22 548 102	39 059 440	61 607 542	90
	2026-2050	60 455 715	51 171 912	111 627 627	129

As shown in the Table 13, Scenarios 3 and 3b share similarly high adoption rates of emerging feed materials and breeding programs (100% by 2050), as well as improved energy efficiency (100% by 2050) and IMTA (20% by 2050). However, the MAC of Scenario 3b is significantly lower than that of Scenario 3 (65 €/t CO_2eq versus 232 €/t CO_2eq in the 2040 period). The critical differentiating factor is that Scenario 3b incorporates the purchase of voluntary carbon credits, a mechanism with a relatively low cost (56 €/t CO_2eq). By leveraging this low-cost tool to offset residual emissions, Scenario 3b emerges as the most cost-effective scenario to achieve net-zero emissions by 2050.

A similar comparison can be made between Scenarios 5 and 5b. Both scenarios employ maximum levels of technological adoption across all tools. However, the key distinction lies in the integration of Scenario 5b with supporting ecosystem conservation and restoration at a significantly lower cost (23.3 €/t CO_2eq) compared to the higher expense of additional internal technological abatement. This integration substantially lowers the overall MAC for Scenario 5b.

Likewise, this principle explains the performance difference seen in Scenario 2, which seeks to achieve net-zero emissions as targeted under the ESR. Scenario 2 combines a progressive renewable energy with the use of carbon credits. Although Scenario 2 also utilises the purchase of carbon credits for offsetting, like Scenario 3, its MAC is considerably higher because it adopts all tools, whereas Scenario 3 focuses on only three tools.

Scenario 4, despite employing a moderate mix of tools, neither incorporates carbon credits nor initiates a renewable energy. As a result, the total emission reduction achieved is relatively low and the cost of abatement remains high.

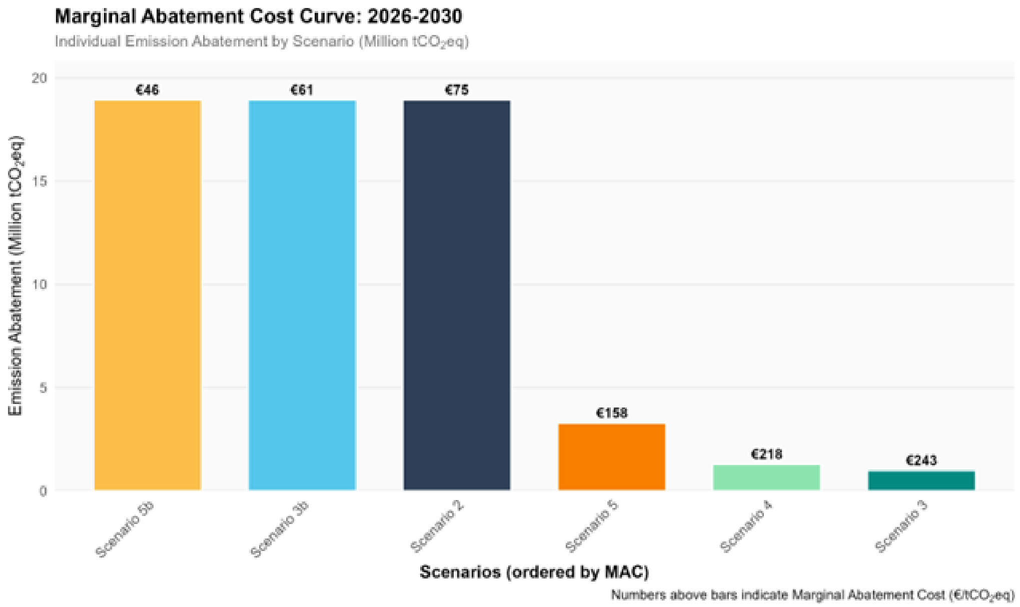
4.3.2 Ranking of scenarios

Figure 8 illustrates the Marginal Abatement Cost Curves for three time periods: (a) in the short term (2026–2030), (b) in the medium term (2026–2040), and (c) in the long-term (2026–2050). Each graph plots the MAC (€/t CO_2eq) against the emission abatement in million tonnes CO_2eq on the vertical axis, with different scenarios (2, 3, 3b, 4, 5, and 5b). The ranking of scenarios is ordered by their respective MACs.

In the **short term** (Figure 6) by 2030, Scenario 5b is the most cost-effective option, with the lowest MAC of 46 €/t CO_2eq, achieving the highest abatement of 18.9 million tonnes CO_2eq. This scenario leverages ecosystem conservation and restoration support as its offsetting tool. Following closely is Scenario 3b, which achieves the same abatement level of 18.9 million tonnes at a slightly higher MAC of 61 €/t CO_2eq by relying on the purchase of voluntary carbon credits to offset emissions. Similarly, Scenario 2 also achieves the same abatement level of 18.9 million but at a marginally higher MAC of 75 €/t CO_2eq, as it combines all available tools, including voluntary carbon credits, to reach ESR target.

In contrast, Scenario 5 achieves a modest abatement of 3.3 million tonnes at a higher MAC of 158 €/t CO_2eq, as it relies only on technological tools without employing offsetting mechanisms. Scenario 4 provides higher abatement of 12.9 million tonnes, but its MAC is also higher at 218 €/t CO_2eq. Finally, Scenario 3 is the least cost-effective, achieving the smallest abatement of 0.99 million tonnes at the highest MAC of 243 €/t CO_2eq.

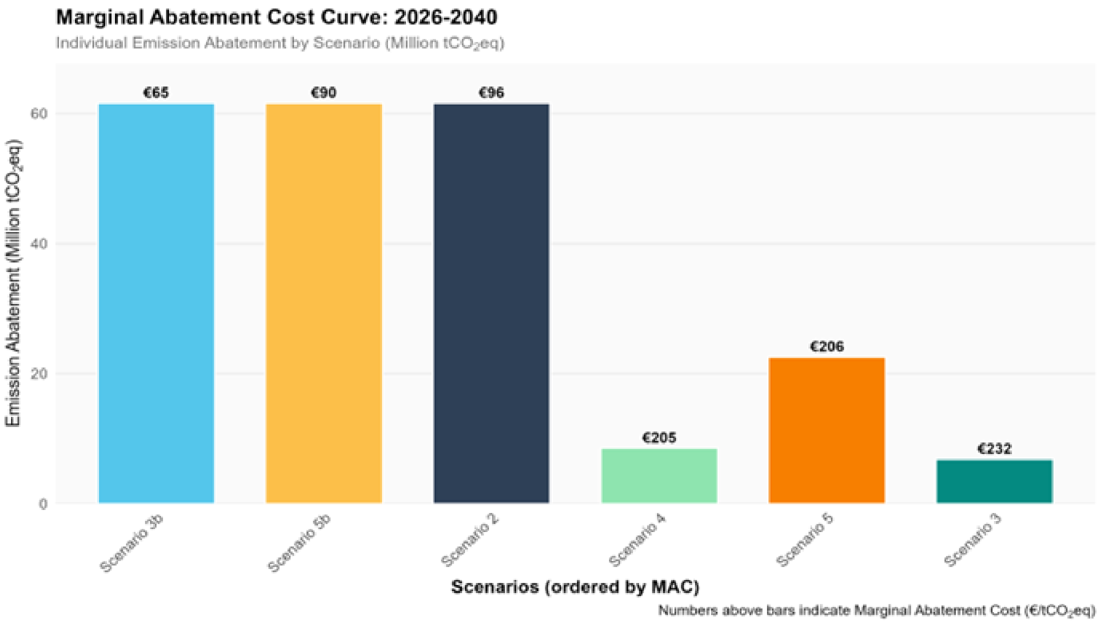
Figure 6 - Marginal abatement cost curves for the periods 2026-2030



In the **medium term** by 2040 (Figure 7), with the adoption rate increase described in task 2, this ranking has slightly changed. Scenario 3b is the most cost-effective option, with the lowest MAC of 65 €/t CO_2eq, while achieving the highest abatement level of 61.6 million tonnes CO_2eq. Closely following Scenario 3b is Scenario 5b, which achieves the same abatement level of 61.6 million tonnes but at a slightly higher MAC of 90 €/t CO_2eq. Similarly, Scenario 2 also reaches an abatement level of 61.6 million tonnes, though at a slightly higher MAC of 96 €/t CO_2eq.

In contrast, Scenario 3 achieves a relatively modest abatement of 6.8 million tonnes, but at the highest MAC of 232 €/t CO_2eq. Scenarios 4 and 5 provide higher abatement levels, 8.6 million tonnes and 22.5 million tonnes, respectively, but their MACs remain high, at approximately 205 €/t CO_2eq.

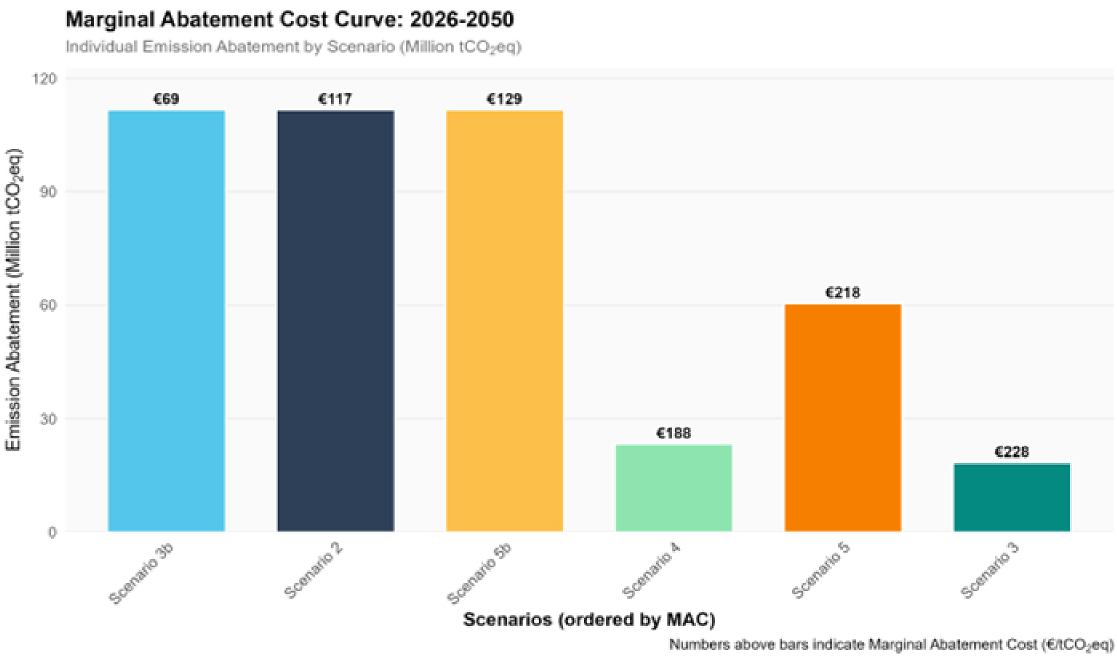
Figure 7 - Marginal abatement cost curves for the periods 2026-2040



In the **long-term** for the period 2026-2050 (Figure 8) as the adoption rate continues to increase to achieve net zero, this ranking remains similar to that of the medium term. Scenario 3b remains the most cost-effective option, with the lowest MAC of 69 €/t CO_2eq, while achieving the highest abatement level of 111.6 million tonnes of CO_2eq. It is followed by Scenario 2, which achieves the same abatement level of 111.6 million but at a higher MAC of 117 €/t CO_2eq. Similarly, Scenario 5b also reaches an abatement level of 111.6 million tonnes, though at a slightly higher MAC of 129 €/t CO_2eq.

In contrast, Scenario 3 and Scenario 4 achieve relatively modest abatement levels of 18.3 million tonnes and 23.2 million tonnes, respectively, but at the highest MACs of 228 €/t CO_2eq and 188 €/t CO_2eq, respectively. Scenario 5 provides a higher abatement level of 60.5 million tonnes, but its MAC remains high at 218 €/t CO_2eq.

Figure 8 - Marginal abatement cost curves for the periods 2026-2050



4.3.3 Sensitivity analysis

This section presents how variations in key variables influence the marginal abatement cost. The three key variables considered are: changes in total costs (including annual CAPEX and OPEX), the discount rate, emissions associated with feed and feed transportation, and growth rate of production projection.

4.3.3.1 Changes in total costs (including annual CAPEX and OPEX)

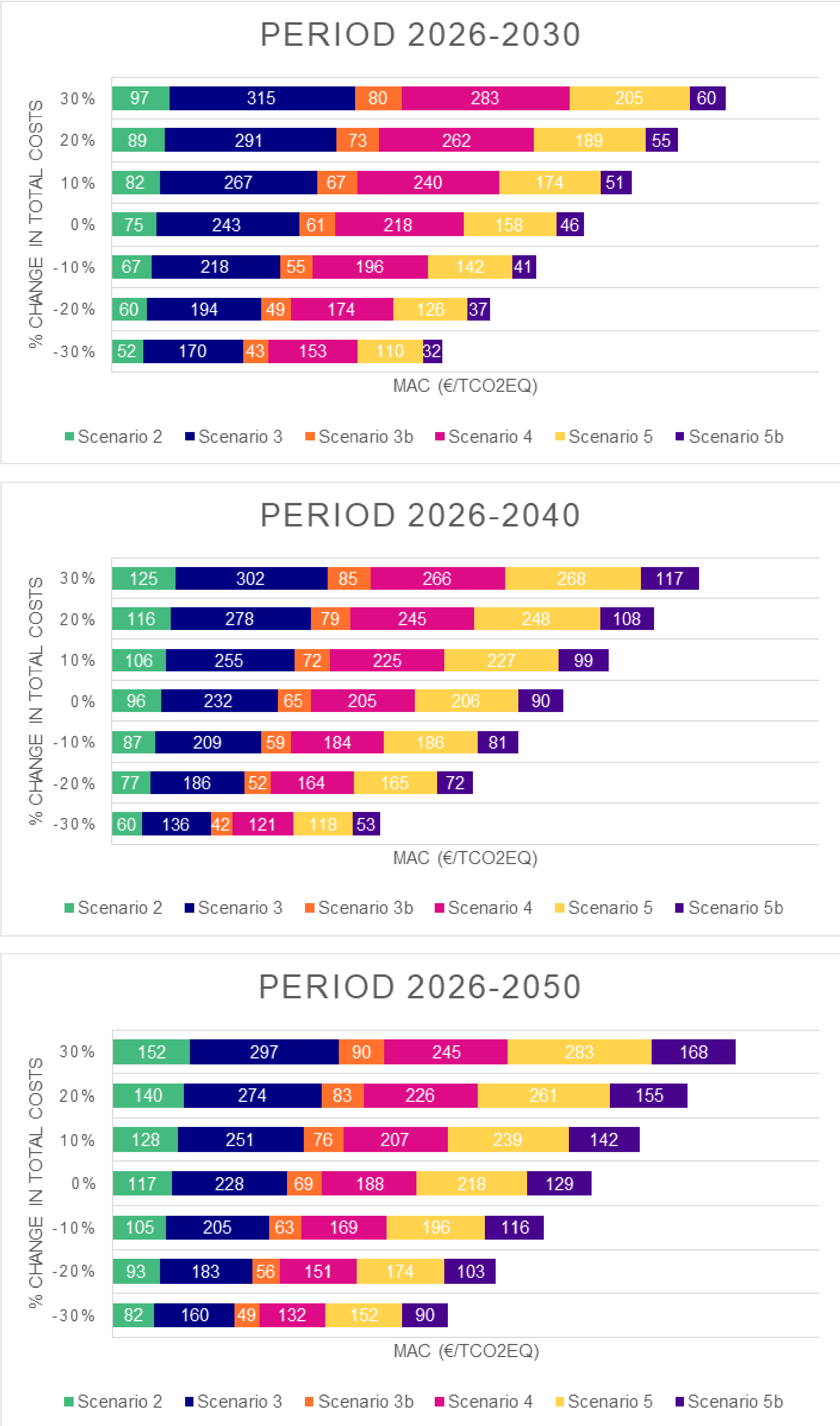
Figure 9 presents how changes in total costs influence the MAC across various scenarios over time. In general, MAC values decrease proportionally with reductions in total costs, demonstrating a direct relationship between total cost changes and MAC, while maintaining emission abatement. The total cost adjustments range from a 30% increase to a 30% decrease.

For instance, during the period 2026-2030, when total costs rise by up to 30%, Scenario 3 shows the highest MAC at 315 €/t CO_2eq, indicating its sensitivity to cost increases. Even when total costs decrease, such as by 20%, Scenario 3 reduces its MAC to 194 €/t CO_2eq but continues to lead the other scenarios.

The sensitivity in Scenario 3 stems from the relatively low abatement potential of its three adopted tools. Emerging feed materials and breeding program, IMTA, and improved equipment efficiency are applied at adoption rate of 100%, 20%, 100% respectively. The adoption of these three tools across all five production systems results in high investment costs. In contrast, their combined emission abatement potential remains modest at 24.3%, 17%, and 10% respectively. As a result, the MAC per tonne of CO_2eq is higher compared to other scenarios, such as Scenarios 4 and 5, which incorporate renewable energy capable of reducing emissions by up to 96%.

Scenarios 2, 3b, and 5b have relatively lower sensitivity to cost variations, maintaining more stable and lower MAC values. This stability is attributed to their reliance on offsetting to address the remaining emissions, which involves relatively lower investment costs compared to the implementation of tools. As a result, the MAC per tonne remains lower in these scenarios.

Figure 9 – Effects of total cost changes on marginal abatement costs

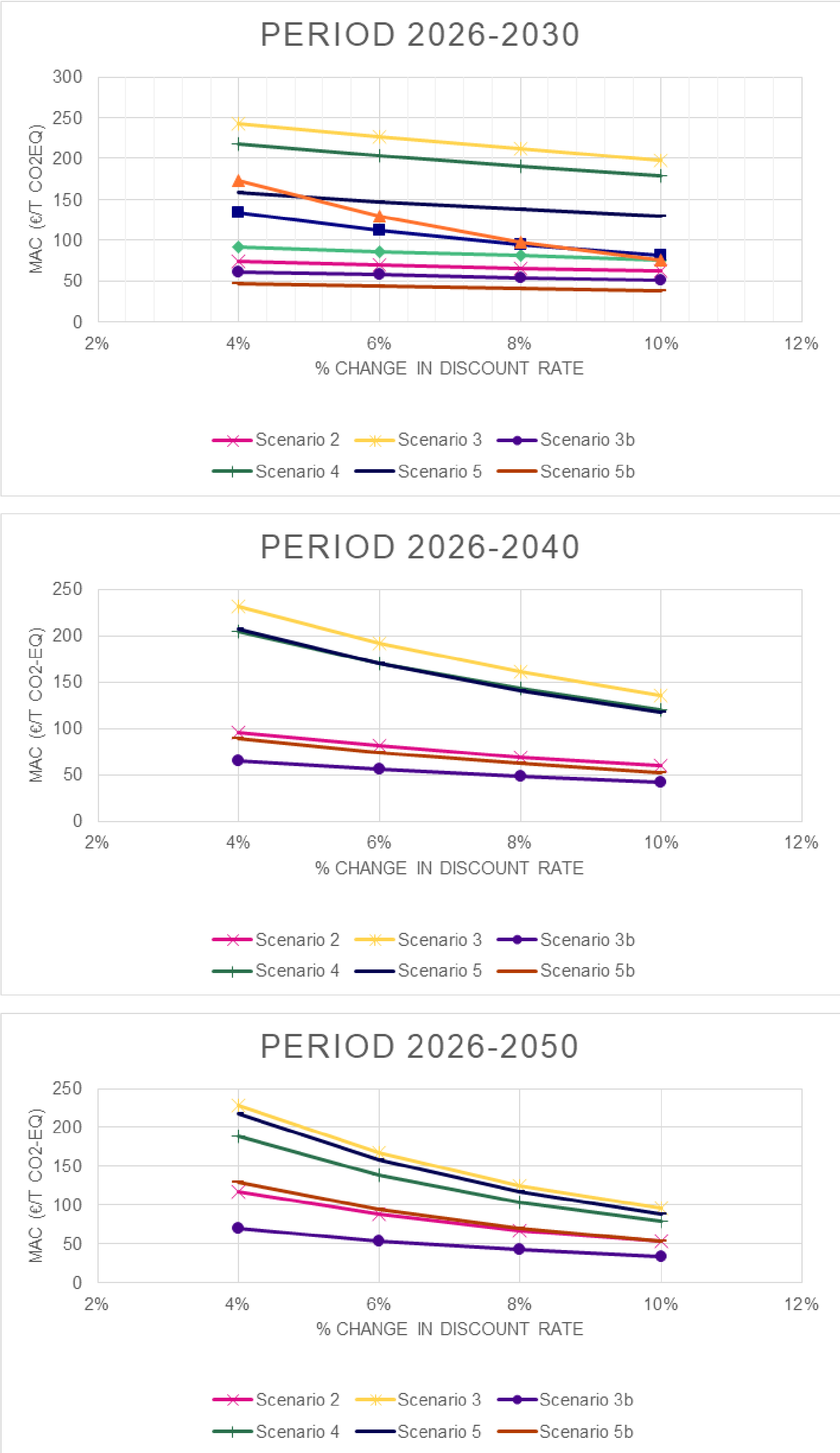


4.3.3.2 Changes in discount rate

The discount rate ([13]) also has an impact on the MAC by determining how future costs and benefits are valued in present terms. A higher discount rate reduces the present value of future expenditures, making long-term costs and benefits appear less significant and lowering the MAC. Conversely, a lower discount rate increases the weight of future costs, raising the overall MAC across scenarios and over periods (Figure 10).

([13]) A discount rate is the rate of return used to discount future cash flows back to their present value

Figure 10 – Effects of discount rate changes on marginal abatement costs



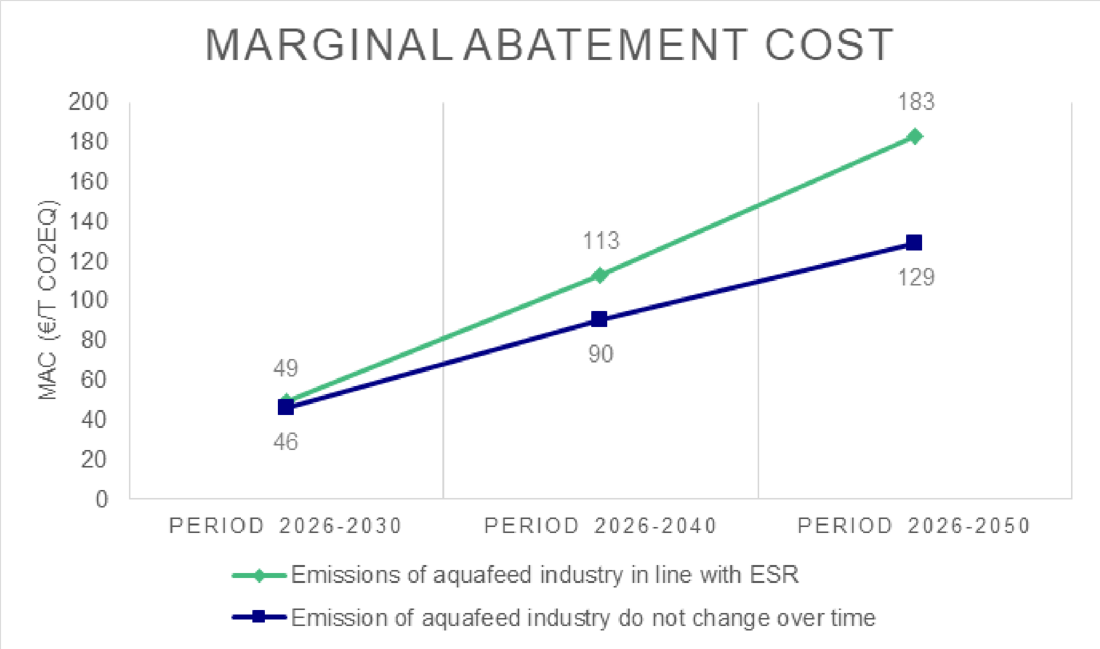
4.3.3.3 Changes in emissions related to feed

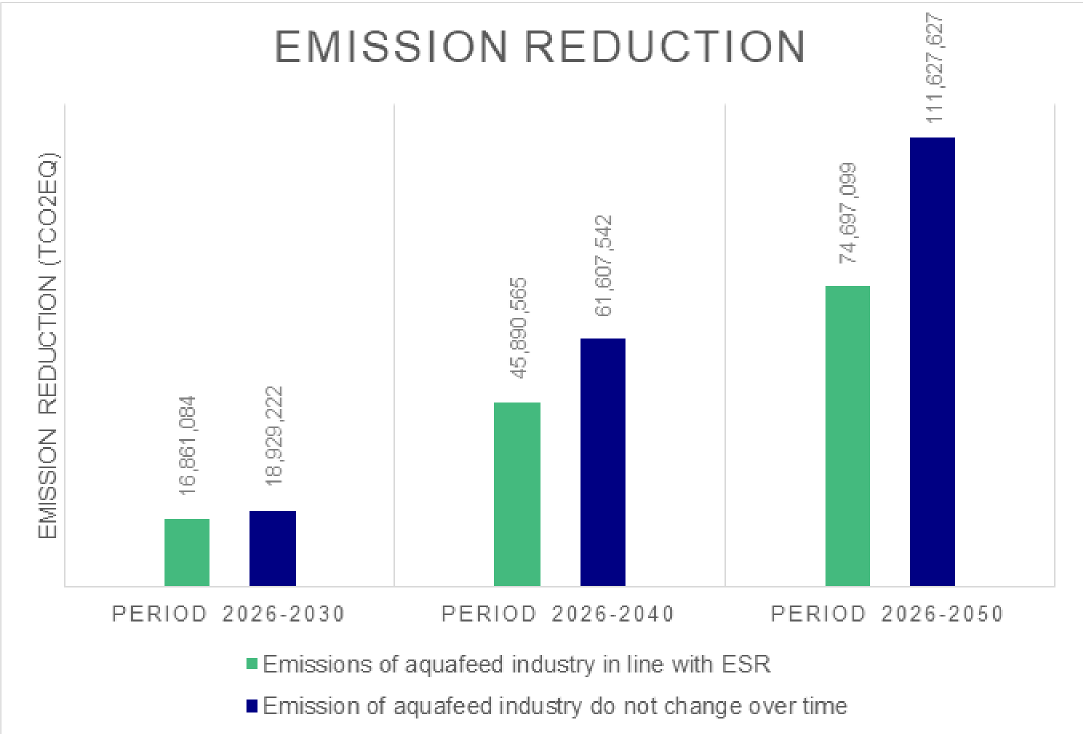
Scenario 5b is used to test the impact of changes of emission reduction by aquafeed production on the MAC. More specifically, the aquafeed industry is expected to align with ESR targets which are 55% emissions reduction by 2030, 90% by 2040 and net zero emissions by 2050. Figure 11 illustrates how reducing emission factors for feed production will impact the MAC of Scenario 5b through 2030, 2040 and 2050.

Under the first assumption, where the emission factors related to feed remain the same over time (2026–2050), the total cost of abatement increases significantly due to the high cumulative emissions abated. For example, by 2050, the total abatement reaches 111 627 627 tonnes, but with a relatively lower MAC of €129, the total cost of abatement is €14.4 billion.

In contrast, under the second assumption, where emission factors decrease over time to achieve net zero emissions by 2050, the total abatement by 2050 is lower at 74 697 099 tonnes, but the MAC is slightly higher at €183. Consequently, the total cost of abatement in 2050 is €13.7 billion, which is lower than the first assumption. This indicates that reducing emission factors over time not only aligns with ESR but also reduces the overall cost of abatement when compared to allowing emission factors to remain constant.

Figure 11 – Effects of emission factor for feed changes on marginal abatement costs for Scenario 5b





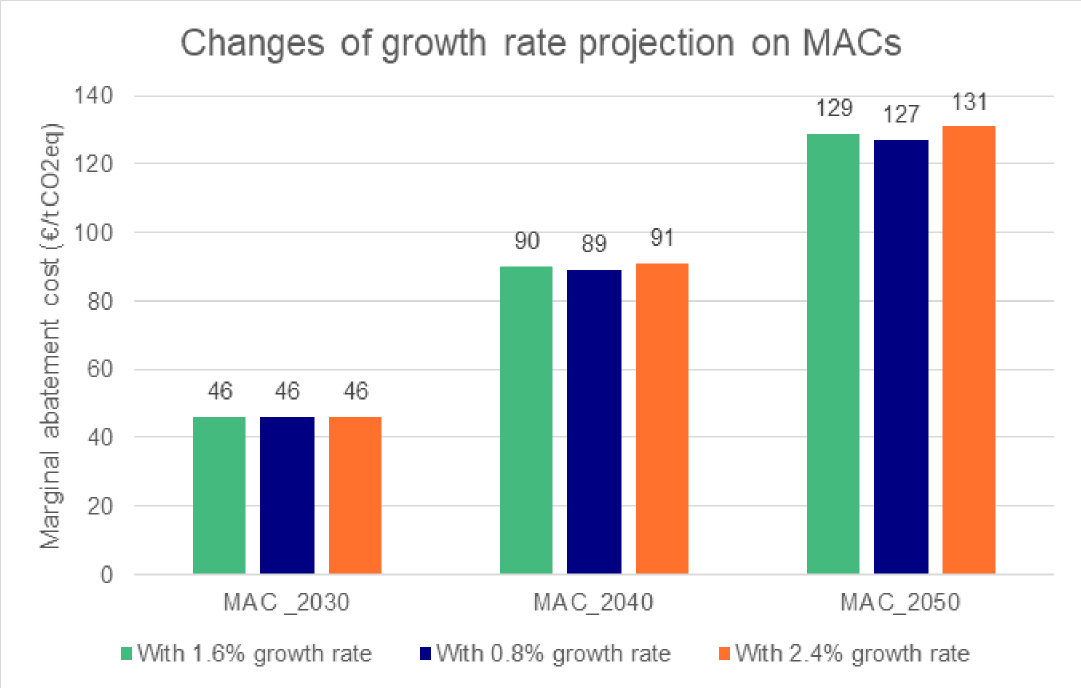
4.3.3.4 Changes in growth rate projection

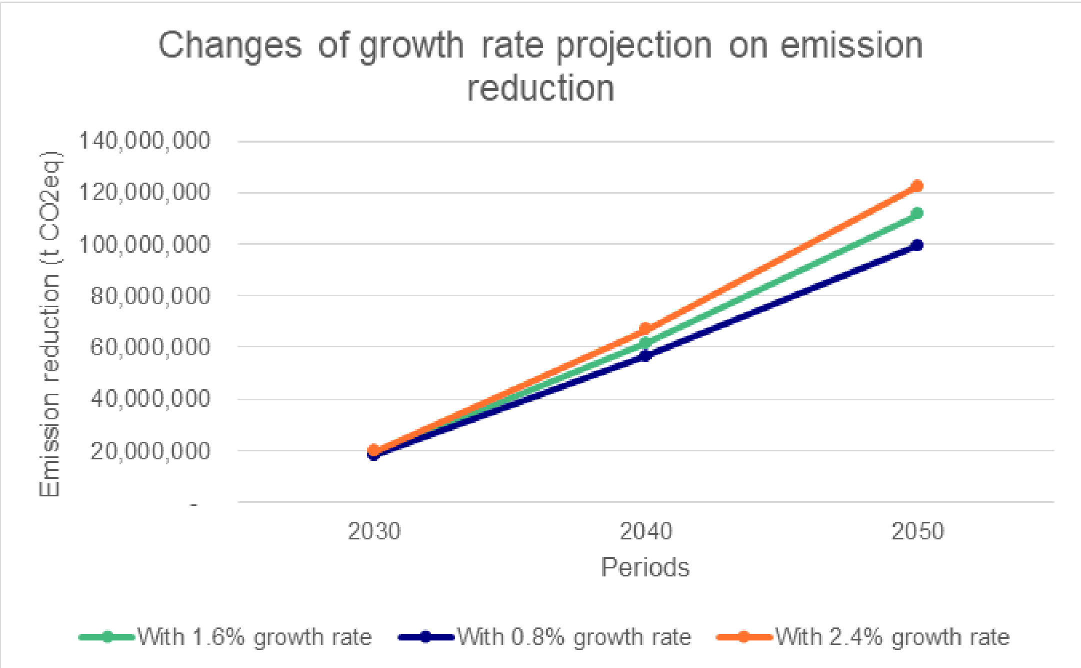
As proposed during the ETP workshop, growth rate projections can vary by ±50% of the baseline rate of 1.6%. To assess the impact of these changes on the MAC for Scenario 5b, we consider growth rates of 0.8%, 1.6% (baseline), and 2.4%.

The results reveal that in 2030, the MAC remains constant at 46 €/t CO_2eq across all growth rates, indicating no immediate impact. By 2040, slight variations emerge: a lower growth rate of 0.8% results in a MAC of 90 €/t CO_2eq, while the baseline (1.6%) and higher growth rate (2.4%) show MACs of 89 €/t CO_2eq and 91 €/t CO_2eq, respectively. By 2050, the MAC increases more noticeably with growth rate changes, ranging from 129 €/t CO_2eq at 0.8% growth to 127 €/t CO_2eq at 1.6% growth and 131 €/t CO_2eq at 2.4% growth.

Emission reductions, on the other hand, show a clear positive correlation with growth rates. By 2030, emission reductions are similar across all growth rates. By 2050, emission reductions reach approximately 100 million tonnes CO_2eq for a 0.8% growth rate, 122 million tonnes CO_2eq for the baseline 1.6% growth rate, and over 120 million tonnes CO_2eq for a 2.4% growth rate.

Figure 12 – Changes of growth rate projection on MACs and Emission reduction for the Scenario 5b





4.3.4 Granularity analysis

We used Scenario 5b to analyse granularity ([14]). Based on the principles "MAC values that fall outside the range of the median plus or minus 2.5 times the

([14]) Granularity analysis examines MAC data at the country level to identify outliers.

median absolute deviation will be identified as significant outliers," as described in the methodology section, four countries are identified as outliers: France, Ireland, Italy, and Portugal. These countries have exceptionally high MAC values compared to the EU average during the periods 2026-2030, 2026-2040, and 2026-2050. The specific MAC values are as follows:

- EU: 46; 90; 129 €/t CO_2eq respectively
- France: 87; 192; 284 €/t CO_2eq respectively
- Ireland: 80; 171; 250 €/t CO_2eq respectively
- Italy: 71; 151; 219 €/t CO_2eq respectively
- Portugal: 69; 144; 209 €/t CO_2eq respectively

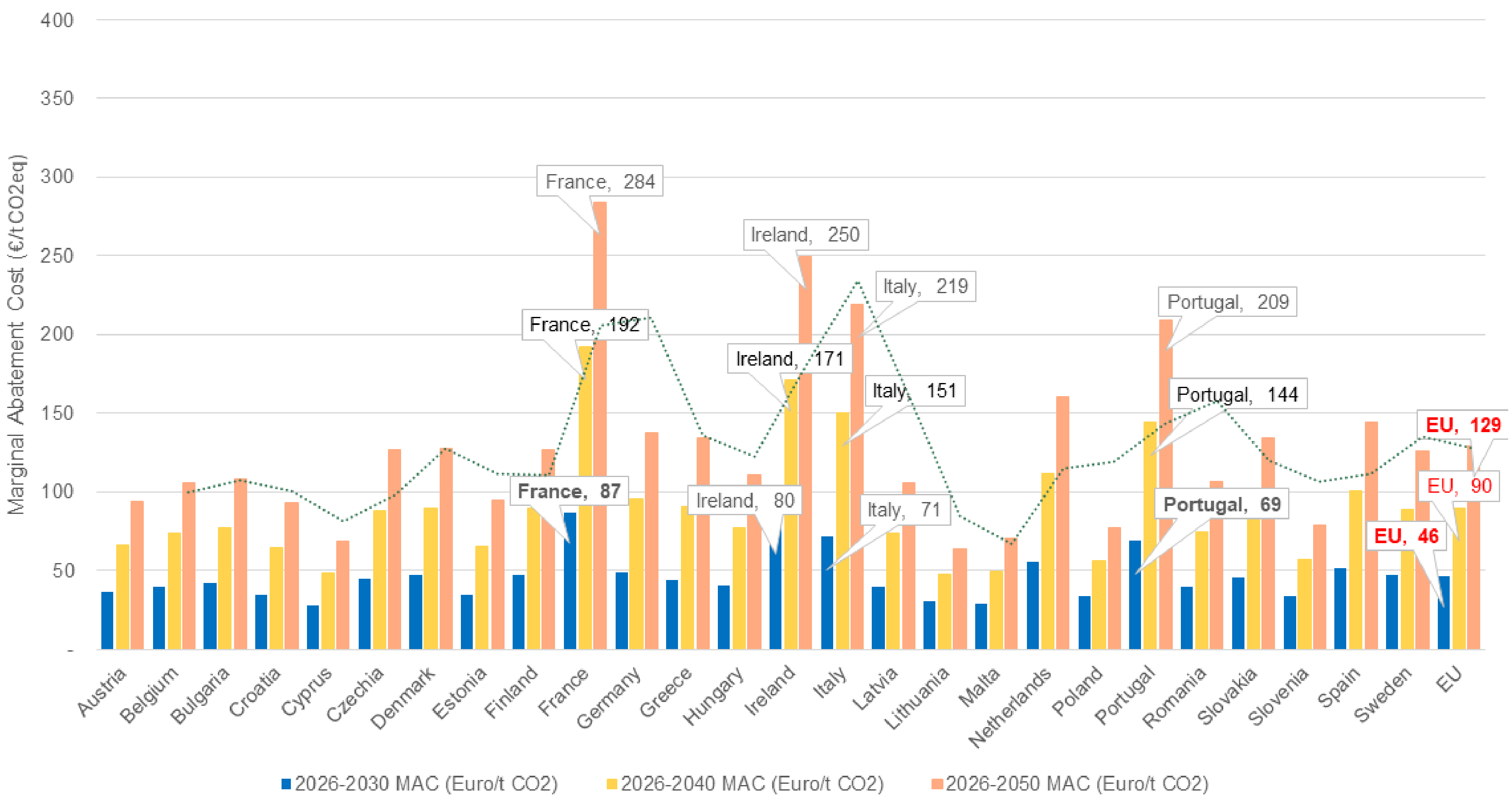
Table 14 reveals the underlying drivers of these MAC outliers, which stem from an unfavourable ratio of high investment costs to limited emission reduction potential. These four countries face substantial investment requirements, with total CAPEX ranging from €210–1 678 million and total annual OPEX reaching €552–4 415 million.

Despite these significant investments, the cost savings remain modest (€22-176 million) and the emission reduction potential is limited (1.8-10.6 tonnes CO_2eq per tonne of LW). The cost burden is particularly significant because all four countries operate both cage and non-fed systems, which require substantial initial investments in electric boats. The combination of high total annual CAPEX and OPEX, and relatively small emission reduction creates the exceptionally high MAC values observed in these countries, making them outliers compared to the EU average.

Table 14 - Summary of costs and emission reductions of outliers for the period 2026-2050

Country	Total production volume (million LW)	Total annual CAPEX (€ million)	Total annual OPEX (€ million)	Total Cost savings (€ million)	Total emission reduction (million t CO_2eq)
France	5.95	1 678	4 415	112	10.6
Ireland	1.1	336	872	52	2.3
Italy	4.0	1 215	3 130	176	9.6
Portugal	1.1	210	552	22	1.8

Figure 13 – Marginal abatement cost of all Member States for Scenario 5b



5 Impact, limitations, gaps, and sensitivity analysis of scenarios

5.1 Summary

Task 4 assesses the wider social-economic impacts of the tools and scenarios, providing input to formulation of pathways. To this end, a survey, focus groups meetings, and interviews were conducted to inform a multi-criteria analysis (MCA) and SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis. The results show the diverging views on applicability and desirability of the tools across different production types. The MCA informs the formulation of pathways in Chapter 6, for each production type, and the SWOT analysis is used to inform the formulation of policy recommendations, also in (Chapter 6).

5.2 Objectives

The objectives of this task are the following:

- To assess the social-economic impacts and policy implications of the scenarios developed in task 2 for aquaculture production.
- To consider possible gaps and limitations and where the ETP should focus its work to reduce the gap.

5.3 Results

5.3.1 Qualitative multi-criteria analysis

To prepare the qualitative MCA, a long list of potential criteria was identified, covering economic, environmental and social aspects. This list includes at least the criteria mentioned in the Terms of Reference and has been extended by a few more based on knowledge of the research team. By adding definitions of each criterion, conducting a weighting exercise (scoring 1-3) to determine the relevance for policy and the level of detail of available data, and by validation with CINEA/DG MARE in the meeting held on 28th August, the final list of criteria was decided.

The final list of criteria, and the definitions provided can be found below in Table 15. The final column indicates whether we had a quantitative or qualitative assessment, and where the expected data will come from. The expert judgement indicates input from the survey where possible, and if that is not enough information, expertise within the consortium and research team can also be used, with the assistance of supporting literature.

The quantitative data on CAPEX, OPEX and GHG emissions from production resulted from the previous tasks 1-3. These data were transformed to the same Likert scale, ranging from -2 to 2, to be able to make the right comparisons in the MCA. This was done by the project team by ranking the tools from having the lowest calculated costs/least calculated emissions (ranked with 0, since negative is not possible) to having the highest calculated costs/most calculated emissions (ranked with 2).

Following the collection of the assessments for the different criteria from the surveys and the available cost data from tasks 1-3, the results are presented in Table 15.

Table 15 - Final criteria selected for multi-criteria analysis

Criteria Category	Criteria	Definition	Explanation Likert scale (-2 to 2)	Data Availability
Social	Match with current regulatory landscape	How well is the tool covered by existing regulations	A positive indicator on this criterion means that the tool matches with the current regulatory landscape.	Qualitative: Expert Judgement
	Number of employees in the sector	The number of employees engaged within the aquaculture sector	A positive indicator on this criterion means that the tools will increase the number of employees in the EU Aquaculture sector.	Qualitative: Expert Judgement
	Potential safety implications	Implications for safety – worker, consumer, working conditions etc.	A positive indicator on this criterion means that the tool will have positive impact on the safety implications for workers.	Qualitative: Expert Judgement
	Impact on skills required	How well is the tool covered by existing skills across the sector	A positive indicator on this criterion means that the tool is currently covered by existing skills in the sector e.g. not much training is required.	Qualitative: Expert Judgement
Economic	CAPEX	Capital costs to implement scenarios	A negative indicator on this criterion means that the tool will have a higher CAPEX compared to not implementing this tool (positive score not possible).	Quantitative: Task 3 -> normalised into qualitative
	OPEX	Operational costs to implement scenarios	A negative indicator on this criterion means that the tool will have higher operational costs compared to not implementing this tool (positive score not possible).	Quantitative: Task 3 -> normalised into qualitative
	Operational cost reductions	How are operational costs for aquaculture producers reduced	A positive indicator on this criterion means that there is a reduction in operational costs (cost savings) perceived for the aquaculture producers (negative not possible).	Qualitative: Expert Judgement
	Industry Readiness	How ready is the industry to implement the tool	A positive indicator on this criterion means that the tool is ready to be implemented by the aquaculture industry.	Qualitative: Expert Judgement
Environmental	GHG emissions from production	Greenhouse gas emissions (per tonne and/or total for industry)	A positive indicator on this criterion means that the tool has a reduction in the GHG emissions emitted during production.	Quantitative: Task 1-2 -> normalised into qualitative
	Impact on wild populations and ecosystems	Impacts like the introduction of invasive species, depletion of wild stocks due to overfishing for fish oil and fish meal, water pollution	A positive indicator on this criterion means that the tool will have a positive impact on wild populations and ecosystems.	Qualitative: Expert Judgement

Criteria Category	Criteria	Definition	Explanation Likert scale (-2 to 2)	Data Availability
	Water usage	Amount of fresh water required for the same volume of production	A positive indicator on this criterion means that the tools will decrease the amount of water usage.	Qualitative: Expert Judgement
	Land usage	Amount of space required for the new aquaculture production systems, also related to the destruction of habitats (e.g. wetland conversion for ponds)	A positive indicator on this criterion means that the tools will decrease the amount of land usage.	Qualitative: Expert Judgement

In total, 16 experts were present in the focus groups or so-called MCA validation workshops (see also Table 16). These experts were asked to divide 100 points between the different criteria. This was done based on four questions to simplify the process. Experts were first asked to divide 100 points between the four social criteria, then 100 points for the four economic criteria and 100 points for the four environmental criteria. Finally, they could divide 100 points between the three aspects: social, economic and environmental. It was allowed to divide the points equally, or to put more emphasis on one or multiple criteria or aspects by giving it more points. By multiplying the scores, for example CAPEX with the score for economic criteria, and diving by 100, the final percentages were generated per expert (e.g. 20*50/100 = 10%). Individual expert scores were then averaged. Results of this for each production system can be found below. The first row shows the number of responses per production system.

Table 16 - Stakeholder weighting for the social, economic and environmental criteria.

		Cage	Pond	Raceway	RAS	Suspended
	Number of stakeholder responses	*4*	*6*	*1*	*3*	*2*
Social	Impact on skills required	5%	7%	12%	8%	5%
	Match with current regulatory landscape	9%	7%	4%	7%	9%
	Number of employees in the sector	3%	3%	2%	5%	9%
	Potential safety implications	3%	4%	2%	4%	3%
Economic	CAPEX	7%	13%	12%	17%	3%
	OPEX	7%	10%	6%	12%	8%
	Operational cost reductions	13%	11%	12%	11%	17%
	Industry readiness	10%	13%	10%	6%	12%
Environmental	GHG emissions from production	12%	6%	8%	10%	7%
	Impact on wild populations and ecosystems	7%	9%	18%	8%	19%
	Land usage	12%	4%	2%	4%	6%
	Water usage	12%	12%	12%	10%	4%

In general, the economic criteria were given most importance by the stakeholders (ranging between 37% (for cage) and 47% (for pond). This is the sum of all economic criteria above) and the social criteria the least importance (ranging between 20-25%). Only for cage systems, all environmental criteria were together perceived slightly more important (42.5%) than the economic criteria (37.5%). For raceway and non-fed systems, the impact on wild populations and ecosystems was considered the most important criterion. We did not classify the background of the expert based on the criteria (i.e. Social/ Economic/ Environmental experts) but rather based on their expertise on production systems. Overall, despite the diverse backgrounds of the experts, it is clear that economic considerations remain substantial in their views, suggesting the continued importance of economic criteria in efforts to reduce GHG emissions in aquaculture.

Once the scores and assessment of each criterion against the technological tool was completed by industry experts, the data was used to create five different MCA's, one for each production system. Both equal weighting and stakeholder weighting is applied to come to the final MCA scores for each scenario.

5.3.1.1 Cage aquaculture

When analysing the MCA results for cages (Table 17) for the social criteria, it can be observed that all tools are expected to increase the number of employees in the sector, but none of them match closely with the current regulatory landscape. This finding aligns with studies showing that European aquaculture could contribute more substantially to employment and coastal development (Falconer et al., 2023). On the one hand, IMTA scores highest for the criterion "number of employees in the sector". On the other hand, IMTA is perceived as the tool that matches the least with the current regulatory landscape. IMTA systems associated with cages have been shown to diversify livelihoods and create additional on-site employment opportunities (Ridler et al., 2007; Hossain, Senff, & Glaser, 2022).

In terms of economic criteria, the stakeholder inputs show that IMTA is the costliest tool (both in CAPEX and OPEX). Renewable energy also involves substantial capital investment, emerging feed materials and Improvement of Energy Use Efficiency are associated with relatively high operational costs. In contrast, purchasing carbon credits and funding ecosystem conservation and restoration support are viewed as the only tools with comparatively low costs, although these options also score lower across other criteria. Additionally, stakeholders indicated that other tools such as AI-based Tools and improvements in energy use efficiency would deliver the greatest cost savings, largely due to increased efficiency. This aligns with previous studies showing that the application of AI and digital decision-support tools in cage aquaculture can optimise feeding, reduce feed waste, and enhance energy management, resulting in operational cost savings and improved environmental performance (Chang et al., 2021; Lu et al., 2022; Huang et al., 2025). Similarly, improving energy-use efficiency, particularly through integrating renewable sources such as hydro, solar, and wind power, can reduce energy intensity and lower production costs over time, while also reducing environmental impacts (Bujas et al., 2022).

According to the stakeholder sessions, industry readiness for Breeding Programs is high, whereas readiness for Ecosystem conservation and restoration support and IMTA is lower. This result aligns with the established role of breeding programs as a cornerstone of productivity and resilience in cage-based finfish aquaculture. Selective breeding has historically delivered substantial improvements in growth rate, feed efficiency, and disease resistance in species such as salmonids, demonstrating a high level of technical maturity and strong readiness for further expansion (Gjedrem & Robinson, 2014). Recent developments, such as the routine use of genomic selection within commercial salmon breeding programs, further highlight that breeding technologies are not emerging concepts but are already embedded in mainstream industry practice (D'Agaro et al., 2021).

Considering the environmental criteria, the stakeholder groups are of the opinion that the tool renewable energy results in most GHG emission reductions. This is in line with literature. Life-cycle assessments of open-water salmonid production systems show that energy and fuel use are major contributors to total greenhouse-gas emissions (Ayer & Tyedmers, 2009; Pelletier et al., 2009). Fuel consumption alone accounts for about one-quarter of total emissions, indicating that reducing fossil-fuel dependence and improving energy efficiency would substantially lower the carbon footprint of cage aquaculture (Pelletier et al., 2009). Similarly, evidence from offshore seabass cage production indicates that vessel fuel use represents a comparable share of emissions, underscoring the potential for emission reductions through improved fuel efficiency and the adoption of low-carbon energy sources (García et al., 2019). Renewable energy could have a negative impact on land usage from all tools for cages. This is because of the space that, for example, wind farms or solar panels require on land. AI-based Tools and emerging feed materials are perceived by stakeholders to be able to reduce the impact on wild populations and ecosystems the most.

Table 17 - MCA results for cage systems

Category	Criterion	Equal weight (total = 100%)	Stakeholder Weighting	Emerging feed materials	Breeding programs	AI-based tools	IMTA	Renewable energy	Improvement of energy use efficiency	Carbon credits	Marine ecosystem restoration
Social	Match with current regulatory landscape	8.3	5.3	-0.33	0.33	0.50	-0.83	0.33	0.50	-0.20	-0.20
Social	Number of employees in the sector	8.3	9.1	1.20	1.20	1.00	1.40	0.40	0.40	0.40	0.80
Social	Potential safety implications	8.3	2.5	0.00	0.20	0.80	0.50	0.40	0.40	0.40	0.40
Social	Covered by skills in sector	8.3	3.1	0.50	0.67	0.83	0.50	0.83	1.00	0.20	-0.40
Economic	CAPEX	8.3	7.1	0.00	-0.50	-1.00	-2.00	-1.50	0.00	0.00	0.00
Economic	OPEX	8.3	7.4	-1.75	-1.00	-1.25	-2.00	-0.75	-1.50	-0.50	-0.25
Economic	Operational cost reductions	8.3	13.1	0.00	0.33	1.50	0.00	1.17	1.50	0.00	0.00
Economic	Industry Readiness	8.3	9.9	0.67	1.33	0.50	-0.33	0.83	0.33	0.60	-0.40
Environmental	GHG emissions from production	8.3	11.5	1.00	0.20	0.40	0.30	1.50	0.40		
Environmental	Impact on wild populations and ecosystems	8.3	7.4	0.80	0.40	1.00	0.60	0.20	0.00	0.40	0.60
Environmental	Water usage	8.3	11.9	-0.20	0.00	0.40	0.20	0.40	0.20	0.40	0.00
Environmental	Land usage	8.3	11.7	-0.20	0.00	0.40	0.20	-0.40	-0.20	-0.20	0.00

A positive number means the tool has a positive impact on the criterion (and vice versa). See Table 17 for a detailed explanation of the Likert scale used (-2 to 2).

When combining the scores from each tool into the scenarios, applying equal weight to each criterion (Table 18), Scenarios 2 and 5 are the most advantageous (0.21). It should be noted that the only difference between Scenario 2 and 5 is the adoption rate, so for the MCA these two scenarios will always have the same outcome (since they consist of the same set of tools). Scenario 4 and 5b score relatively high as well (0.19). The stakeholders gave operational cost reductions on average the highest weight, followed by almost all environmental criteria (Table 19). In the end, Table 19 shows the same results as for the equal weighting: Scenarios 2 and 5 still score the best.

Table 18 – Equal weighted scores for each scenario for cage systems

	Scenario 1	Scenario 2	Scenario 3	Scenario 3b	Scenario 4	Scenario 5	Scenario 5b
Weighted Social Score	0.00	0.18	0.16	0.14	0.18	0.18	0.15
Weighted Economic Score	0.00	-0.08	-0.10	-0.08	-0.09	-0.08	-0.06
Weighted Environmental Score	0.00	0.11	0.08	0.08	0.10	0.11	0.10
Weighted Total Score	**0.00**	**0.21**	**0.13**	**0.14**	**0.19**	**0.21**	**0.19**

Table 19 – Stakeholder weighted scores for each scenario for cage systems

	Scenario 1	Scenario 2	Scenario 3	Scenario 3b	Scenario 4	Scenario 5	Scenario 5b
Weighted Social Score	0.00	0.12	0.12	0.10	0.13	0.12	0.10
Weighted Economic Score	0.00	-0.01	-0.05	-0.04	-0.02	-0.01	-0.01
Weighted Environmental Score	0.00	0.13	0.09	0.09	0.11	0.13	0.12
Weighted Total Score	**0.00**	**0.24**	**0.16**	**0.16**	**0.22**	**0.24**	**0.22**

Key takeaways from the MCA for cage aquaculture for the formulation of reduction pathways are the following:

- Improving energy use efficiency and use of AI-based tools are both seen as attractive tools to reduce GHG emissions from the sector.
- IMTA is conceptually interesting but at the moment not a production practice that is commercially attractive. Various barriers impede the large-scale adoption of IMTA.
- The renewable energy will require a substantive investment, among others in electric vessels.
- The use of emerging feed materials is impeded by constraining regulations and high operational costs.
- When comparing the various scenarios, Scenarios 2, 4, 5 and 5b, in which all tools to reduce GHG emissions are adopted, score best.

5.3.1.2 Low-trophic aquaculture

Low-trophic aquaculture was not presented as a tool as such. However, it might be interesting to introduce it in certain systems or increase its share of production. Stakeholders were therefore asked to score low-trophic aquaculture against the criteria for raceway, RAS and non-fed aquaculture. For non-fed systems, low-trophic aquaculture is by its nature already included. It thus follows logically from the MCA that low-trophic aquaculture scores highest for many criteria (Table 20). Low-trophic aquaculture is therefore left out of the interpretation of results below.

Stakeholder inputs from the survey indicated that IMTA does not align well with the current regulatory landscape for non-fed aquaculture, and similar challenges were noted for purchasing carbon credits and funding ecosystem conservation and restoration support, which lack clear governance frameworks and established implementation pathways. This matches evidence from the literature highlighting regulatory fragmentation, licensing uncertainty, and limited institutional support as major barriers to IMTA development (Hossain et al., 2022; Buck et al., 2018). The stakeholders also noted that IMTA is not well supported by existing skills in the sector, reflecting broader skill and infrastructure gaps documented in the aquaculture governance literature (Jolly, 2023). In contrast, the Renewable energy was viewed as more achievable from a skills perspective. Despite these constraints, IMTA was recognised as having the potential to increase employment, as its multi-species production structure generally requires more labour than conventional non-fed systems (Hossain et al., 2022).

Insights from task 3 indicate that CAPEX and OPEX patterns remain consistent with earlier findings for cage systems. In accordance with that, breeding Programs are expected to deliver the greatest cost savings after Low Trophic Aquaculture, reflecting well-documented gains in growth rate, feed efficiency and survival that reduce production costs over time (Abaho et al., 2025; Gjedrem et al., 2012). The other tools are not expected to lower operational costs. In terms of implementation capacity, industry readiness is highest for the Renewable energy. By contrast, readiness for IMTA, carbon credits, and ecosystem conservation and restoration support remains low due to regulatory uncertainty and technical skill gaps commonly noted in the literature (Hossain et al., 2022; Buck et al., 2018).

The stakeholders identified that implementation of renewable energy is expected to deliver the greatest reduction in GHG emissions, consistent with evidence showing that decarbonising energy use is one of the most effective pathways to reduce emissions in open-water aquaculture systems. Breeding Programs were viewed as having a slightly negative impact on wild populations and ecosystems, reflecting concerns about genetic interactions and ecological effects if selectively bred stocks escape into surrounding environments, risks documented for domesticated fish in marine cage systems (Glover et al., 2017; Bolstad et al., 2021). By contrast, IMTA was considered a tool that could reduce land requirements, as its multi-trophic design makes more efficient use of marine space without the need for additional terrestrial infrastructure (Buck et al., 2018).

Table 20 – MCA results for non-fed systems

Category	Criterion	Equal weight (total = 100%)	Stakeholder Weighting	Breeding programs	IMTA	Renewable energy	Low trophic aquaculture	Carbon credits	Marine ecosystem restoration
Social	Match with current regulatory landscape	8.3	4.8	0.67	-1.67	0.33	1.33	-0.67	-1.33
Social	Number of employees in the sector	8.3	8.5	1.00	1.33	-0.33	1.50	0.33	0.00
Social	Potential safety implications	8.3	8.8	0.33	-0.33	0.33	1.50	0.00	0.00
Social	Covered by skills in sector	8.3	3.0	0.00	-1.00	1.50	1.00	0.50	-1.00
Economic	CAPEX	8.3	3.0	0.00	-2.00	-1.00		0.00	0.00
Economic	OPEX	8.3	8.0	-1.00	-2.00	-0.75		-0.50	-0.25
Economic	Operational cost reductions	8.3	17.0	1.33	0.00	0.00	1.50	0.00	0.00
Economic	Industry Readiness	8.3	12.0	0.50	-1.00	1.50	1.50	-0.50	-1.00
Environmental	GHG emissions from production	8.3	7.0	0.20	0.30	1.50			
Environmental	Impact on wild populations and ecosystems	8.3	19.0	-0.33	0.00	0.00	1.00	0.00	0.00
Environmental	Water usage	8.3	5.5	0.33	0.50	0.50	1.00	0.00	0.00
Environmental	Land usage	8.3	3.5	0.67	1.33	0.67	-0.33	0.33	0.67

A positive number means the tool has a positive impact on the criterion (and vice versa). See Table 17 for a detailed explanation of the Likert scale used (-2 to 2).

When combining the scores from each tool into the scenarios, Scenarios 2 and 5 score most positive (both for equal and stakeholder weighting). This is mainly due to the GHG emissions from production that would be reduced because of the Renewable energy. When applying equal weighting, Scenarios 3, 3b and 4 are not positive because the negative scores of the economic criteria do not outweigh the positive environmental scores.

Table 21 – Equal weighted scores for each scenario for non-fed systems

	Scenario 1	Scenario 2	Scenario 3	Scenario 3b	Scenario 4	Scenario 5	Scenario 5b
Weighted Social Score	0.00	0.06	0.01	0.01	0.01	0.06	0.00
Weighted Economic Score	0.00	-0.12	-0.17	-0.14	-0.17	-0.12	-0.11
Weighted Environmental Score	0.00	0.16	0.13	0.10	0.13	0.16	0.13
Weighted Total Score	**0.00**	**0.09**	**-0.03**	**-0.03**	**-0.03**	**0.09**	**0.02**

Table 22 – Stakeholder weighted scores for each scenario for non-fed systems

	Scenario 1	Scenario 2	Scenario 3	Scenario 3b	Scenario 4	Scenario 5	Scenario 5b
Weighted Social Score	0.00	0.06	0.06	0.04	0.06	0.06	0.02
Weighted Economic Score	0.00	-0.01	-0.07	-0.08	-0.07	-0.01	-0.06
Weighted Environmental Score	0.00	0.08	0.04	0.04	0.04	0.08	0.07
Weighted Total Score	**0.00**	**0.13**	**0.04**	**0.01**	**0.04**	**0.13**	**0.04**

Key takeaways from the MCA for non-fed aquaculture for the formulation of reduction pathways are the following:

- Increasing the share of low-trophic aquaculture in the EU is evaluated positively because of relatively low GHG emissions.
- Improving energy use efficiency and use of AI-based tools are both seen as attractive tools to reduce GHG emissions from the sector.
- IMTA is conceptually interesting but at the moment not a production practice that is commercially attractive. Various barriers impede the large-scale adoption of IMTA.
- When comparing the various scenarios, Scenarios 2 and 5, in which all relevant tools are adopted, score best.

5.3.1.3 Pond aquaculture

During the discussion, stakeholders suggested that the pond industry is ready for the emerging feed materials and breeding programs tools. This is in line with the long-standing use of selective breeding and feed innovation in pond aquaculture, particularly for species such as carp, tilapia, and catfish. Breeding programs for these species have already delivered substantial genetic gains in growth, feed efficiency, and disease resistance, indicating a high level of technical readiness (Gjedrem, Robinson, & Rye, 2012; Nguyen, 2016). The integration of emerging feed materials, including plant proteins, insect meals, and microalgae, has also become common practice, helping to reduce reliance on fishmeal in many pond systems (Rana et al., 2009).

The stakeholders' discussion also highlighted that GHG emissions from production will reduce significantly with the renewable energy, but it does require a lot more land. Accordingly, recent studies show that greenhouse-gas (GHG) emissions from pond aquaculture are strongly influenced by management practices, including feed input, aeration, and stocking density. Improved system designs, such as in-pond raceways, can reduce carbon emissions while maintaining high productivity, demonstrating considerable potential for emission reductions through energy-transition measures (Li et al., 2025). However, expanding pond-based production or installing on-site renewable-energy systems would require additional land, potentially increasing competition with agricultural and wetland areas (Boyd et al., 2010; Bosma & Verdegem, 2011).

Another insight from the session is that the tool of carbon credits is currently not supported by existing skills in the sector. This is consistent with recent studies showing that producers in pond aquaculture typically lack the technical capacity required to participate in carbon-accounting or low-carbon certification systems (Zhang et al., 2024). Similarly, AI tools and Renewable energy are also facing a challenge regarding the lack of current skills in the sector. Adoption of digital tools and AI is constrained, as many producers lack the practical knowledge required to operate appropriate hardware and software, and confidence in the reliability of AI systems remains low (Fernandes & D'Mello, 2024; McDonald et al., 2024). Comparably, capacity gaps are evident for renewable energy, where high upfront costs and limited technical expertise remain key obstacles to integrating solar and other renewable-energy systems into pond operations (Vo et al., 2021; Isaac, 2025).

Table 23 - MCA results for pond systems

Category	Criterion	Equal weight (total = 100%)	Stakeholder Weighting	Emerging feed materials	Breeding programs	AI-based tools	IMTA	Renewable energy	Carbon credits	Marine ecosystem restoration
Social	Match with current regulatory landscape	8.3	7.3	0.00	-0.25	-0.25	0.75	-0.50	-0.50	-0.25
Social	Number of employees in the sector	8.3	7.5	0.00	0.50	0.00	1.00	1.00	0.75	1.25
Social	Potential safety implications	8.3	3.0	0.25	0.50	0.75	-0.50	-0.25	0.25	0.75
Social	Covered by skills in sector	8.3	3.9	0.50	0.50	-0.75	0.50	-0.75	-1.00	-0.50
Economic	CAPEX	8.3	13.4	0.00	-0.67	-1.33	-2.00	0.00	0.00	0.00
Economic	OPEX	8.3	10.1	-1.75	-1.00	-1.25	-2.00	-0.75	-0.50	-0.25
Economic	Operational cost reductions	8.3	10.7	0.00	0.00	0.40	0.50	0.00	0.00	0.00
Economic	Industry Readiness	8.3	12.5	1.25	1.25	0.75	1.00	-0.33	-0.75	-0.50
Environmental	GHG emissions from production	8.3	6.0	1.00	0.20	0.40	0.30	1.50		
Environmental	Impact on wild populations and ecosystems	8.3	8.9	0.25	-0.75	0.75	1.00	-0.25	0.50	1.25
Environmental	Water usage	8.3	4.5	0.00	-0.25	0.50	1.00	0.00	0.25	1.00
Environmental	Land usage	8.3	12.3	-0.25	-0.75	0.25	0.00	-1.25	0.00	0.00

A positive number means the tool has a positive impact on the criterion (and vice versa). See Table 17 for a detailed explanation of the Likert scale used (-2 to 2).

When combining the scores from each tool into the scenarios, Scenario 3 scores the best for pond systems when using equal weighting (Table 24). This is mainly due to the positive score of the social criteria. When using the stakeholder weighting, the positive scores of the social and environmental criteria do not outweigh the negative economic scores (Table 25). This is because the pond experts gave the economic criteria the most importance (Table 25). This would mean that, according to stakeholders, none of the scenarios will result in a more overall positive impact than the Business-as-Usual scenario (Scenario 1). If only social criteria would be considered, Scenario 3 scores best. If only environmental criteria would be considered, Scenario 5b scores best.

Table 24 – Equal weighted scores for each scenario for pond systems

	Scenario 1	Scenario 2	Scenario 3	Scenario 3b	Scenario 4	Scenario 5	Scenario 5b
Weighted Social Score	0.00	0.05	0.10	0.07	0.07	0.05	0.04
Weighted Economic Score	0.00	-0.10	-0.10	-0.10	-0.10	-0.10	-0.09
Weighted Environmental Score	0.00	0.06	0.05	0.06	0.08	0.06	0.10
Weighted Total Score	**0.00**	**0.01**	**0.06**	**0.03**	**0.05**	**0.01**	**0.05**

Table 25 – Stakeholder weighted scores for each scenario for pond systems

	Scenario 1	Scenario 2	Scenario 3	Scenario 3b	Scenario 4	Scenario 5	Scenario 5b
Weighted Social Score	0.00	0.04	0.07	0.05	0.05	0.04	0.04
Weighted Economic Score	0.00	-0.13	-0.12	-0.12	-0.13	-0.13	-0.12
Weighted Environmental Score	0.00	0.02	0.02	0.03	0.05	0.02	0.06
Weighted Total Score	**0.00**	**-0.07**	**-0.03**	**-0.04**	**-0.03**	**-0.07**	**-0.03**

Key takeaways from the MCA for pond aquaculture for the formulation of reduction pathways are the following:

- IMTA is an interesting production practice that is expected to reduce the GHG emissions from pond aquaculture.
- The use of AI-based tools is seen as attractive tools to reduce GHG emissions from the sector.
- The renewable energy will require a substantive investment and is not evaluated positively.
- The use emerging feed materials is evaluated mildly positively but is expected to increase operational costs.
- There are little differences in the scoring of the scenarios.

5.3.1.4 Raceway aquaculture

The tool of “renewable energy” has the strongest positive effect on GHG emissions reduction. More efficient system designs, such as in-pond raceways, have been shown to lower direct GHG emissions compared with traditional pond systems (Li et al., 2025). Globally, species produced in energy-intensive systems, particularly shrimp and prawns, exhibit high emission intensities due to substantial aeration and pumping requirements, whereas low-input species such as bivalves show much lower emissions (MacLeod et al., 2020). Research on U.S. catfish production further demonstrates the mitigation potential of cleaner energy sources, farmed catfish operations currently source only limited amount of their direct energy use from renewables, indicating considerable scope for decarbonisation as energy systems evolve (Scroggins et al., 2022).

Stakeholders indicate that AI tools are currently not supported by current skill base in the sector and it will decrease the number of employees in the sector. The industry of raceway production systems is not ready for AI tools. The limited readiness of raceway systems for AI tools reflects broader skill and infrastructure gaps in aquaculture.

Intelligent farm systems require stable data transmission, reliable networking, and specialised hardware-software integration, yet these capacities remain underdeveloped in many production settings (Wang et al., 2021). Other findings show that uptake of advanced technologies is hampered by a lack of trained personnel, insufficient technical knowledge, and limited access to extension support, factors that challenge the adoption of technology-intensive systems such as raceways (Ayisi et al., 2016; Kyule et al., 2025). Some studies also confirm that high investment costs, data-security concerns, and unfamiliarity with AI remain key barriers to adoption, alongside low confidence in the reliability of AI systems (Georgopoulos et al., 2023; Fernandes & D’Mello, 2025).

Breeding programs are perceived by stakeholders to significantly reduce the water and land usage. This is in accordance with the earlier research which stated that selective bred stocks typically achieve higher growth rates, on average 12.5% per generation, and show improved feed conversion and survival (Gjedrem et al., 2012). These gains enable farms to produce more biomass within the same production area and with lower water input per unit of output. Other studies also show that faster growth and better feed efficiency directly translate into more efficient utilisation of production area and water resources (Olesen et al., 2003; Gjedrem & Baranski, 2009).

Furthermore, emerging feed materials are perceived to have a positive impact on wild populations and ecosystems but increase the operational costs. Reducing reliance on fishmeal and fish oil through alternative materials can lessen pressure on wild stocks and mitigate pollution associated with intensive production (Huntington and Hasan, 2009). However, these benefits come with higher operational costs. Emerging feed materials, including functional additives and plant-based components, often raise feed costs, with increases depending on material type and inclusion level (Hossain et al., 2024). High production and processing costs also limit the affordability of algal meals and microbial biomasses compared with conventional feed commodities (Cottrell et al., 2020).

Table 26 – MCA results for raceway systems

Category	Criterion	Equal weight (total = 100%)	Stakeholder Weighting	Emerging feed materials	Breeding programs	AI-based tools	IMTA	Renewable energy	Improvement of energy use efficiency	Low trophic aquaculture	Carbon credits	Marine ecosystem restoration
Social	Match with current regulatory landscape	8.3	12.0	0.50	0.25	-0.25	-0.25	0.00	0.25	0.25	-1.50	-1.00
Social	Number of employees in the sector	8.3	4.0	0.00	1.00	-1.50	0.75	0.00	0.00	0.75	-0.33	0.33
Social	Potential safety implications	8.3	2.0	0.25	0.50	1.00	-0.25	0.25	0.50	0.00	-0.25	0.00
Social	Covered by skills in sector	8.3	2.0	0.75	0.50	-1.50	0.00	0.25	-0.50	0.25	-0.75	-0.25
Economic	CAPEX	8.3	12.0	0.00	-0.67	-1.33	-2.00	0.00	0.00		0.00	0.00
Economic	OPEX	8.3	6.0	-1.75	-1.00	-1.25	-2.00	-0.75	-1.50		-0.50	-0.25
Economic	Operational cost reductions	8.3	12.0	-1.00	0.25	0.50	-0.25	0.50	0.50	-0.25	0.00	0.00
Economic	Industry Readiness	8.3	10.0	0.00	0.25	-1.25	-0.75	0.00	-0.50	-0.25	-1.25	-0.25
Environmental	GHG emissions from production	8.3	8.0	1.00	0.20	0.40	0.30	1.50	0.40			
Environmental	Impact on wild populations and ecosystems	8.3	18.0	1.33	0.67	1.00	1.00	0.00	0.00	0.00	0.00	0.50
Environmental	Water usage	8.3	2.0	0.75	1.25	0.50	1.25	0.00	0.00	0.50	0.25	0.50
Environmental	Land usage	8.3	12.0	0.75	1.25	0.75	0.50	0.25	0.00	0.25	-0.25	0.25

A positive number means the tool has a positive impact on the criterion (and vice versa). See Table 17 for a detailed explanation of the Likert scale used (-2 to 2).

When combining the scores from each tool into the scenarios, Scenario 3 scores the best for raceway systems when using equal weighting (Table 27). This is mainly due to the relatively high scores for environmental criteria, which score considerably higher than the social and economic scores for all scenarios. When the stakeholder weights are used to assess the scenarios (Table 28), the result is similar. Scenario 3 is still perceived as the most positive, followed by Scenario 2 and 5. Scenario 3b and 5b do not add much compared to the business-as-usual.

Table 27 – Equal weighted scores for each scenario for raceway systems

	Scenario 1	Scenario 2	Scenario 3	Scenario 3b	Scenario 4	Scenario 5	Scenario 5b
Weighted Social Score	0.00	0.03	0.09	0.02	0.03	0.03	-0.01
Weighted Economic Score	0.00	-0.18	-0.19	-0.18	-0.21	-0.18	-0.16
Weighted Environmental Score	0.00	0.21	0.22	0.19	0.22	0.21	0.18
Weighted Total Score	**0.00**	**0.07**	**0.12**	**0.03**	**0.05**	**0.07**	**0.01**

Table 28 – Stakeholder weighted scores for each scenario for raceway systems

	Scenario 1	Scenario 2	Scenario 3	Scenario 3b	Scenario 4	Scenario 5	Scenario 5b
Weighted Social Score	0.00	0.02	0.05	0.00	0.02	0.02	-0.03
Weighted Economic Score	0.00	-0.17	-0.18	-0.17	-0.20	-0.17	-0.15
Weighted Environmental Score	0.00	0.25	0.26	0.21	0.27	0.25	0.22
Weighted Total Score	**0.00**	**0.11**	**0.14**	**0.04**	**0.09**	**0.11**	**0.04**

Key takeaways from the MCA for raceway aquaculture for the formulation of reduction pathways are the following:

- The use emerging feed materials is evaluated positively yet is expected to increase operational costs.
- IMTA is an interesting production practice than is expected to improve the environmental performance of raceway aquaculture, including a reduction of GHG emissions. It is expected to come with higher CAPEX and OPEX.
- The use of AI-based tools is evaluated quite negatively for raceway aquaculture.
- The renewable energy is evaluated positively although an increase in operational expenditures is foreseen.
- There are little differences in the scoring of the scenarios, slightly favouring the scenarios in which all tools are used.

5.3.1.5 RAS aquaculture

Across the tools assessed, the stakeholders find that renewable energy is the tool that aligns most clearly with the current regulatory landscape for RAS aquaculture. Accordingly, prior research highlighted that aquaculture decarbonisation requires lowering energy-intensive inputs, improving feed and energy efficiency, and reducing fuel use across production systems (He et al., 2018). This focus is reinforced by life-cycle assessment studies showing that electricity consumption is a dominant environmental hotspot in RAS, positioning energy efficiency and low-carbon technologies as the most direct pathways for meeting environmental and climate expectations (Bohnes et al., 2019; Bergman et al., 2020).

Findings indicate that AI based tools are expected to have a positive impact on worker safety in RAS facilities, as manual tasks such as water-quality monitoring, sampling and inspection continue to expose operators to chemical, biological and ergonomic risks. Emerging AI systems, including sensor networks, computer vision and predictive analytics, enable continuous system monitoring, early anomaly detection and reduce the frequency of direct manual interventions, hence, could improve overall safety in aquaculture operations (Capetillo-Contreras et al., 2024; Ragab et al., 2024; Ma et al., 2025).

In terms of skills of the workforce, the emerging feed materials appear to be the tool that is best supported within the RAS system, according to the stakeholders. As observed in other literature, the feed formulation, nutritional monitoring and ingredient evaluation are well-established practices in aquaculture, and industry reviews of insect meals, algal proteins and single-cell protein emphasis that these innovations can be incorporated into existing feeding strategies rather than requiring entirely new production paradigms (Glencross, 2020; Rumbos et al., 2021).

According to the economic criteria, we found that capital expenditure requirements were identified only for Breeding Programs, AI-based Tools and IMTA, with IMTA showing the highest associated costs. Stakeholders identified Improved Energy Use Efficiency as the measure with the greatest potential to reduce operational costs, reflecting the high energy intensity of RAS and the demonstrated impact of efficiency measures on lowering operating expenditures (Badiola et al., 2018). Breeding Programs were ranked second, consistent with evidence that genetic improvement enhances growth performance and feed conversion efficiency, thereby reducing feed-related costs, which represent the largest share of operational expenses in aquaculture (Gjedrem & Rye, 2018; Houston et al., 2020).

From the stakeholder session, we learn that RAS industry is not ready for Ecosystem conservation and restoration support, as current evaluations show major economic and technical limitations. Likewise, Vielma et al. (2022) report that many RAS farms remain unprofitable, suggesting the sector lacks the capacity required for more complex restoration efforts. Industry readiness is similarly low for IMTA and purchasing voluntary carbon credits, while readiness is higher for emerging feed materials and breeding programs.

Similar to the previous findings, the renewable energy is expected to deliver the largest overall reduction in greenhouse-gas emissions in RAS systems. Artificial-intelligence applications are also increasingly demonstrated to support biodiversity conservation by improving species detection, habitat monitoring, and ecological forecasting at large spatial scales (Alotabi and Nassif, 2024; Ullah et al., 2025). None of the tools for RAS are perceived to have a negative impact on water and land usage, as supported by some studies that RAS notably exhibits lower water and land-use intensity (Tian and Dong, 2023; Brown et al., 2024).

Table 29 - MCA results for RAS systems

Category	Criterion	Equal weight (total = 100%)	Stakeholder Weighting	Emerging feed materials	Breeding Programs	AI-based tools	IMTA	Renewable energy	Improvement of energy use efficiency	Low trophic aquaculture	Carbon credits	Marine ecosystem restoration
Social	Match with current regulatory landscape	8.3	7.8	-0.14	0.29	0.29	0.17	0.86	0.57	0.67	-0.43	-0.29
Social	Number of employees in the sector	8.3	6.8	0.29	0.33	0.00	0.80	0.33	0.00	0.60	0.17	0.83
Social	Potential safety implications	8.3	5.0	0.14	0.57	1.29	0.50	0.29	0.57	0.67	-0.43	0.29
Social	Covered by skills in sector	8.3	3.7	1.14	0.71	0.00	0.00	0.43	0.00	0.83	-0.14	-0.57
Economic	CAPEX	8.3	16.5	0.00	-0.67	-1.33	-2.00	0.00	0.00		0.00	0.00
Economic	OPEX	8.3	12.3	-1.75	-1.00	-1.25	-2.00	-0.75	-1.50		-0.50	-0.25
Economic	Operational cost reductions	8.3	10.7	1.00	1.57	1.14	0.00	1.14	2.00	0.83	0.14	0.43
Economic	Industry Readiness	8.3	5.5	1.29	1.14	0.14	-0.33	1.00	0.29	0.50	-0.14	-1.00
Environmental	GHG emissions from production	8.3	9.8	1.00	0.20	0.40	0.30	1.50	0.40			
Environmental	Impact on wild populations and ecosystems	8.3	7.9	1.00	0.43	1.17	0.50	0.57	0.57	0.83	-0.43	1.00
Environmental	Water usage	8.3	3.8	0.43	0.86	0.43	0.83	0.71	0.86	0.80	0.14	0.29
Environmental	Land usage	8.3	10.2	0.67	1.00	0.50	0.00	0.50	0.83	0.33	0.00	1.17

A positive number means the tool has a positive impact on the criterion (and vice versa). See Table 15 for a detailed explanation of the Likert scale used (-2 to 2).

When combining the scores from each tool into the scenarios, Scenarios 2 and 5 score the best for both equal and stakeholder weighting. With equal weighting, Scenario 3 scores second best, while Scenario 5b scores second best with the stakeholder weighting. The environmental scores are relatively equal (and high) for both weighting exercises, while the stakeholders put a higher importance on the economic criteria compared to the equal weighting.

Table 30 - Equal weighted scores for each scenario for RAS systems.

	Scenario 1	Scenario 2	Scenario 3	Scenario 3b	Scenario 4	Scenario 5	Scenario 5b
Weighted Social Score	0.00	0.13	0.12	0.09	0.13	0.13	0.09
Weighted Economic Score	0.00	-0.03	-0.04	-0.04	-0.05	-0.03	-0.03
Weighted Environmental Score	0.00	0.22	0.21	0.17	0.21	0.22	0.20
Weighted Total Score	**0.00**	**0.32**	**0.29**	**0.21**	**0.28**	**0.32**	**0.26**

Table 31 - Stakeholder weighted scores for each scenario for RAS systems.

	Scenario 1	Scenario 2	Scenario 3	Scenario 3b	Scenario 4	Scenario 5	Scenario 5b
Weighted Social Score	0.00	0.09	0.08	0.05	0.08	0.09	0.06
Weighted Economic Score	0.00	-0.13	-0.15	-0.13	-0.17	-0.13	-0.11
Weighted Environmental Score	0.00	0.20	0.19	0.15	0.19	0.20	0.19
Weighted Total Score	**0.00**	**0.17**	**0.12**	**0.08**	**0.10**	**0.17**	**0.15**

Key takeaways from the MCA for RAS aquaculture for the formulation of reduction pathways are the following:

- The use of emerging feed materials is evaluated positively yet is expected to increase operational costs.
- IMTA is an interesting production practice than is expected to improve the environmental performance of aquaculture, including a reduction of GHG emissions. It is expected to come with higher CAPEX and OPEX.
- The use of AI-based tools is seen as attractive tools to reduce GHG emissions from the sector.
- Improving energy use efficiency is evaluated as a tool that can increase operational expenditures.
- The renewable energy is evaluated positively although an increase in operational expenditures is foreseen.
- There are little differences in the scoring of the scenarios, slightly favouring the scenarios in which all tools are used.

5.3.2 Limitations

5.3.2.1 PESTEL Analysis for EU Aquaculture

Prior to the SWOT analyses, a brief PESTEL analysis for the European aquaculture sector was conducted. This analysis aimed to shed light on the key factors that may influence the feasibility and the pace at which the transition toward carbon neutrality is to take place.

P - Political Factors

The EU aquaculture sector operates under a strategic framework driven by European policies aiming for sustainability, competitiveness, and resilience (European Commission 2021; European Court of Auditors 2023).

- Strategic Policy Alignment: The sustainable development of aquaculture is a main objective of the Common Fisheries Policy (CFP)(European Court of Auditors 2023), and it is promoted by the European Green Deal as a source of protein with a lower carbon footprint (European Commission 2021). Aquaculture is also an important component of the EU sustainable blue economy and the European Ocean Pact (European Commission 2025).
- **The Farm to Fork Strategy** sets specific objectives for aquaculture, including the significant increase of organic aquaculture by 2030 and the reduction of antimicrobial use for farmed animals and in aquaculture by 50% by 2030 (European Commission 2020b).
- **Strategic Guidelines**: The European Commission provides strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030. Member States (MS) are required by the CFP Regulation to draw up Multi-annual National Strategic Plans (MNSPs) for aquaculture, which should be aligned with the Commission's guidelines (European Commission 2021).
- **EU Funding**: EU funds are allocated through mechanisms like the European Maritime and Fisheries Fund (EMFF, 2014-2020) and its successor, the European Maritime, Fisheries and Aquaculture Fund (EMFAF, 2021-2027) (€1.0 billion allocated). The overall aim of CFP support is to ensure long-term environmental sustainability and achieve economic and social benefits (European Court of Auditors 2023)

- Policy Support Mechanisms: The Commission launched the EU Aquaculture Assistance Mechanism ([15]) to support MS and stakeholders in implementing the strategic guidelines, offering logistical, administrative, and technical assistance.

E - Economic Factors

The EU aquaculture sector is characterized by stagnation in production volume alongside increases in value, operating within a highly import-dependent market (European Court of Auditors 2023) (Scientific Technical and Economic Committee for Fisheries 2025).

- **Market Position**: The EU aquaculture sector is small, accounting for less than 1% of global aquaculture production (1.1 million tonnes in 2020). Imports represent more than 60% of the EU's seafood supply. (European Court of Auditors 2023; Scientific Technical and Economic Committee for Fisheries 2025))
- **Production Trends**: Between 2014 and 2020, EU aquaculture production volume remained relatively stable. However, the value of production increased by 25% during the same period. In 2022, the total nominal turnover was €4.8 billion (European Court of Auditors 2023; Guillen et al 2025).
- **Competitiveness and Profitability**: The sector has experienced increased value and strong recovery in Gross Value Added (GVA) and Earnings Before Interest and Taxes (EBIT) in 2021 and 2022, suggesting resilience (Scientific Technical and Economic Committee for Fisheries 2025). However, key economic indicators like Return on Investment (ROI), Future Expectations of the Industry (FEI), labour productivity, and capital productivity show declines or challenges, indicating a need for improvements in efficiency and investment strategy (Scientific Technical and Economic Committee for Fisheries 2025).
- **Cost Pressures**: Rising operational costs, particularly high energy prices and increased raw material (feed) prices (which rose 32% between 2021 and 2023), negatively impact profitability (Scientific Technical and Economic Committee for Fisheries 2025). Competition from international markets where production costs may be lower (e.g., wages, regulatory compliance) poses a threat to competitiveness (Scientific Technical and Economic Committee for Fisheries 2025).

([15]) https://aquaculture.ec.europa.eu/

- **Financial Allocation**: EMFF support allocated to aquaculture (€1.2 billion for 2014-2020) had a relatively low absorption rate compared to other priorities (European Court of Auditors 2023).
- **Structure**: Production is highly concentrated in four countries (Spain, France, Greece, and Italy), accounting for 64% of total EU aquaculture volume in 2022 (European Court of Auditors 2023).

S - Social Factors

Social factors revolve around employment stability, community impact, cultural heritage, and the crucial issue of public perception and acceptance.

- **Employment**: The sector had approximately 41 000 full-time equivalent (FTE) employees in 2022 (Scientific Technical and Economic Committee for Fisheries 2025).
- **Rural Contribution**: Aquaculture generates jobs and economic opportunities, particularly supporting rural coastal communities and remote island areas where alternative employment may be limited (European Commission 2021; Publications Office of the European Union 2022).
- **Social Acceptance (or lack thereof)**: Social acceptance is a key priority and a major challenge (European Commission 2021))(Scientific Technical and Economic Committee for Fisheries 2025). A negative perception of aquaculture activities by local stakeholders, often related to environmental impact, can be an obstacle to establishing new facilities (Billing et al 2021; European Commission 2021).
- **Consumer Trends**: There is increasing consumer demand for sustainable products, high quality standards, and local origin information (European Commission 2021; Publications Office of the European Commission 2021). Efforts are needed to improve communication and transparency about EU aquaculture activities to dispel "myths" and highlight benefits (European Commission 2021; Publications Office of the European Union 2022).
- **Cultural Heritage**: Traditional freshwater aquaculture, particularly pond fish production (e.g., carp), maintains cultural heritage and culinary traditions in Central and Eastern Europe, often linked to seasonal consumption (Christmas/Easter)(Publications Office of the European Commission 2021).
- **Animal Welfare**: Animal welfare is an increasing public concern, though it has not featured prominently in scientific literature. Improving welfare regulations is considered a clear priority (European Commission 2021)(

(Publications Office of the European Union 2022), see also EU Reference Centre for Animal Welfare ([16]).

T - Technological Factors

Innovation is driven by the need for sustainability, efficiency, and resilience, focusing heavily on modern production systems and alternative feeds.

- **Advanced Production Systems**: The development and adoption of high-tech production systems are emphasized:
  - **Recirculating Aquaculture Systems (RAS)**: These systems offer a fully controlled environment, low water use, full disease control, and efficient land use, enabling production close to markets. However, they require significant investment, high energy use, and specialized staff (European Commission 2021)(Publications Office of the European Commission 2021).
  - **Integrated Multi-Trophic Aquaculture (IMTA)**: This involves cultivating species from different trophic levels together to utilize waste products (European Commission 2021)(Publications Office of the European Commission 2021).
- **Feed Innovation**: There is a critical need to ensure sustainable feed systems by developing and using emerging feed materials, such as algae or insects, to limit reliance on fish meal and fish oil sourced from wild stocks (European Commission 2021; European Court of Auditors 2023). Emerging feed materials are also developed to reduce dependency on wild-caught fish for fish oil and meal (Van Riel et al 2023) and reduce the environmental impacts of aquaculture feed (Modahl and Brekke 2022; Serra *et al* 2024).
- **Modernization**: Investments in modernization or the development of closed recirculation systems are popular funding measures (European Court of Auditors 2023). Funds are directed towards the green transition in aquaculture, supporting the modernization of fish farms into more environmentally friendly and climate-adapted facilities (Scientific Technical and Economic Committee for Fisheries 2025).
- **Knowledge Transfer**: Promoting research, innovation, and the transfer of knowledge and best practices is a strategic action supported by EU funds (European Commission 2021)(European Court of Auditors 2023).

([16]) EURCAW Aqua - Home

E - Environmental Factors

The environmental impacts of aquaculture are under regulatory scrutiny. There are weaknesses in implementation, monitoring, and specific challenges related to climate change and production inputs. On the other hand, the environmental benefits of aquaculture are promoted as well.

- **Sustainability Goal**: Aquaculture is positioned as contributing to a sustainable food system, offering a protein source with a low carbon footprint compared to terrestrial animal husbandry (Tsakiridis et al 2020). This goes especially for non-fed species like shellfish (European Commission 2021)(European Court of Auditors 2023).
- **Negative Impacts**: Potential negative environmental impacts include sedimentation, water pollution/effluents (nitrogen/phosphorus discharge), habitat degradation, contamination, genetic interaction (escapes), and the spread of diseases and parasites. The introduction of alien species is also a concern (European Commission 2021)(European Court of Auditors 2023)((Publications Office of the European Union 2022).
- **Climate Change**: The sector must adapt to the disruptive impacts of climate change, such as drought (affecting freshwater farms) and potential sea-level rise/floods (Cubillo et al 2021; European Commission 2021).
- **Environmental Benefits**: Certain types of aquaculture offer ecosystem services, such as biodiversity conservation, water/landscape management, carbon capture, and reduction of nutrient concentration (e.g., shellfish water filtering capacity or extensive pond fish production) (European Commission 2021)(Publications Office of the European Commission 2021)(Publications Office of the European Union 2022).
- **Policy Gaps in MS**: Some key national strategies for the environment, such as Marine strategies and River Basin Management Plans (RBMPs), do not properly take aquaculture into account (European Court of Auditors 2023).
- **Monitoring Deficiency**: At EU level, there are currently no reliable indicators or monitoring data available to track the sector's overall environmental sustainability or the effectiveness of increased EU funding toward this goal. Various methodological challenges hamper the consistency and comparability of LCA studies (Bohnes et al 2019). The development of Product Environmental Footprint Category Rules (PEFCR) for aquaculture addresses this problem. In May 2025, the PEFCR for marine fish was accepted.

L - Legal Factors

Aquaculture, unlike fisheries, is not an exclusive EU competence but it is still regulated by EU rules for environmental protection and health. The first non-binding strategic guidelines for the sustainable development of EU aquaculture were adopted in 2013. New strategic guidelines were adopted in 2021 and EU countries have reviewed their national strategies in light of the new guidelines.

- **Regulatory Complexity**: The regulatory framework is "diverse and extremely complex," encompassing a wide range of EU instruments and MS legislation, relating to everything from land-use planning to food safety and animal health (Publications Office of the European Union 2022).
- **Administrative Barriers (Licensing)**: Member States' spatial planning and licensing procedures still hamper aquaculture growth (European Court of Auditors 2023). Producers frequently face a high administrative burden, complicated procedures, and long licensing processes. In some regions (e.g., Galicia, Spain; Italy), issues like competition requirements or uncertainty regarding license duration have discouraged investment (European Court of Auditors 2023).
- **Spatial Planning Mandates**: Maritime spatial planning (MSP) is mandatory. While implementation has been slow in some Member States, all now have plans. Two Staff Working documents have been prepared to provide relevant authorities in EU Member States and other policymakers with potential solutions to the challenges of aquaculture (SWD(2024) 281 final for freshwater and land-based aquaculture (SWD(2024) 107 final for marine aquaculture).
- **EU Legislation Enforcement**: The legal framework seeks to regulate impacts in line with best practice and is largely effective in mitigating many negative impacts (Publications Office of the European Union 2022). Reportedly, the interpretation of EU legislation, particularly regarding water quality and environmental impact (Water Framework Directive/Marine Strategy Framework Directive), is not uniform across all MS, undermining the level playing field for producers (European Commission 2021).
- **Specific Legal Concerns**: There are emerging areas where the regulatory framework needs strengthening, specifically concerning animal welfare and the framework surrounding the aquaculture of macroalgae and microalgae (Publications Office of the European Union 2022).

For each of the five scenarios a SWOT analysis diagram has been developed, incorporating results of the analyses conducted in tasks 1-3, the expert focus groups and the validation interviews with experts to validate the findings of the gaps and limitations:

5.3.3 SWOT Scenario Business as usual

The first scenario (Business-as-usual) assumes no policy or technological change. The production is based on trends and estimations made accordingly.

Scenario 1 assumes a growth rate of 1.6% for all production systems. Scenario 1b assumes different grow rates for fed (1%) and non-fed aquaculture (2%). Both scenarios are included in the SWOT below.

Table 32 – SWOT analysis for Scenario 1 and 1b

Strengths	Weaknesses
• Mature sector that has proven viability. • 1b: Low-trophic (non-fed) aquaculture is credited for its environmental benefits. • Aquaculture products have low carbon footprint compared to other food products containing protein. • Aquaculture products contribute to food security.	• Current trends are not in line with what we assume (fed aquaculture is growing faster than non-fed). • The sector does not grow 1.6% per year for all systems.
Opportunities	**Threats**
• There is policy support for aquaculture. • There is consumer demand for fish products.	• Lack of space, both on land (pond) and on sea (cages, non-fed). • Weak regulatory landscape is a barrier to further growth.

5.3.4 SWOT Scenario Alignment with EU Climate Targets

The second scenario aligns with the EU climate targets set under the ESR and Green Deal, assuming proportional emissions reduction in aquaculture to meet the 2030, 2040, 2050 climate goals. This scenario includes the following tools: emerging feed materials, AI-based tools, renewable energy, IMTA and improvement of energy use efficiency.

Table 33 – SWOT analysis for Scenario 2

Strengths	Weaknesses
• Some of the scenarios are ready to implement (e.g. improvement of energy use efficiency) and will reduce the costs for the sector. • AI-based tools will reduce the costs of operations because of increased efficiency. • AI-based tools could reduce the impact on wild populations and ecosystems, animal welfare, and reduce mortality. • Using co-products for feed materials would make an aquaculture company more circular. • Aquaculture products contribute to food security.	• IMTA is still a 'new' concept (does not match with current regulatory landscape, costly to implement, industry not ready). • AI-based tools can currently not observe fish behaviour well enough. • Currently low adoption rate of emerging feed materials, the industry does not seem ready for it. • Insect production for feed is energy intensive.
Opportunities	**Threats**
• The energy mix per Member State will become more renewable, their climate impact will reduce. • AI-based tools are in rapid development and can create new applications and data driven decisions. Due to these developments, the technology will become more affordable. • Using co-products for emerging feed materials will result in a lower carbon footprint. • With emerging feed materials, there will be less reliance on feed import from outside the EU (fish meal, fish oil, soybean). • Electrification of fishing vessels means technologies are developed.	• AI-based tools need computational capacity, which is energy intensive (displacement effect: energy is saved in aquaculture sector but consumed in data centres). • Complex regulations make it difficult to implement emerging feed materials. • There is little demand for 'low carbon products' from consumers. • Member States are dependent on electricity prices and renewable energy rates of their country, which influences their competitiveness with the EU sector. • There is a disparity in marginal abatement costs between EU Member States.

5.3.5 SWOT Scenario Prioritise low investment

The third scenario prioritizes low-cost tools such as replacing conventional feed with emerging feed materials, promoting non-fed aquaculture, IMTA and conducting energy audits. Scenario 3 and the extended Scenario 3b are considered together in this SWOT. Scenario 3 includes the following tools: emerging feed materials, IMTA and improvement of energy use efficiency. Scenario 3b also includes carbon credits.

Table 34 – SWOT analysis for Scenario 3 and 3b

Strengths	Weaknesses
• There is policy support for alternative breeding. • Aquaculture products contribute to food security. • 3b: carbon credits are a relatively cheap way to reduce emissions.	• IMTA is still a 'new' concept (does not match with current regulatory landscape, costly to implement, industry not ready). • There is reluctance of adoption from the feed companies. • Complicated EU legislation about using waste from the processing back into the fish feed. • The high carbon footprint of some emerging feed materials is a concern. • Individual farmers are not in control for the renewable energy. The infrastructure is managed on EU level. • There could be a conflict of regulations, when ponds are in Natura2000. Ponds are seen as nature beneficial, but that limits co-production with electricity.
Opportunities	**Threats**
• There is funding available. • Regulatory landscape is a match, for feed, breeding and energy use efficiency. • Improvement of energy use efficiency will result in cost reductions. • The renewable energy tool will result in the highest GHG reduction potential (95%). • 3b: the voluntary carbon market is in place • 3b: only small differences in marginal abatement costs between EU Member States.	• Availability of emerging feed materials is a concern. • 3b: debatable actual GHG reductions of the voluntary market. • Competition with others, long-term supply of credits (there is not enough to offset things).

5.3.6 SWOT Scenario Prioritise the resilience of the sector to climate change

The fourth scenario focuses on building climate resilience by replacing conventional materials with emerging feed materials, integrating multi-trophic aquaculture in existing farms, improving energy use efficiency, and using AI-based tools for pathogen detection or harmful events. The strengths, weaknesses, opportunities and threats of this scenario are included in Table 35 below. There is much overlap with Scenario 2, only renewable energy is not included in Scenario 4.

Table 35 – SWOT analysis for Scenario 4

Strengths	Weaknesses
• For emerging feed materials, AI-based tools, IMTA, and improvement of energy use efficiency, the same applies as in the SWOT for Scenario 2. • Capital investments are lower compared to Scenario 2/5. • There is no extra land needed to produce renewable energy (since the tool of renewable energy is not included).	• For emerging feed materials, AI-based tools, IMTA, and improvement of energy use efficiency, the same applies as in the SWOT for Scenario 2. • Without the Renewable energy, GHG emissions from production are difficult to reduce. • The tools included in this scenario are all very costly.
Opportunities	**Threats**
• For emerging feed materials, AI-based tools, IMTA, and improvement of energy use efficiency, the same applies as in the SWOT for Scenario 2. • Without renewable energy, there will be less competition between EU Member States about energy prices.	• For emerging feed materials, AI-based tools, IMTA, and improvement of energy use efficiency, the same applies as in the SWOT for Scenario 2.

5.3.7 SWOT Scenario Maximum potential for emission reduction

Finally, the fifth scenario maximises the CO_2eq emissions reduction without cost constraints by fully deploying emerging feed materials and breeding, AI-based tools, renewable energy, extensive IMTA systems across the EU, and improvement of energy use efficiency. Scenario 5 is similar to Scenario 2 (includes same tools) but differs in adoption level. Scenario 5b is different because it includes the purchase of voluntary carbon credits and funding ecosystem conservation and restoration support as well. Therefore, mainly Scenario 5b is considered in this SWOT.

Table 36 – SWOT analysis for Scenario 5 and 5b

Strengths	Weaknesses

• The same applies as in the SWOT for Scenario 2. • 5b: carbon credits and ecosystem conservation and restoration support could increase the number of employees in the sector. • 5b: carbon credits and ecosystem conservation and restoration support are relatively cheap tools to implement.	• The same applies as in the SWOT for Scenario 2. • 5b: the industry readiness for carbon credits and ecosystem conservation and restoration support is low. • 5b: carbon credits and ecosystem conservation and restoration support are not yet covered in regulation. Unclear for farmers how to show that they contribute.
Opportunities	**Threats**
• The same applies as in the SWOT for Scenario 2. • 5b: carbon credits and ecosystem conservation and restoration support would contribute to EU's sustainability goals.	• The same applies as in the SWOT for Scenario 2.

5.3.8 Identification of key parameters for sensitivity analysis

An initial inventory of parameters that could be used in the sensitivity analysis, and which task they come from, is presented below in Table 37.

Table 37 – Possible parameters to investigate with MCA and the relevant tasks information can be sourced from

Parameter	Relevant task
Energy price	Task 1
CO_2 emissions *total/per t of LW/related to feed (transportation)/related to energy use*	Task 1
Electricity use	Task 1
Number of different systems used in MS	Task 1
Production (t)	Task 1
Production levels for 2030/2040/2050 per MS	Task 2
Electricity price	Task 3
Energy mix price	Task 3
FCR (feed conversion ratio)	Task 3
Feed market price	Task 3
Feed consumption	Task 3
AI based feeding	Task 3
Fishmeal market price	Task 3

Parameter	Relevant task
Fishmeal used	Task 3

The expert focus groups were used to verify this list and identify additional parameters. The above list of parameters was presented to the experts in the focus groups, followed by the question which other parameters they would add or remove. None of the parameters were suggested to be removed. Experts suggested to add some parameters, such as:

- Legal support framework and enforcement
- Space availability for extensive aquaculture production
- Water availability
- Conflict of interest with other uses
- Circularity
- Environmental parameter variations (e.g. changing temperatures due to climate change)
- Market acceptance of the tool
- Financial incentives

During the stakeholder workshop session, some additional inputs were suggested to sharpen the sensitivity analysis. For instance, legal frameworks and enforcement capacity were highlighted as essential parameters, while space availability and retailer acceptance were emphasised as critical external constraints that could influence the viability of several tools. There was also a question raised concerning the reliability of adoption-rate assumptions and it is recommended to further examine the recommended parameters.

Taken together, these inputs indicate that the sensitivity analysis should not be limited to technical performance or cost variables. Instead, it must also account for regulatory, spatial, financial, and market-related conditions to more accurately capture the range of uncertainties that affect the implementation of sustainable tools in aquaculture systems.

Due to the limitations of this study, it was not possible to incorporate all of these proposed parameters into the sensitivity analysis. The analysis focuses on the most influential technical and cost-related factors. Future research should expand the analysis to include other potential parameters, such as regulatory, spatial, environmental, financial, and market-related parameters, which would support a more thorough analysis of the conditions that shape the feasibility and uptake of sustainable aquaculture tools.

6 Proposed reduction pathways

6.1 Summary

This study evaluates and proposes reduction pathways for the 5 aquaculture production systems. The reduction pathways consist of time-specific adoption targets for the relevant tools. Building upon the scenario analysis (presented in Chapter 5) it is concluded that, in order to achieve carbon neutrality, all available tools (which have been presented in Chapter 4) need to be implemented and compensatory measures (presented in Chapter 4) also need to be taken. The realistically desirable pace and adoption rates however vary per production type.

The MCA and stakeholder consultations informed the formulation of adoption pathways per tool per aquaculture type. The calculation tools presented in Chapter 5 are used to calculate emission reduction achieved for the pathways and the MACs. For most systems, MACs remain relatively stable across the short-term (2026–2030), medium-term (2026–2040), and long-term (2026–2050) periods. However, the non-fed production system shows a significant increase in MAC during 2040 and 2050 compared to 2030.

While the MAC for pond, raceways, RAS, and cage systems ranges between 46–71 €/t CO_2eq, the non-fed system reaches up to 221 €/t CO_2eq. This discrepancy can be explained by (i) the considerably higher investment costs for adopting tools with higher production volume of the non-fed system; (ii) the already lower emissions of the system making further improvements more difficult; as well as (iii) the smaller range of tools that can be applied to this production system.

This assessment, in conjunction with interviews and the SWOT analysis, is the basis for the formulation of policy recommendations, which are formulated along the following eight lines:

- Drive energy efficiency and digitalization
- Support decarbonisation of feed and raw materials
- Accelerate the Renewable energy for transport and operations
- Support breeding programs for resilience and efficiency
- Continue support for IMTA
- Developed recognized methods for carbon offsetting
- Stimulate market development and consumer awareness for low-carbon footprint
- Strengthen the aquaculture regulatory framework increasing clarity and specificity and streamlining licensing

6.2 Objectives

The objective of task 5 was to propose recommendations for carbon neutrality by 2050 and CO_2eq emissions reduction pathways with intermediate milestones for 2030 and 2040 being consistent with the targets set in the Effort Sharing Regulation. This is done using the results collected in the previous tasks.

6.3 Guidance in the interpretation and shortcomings of the results of the scenarios

In reading and analysing the scenarios and pathway, the following limitations should be taken into account.

This study provides an insight into the potential to reduce GHG emissions from aquaculture, and the costs associated with that. Calculations assume a uniformity in aquaculture practices that is not found in reality.

The pathways are prepared based on the scenario analysis (task 3) and stakeholders' input (task 4). The study team sought for an equal representation of stakeholders, taking into account experience with aquaculture types and location, yet acknowledge that there is always a risk of biased stakeholder input.

It is assumed that the adoption of IMTA leads to a transversal reduction in GHG emissions. The argument is that IMTA systems have various benefits (including effluent management, better FCR, improved animal health) that together results in a reduction of CO_2eq emissions. A similar assumption is made for emissions reductions expected from the use of AI-based tools.

The GHG emission reduction potential for each of the tools is considered in isolation and when a combination of tools is adopted, it is not assumed this will change reduction potential positively or negatively.

The method to calculate GHG emissions is based on LCA methodology. In LCA methodology, results are dependent on the system boundaries, choice of impacts and allocation. When reading the scenarios and pathways, the following should be taken into account.

- GHG emissions from feed production contribute to the GHG emissions of the aquaculture sector. The decision to consider the emission stemming from feed production in scope is consistent with the PEF-CR Marine Fish ([17]), which claims that “Feed for fish production is within the system

([17]) https://www.marinefishpefcr.eu/

boundaries of this PEFCR, meaning that the feed production shall be included in the PEF profile of farmed marine fish products". The consequence is that a significant part of the GHG emissions result from activities beyond direct control of aquaculture producers.

- In this study, the only impact category looked at is global warming, with an analysis of CO_2eq emissions. All aquaculture production processes, as well as the production of feed, have others impacts that are not studied in this analysis.
- The choice for allocation method has impact on calculated GHG emissions. Typically, economic allocation is used, in line with the PEFCR Marine Fish, which states that "that economic allocation shall be used when allocation cannot be avoided". Consequentially, the use of by-products is, from a GHG emission perspective, favourable.

With the exception of Scenario 1b, it is assumed that the share of the various aquaculture types to total production remains equal. Given that per unit CO_2eq emissions vary between the aquaculture types, a future change in shares can support the transition towards carbon neutrality. This option is not included in the scenarios and pathways.

In Scenario 1b, like in task 1, the estimation of emissions of non-fed aquaculture does not take into account the carbon sequestered in the shell. The choice to not consider this carbon-negative process was made because of the difficulty to estimate how much of the carbon captured is re-released into the environment.

The presented marginal abatements costs are illustrative and scenario-dependent—they show the relative cost-effectiveness of different options, are strongly influenced by upstream decarbonisation in feed, fisheries, agriculture and energy, and are dynamic over time as technologies become cheaper. Being total average costs, these include both the costs associated with internal abatement measures implemented within aquaculture operations; and compensation for indirect, upstream emissions (feed, energy, transport, hatcheries) that, in a strict Climate Law perspective, should be addressed within those other sectors rather than by aquaculture alone.

6.4 Results

6.4.1 Proposed reduction pathways

The reduction pathways below have been developed per production type yet share a set of foundational assumptions, as described below.

The MCA and stakeholder consultations informed the formulation of adoption pathways per tool per aquaculture type. There is a general consensus among stakeholders that tools (outlined in section 3.3) to increase energy use efficiency and stimulate energy savings are the easiest to implement. These areas are seen as a quick way to contribute to GHG emissions reduction and at the same time provide savings to the operational expenditures of companies. Producers have experience with energy savings and steps to improve energy use efficiency, yet for the sake of the model the current adoption rate is set at zero, in that it assumes that there still is potential to review energy use efficiency within all companies. The proposed tool “energy use efficiency” is expected to be adopted by all companies by 2034.

In all proposed reduction pathways, the adoption rate of the renewable energy reflects the EU’s progress and ambitions in shifting towards renewable energy sources. All pathways are based on the observation that in 2024, 25.4% of all final energy consumed in the EU was obtained from renewable energy sources. The revised Renewable Energy Directive (EU/2023/2413) raises the EU's binding renewable target for 2030 to a minimum of 42.5% share of renewables in the energy mix. EU aims for climate neutrality by 2050. It is assumed that growth of the share of renewable energy follows a linear path between 2026 – 2030 and between 2030-2050. It is also assumed that the aquaculture sector, for its renewable energy use, follows the same trajectory either using renewable energy from the grid or by producing it on site.

AI is seen as promising technology, supporting the aquaculture sector in achieving overall efficiency gains and reducing per unit GHG emissions. The benefits of AI stretch beyond increased efficiency at the farm-level through precision fish farming and improved feeding efficiency. Predicting changes in environmental conditions and subsequently adapting production accordingly, can help to reduce mortality. Adoption rates of the different tools are expected to vary between the production types depending on farming practices and feasibility further discussed below.

6.4.1.1 Proposed reduction pathway for cages

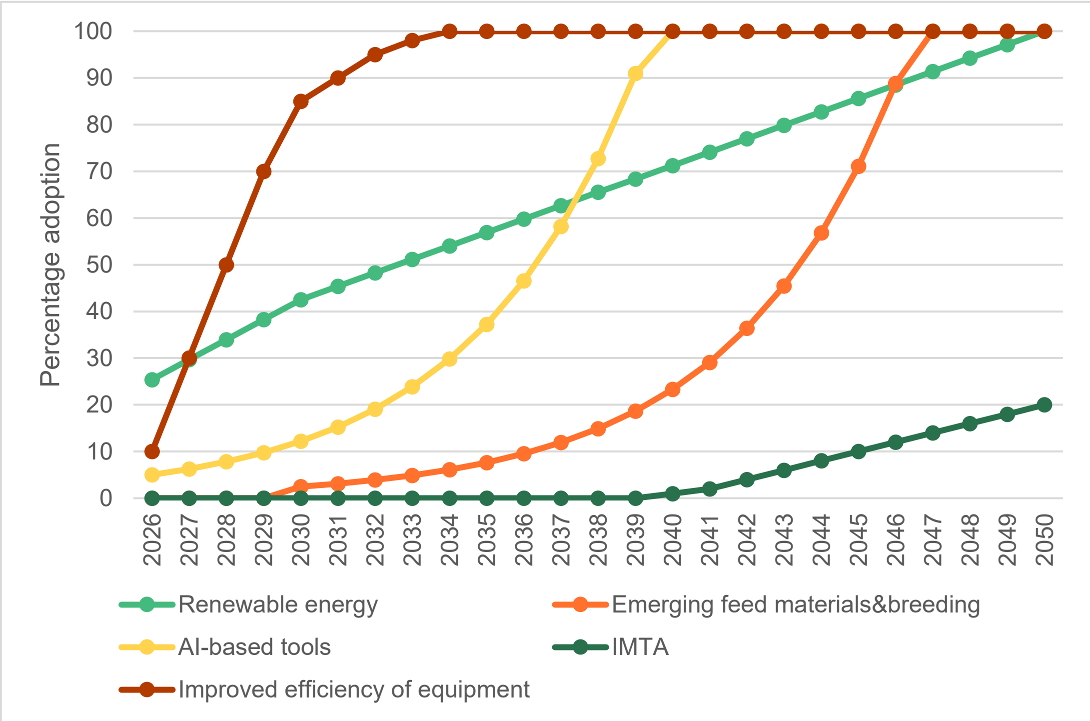
On the basis of the analysis performed, the best proposed reduction pathway for cage aquaculture (Figure 15) would involve:

- Adoption of renewable energy sources in line with the EU’s progress and ambitions.
- Rapid adoption of the tool “improved efficiency of equipment,” with a 100% adoption rate in 2034.
- An assumed adoption of AI-based tools of 5% in 2026, growing by 25% annually. In 2040, adoption rate is then 100%.
- Taking into account that the production and large-scale use of emerging feed materials is challenging due to potential specific biological requirements, and may require dedicated breeding programs to overcome the issues, acknowledging that research is going on, it is

assumed this tool will start to be implemented in 2030 (2.5%) and grow by 25% annually from there onwards. A 100% adoption rate is then achieved in 2047.

- IMTA is a conceptually promising approach to increase the productivity in marine aquaculture while reducing per unit GHG emissions. Given the challenges to develop into a commercially interesting practice for cage aquaculture, for managerial and legislative reasons, the adoption rate is expected to remain zero until 2040. Assuming a slow growth from there on, the adoption rate in 2050 is set at 20%.

Figure 14 – Proposed reduction pathway for cage aquaculture

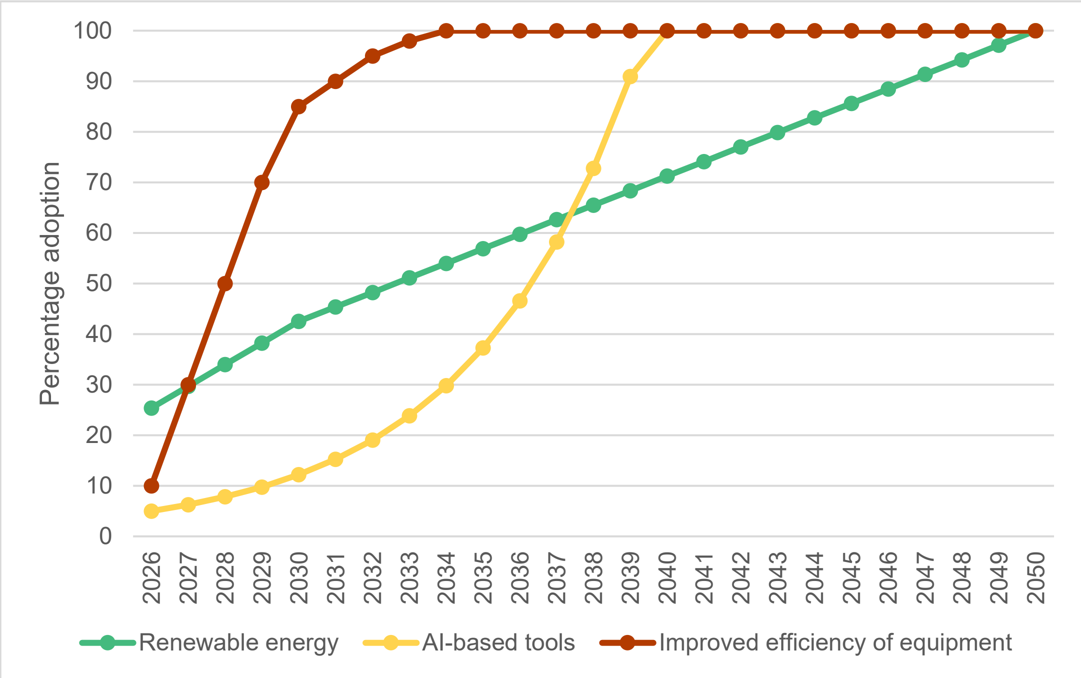


6.4.1.2 Proposed reduction pathway for non-fed aquaculture

The proposed reduction pathway for non-fed aquaculture (Figure 16) includes:

- Adoption of renewable energy sources in line with the EU's progress and ambitions.
- Rapid adoption of the tool "improved efficiency of equipment," with a 100% adoption rate in 2034.
- An assumed adoption of AI-based tools of 5% in 2026, growing by 25% annually. In 2040, adoption rate is then 100%.

Figure 15 – Proposed reduction pathway for non-fed aquaculture

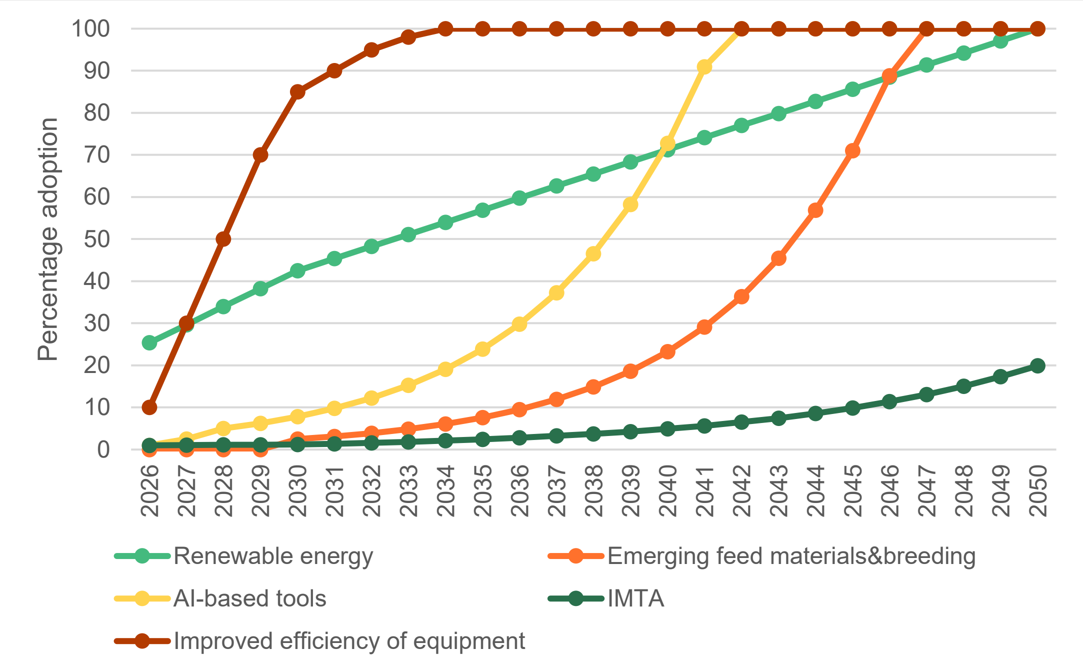


6.4.1.3 Proposed reduction pathway for ponds

The proposed reduction pathway for pond aquaculture (Figure 17) includes:

- Adoption of renewable energy sources in line with the EU's progress and ambitions.
- Rapid adoption of the tool improved efficiency of equipment, with a 100% adoption rate in 2034.
- An assumed adoption of AI-based tools of 1% in 2026, 5% by 2028 and growing by 25% annually from there on. In 2042, adoption rate is then 100%.
- Taking into account that the production and large-scale use of emerging feed materials is challenging, and could require dedicated breeding programs, it is assumed this tool will start to be implemented in 2030 (2.5%) and grow by 25% annually from there onwards. An adoption rate of 100% is achieved in 2047.
- IMTA is a conceptually promising approach to increase the productivity in pond aquaculture while reducing per unit GHG emissions. It is used on small scale as of now. Assuming a slow growth between 2026- and 2030 (5% annually) and faster growth in the period 2030-2050 (15% annually), the adoption rate in 2050 is set at 20%.

Figure 16 – Proposed reduction pathway for pond aquaculture

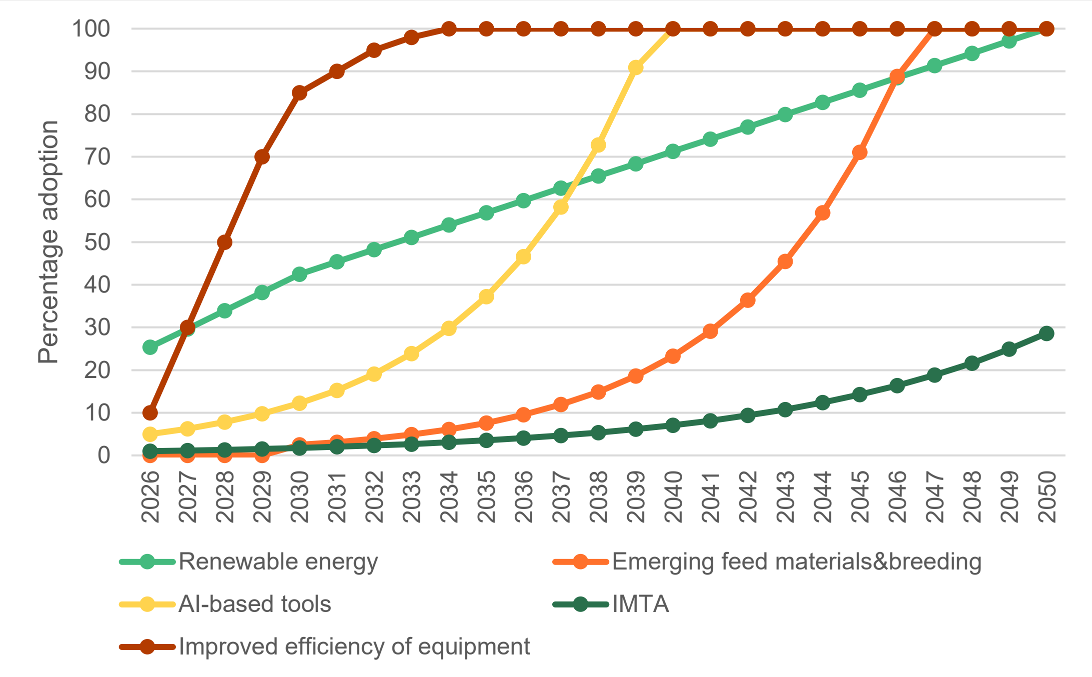


6.4.1.4 Proposed reduction pathway for raceways

The proposed reduction pathway for raceway aquaculture (Figure 18) includes:

- Adoption of renewable energy sources in line with the EU's progress and ambitions.
- Rapid adoption of the tool improved efficiency of equipment, with a 100% adoption rate in 2034.
- An assumed adoption of AI-based tools of 5% in 2026, growing by 25% annually. In 2040, adoption rate is then 100%.
- Taking into account that the production and large-scale use of emerging feed materials is challenging, and could require dedicated breeding programs, it is assumed this tool will start to be implemented in 2030 (2.5%) and grow by 25% annually from there onwards. An adoption rate of 100% is achieved in 2047.
- IMTA can be used in raceways to increase the productivity while reducing per unit GHG emissions. Given the challenges to develop into a large-scale commercially interesting practice, and in light of the current situation, a 2026 adoption rate of 1% is assumed, growing from there on with 15% per year to reach an adoption rate of 28.6% in 2050.

Figure 17 - Proposed reduction pathway for raceways aquaculture

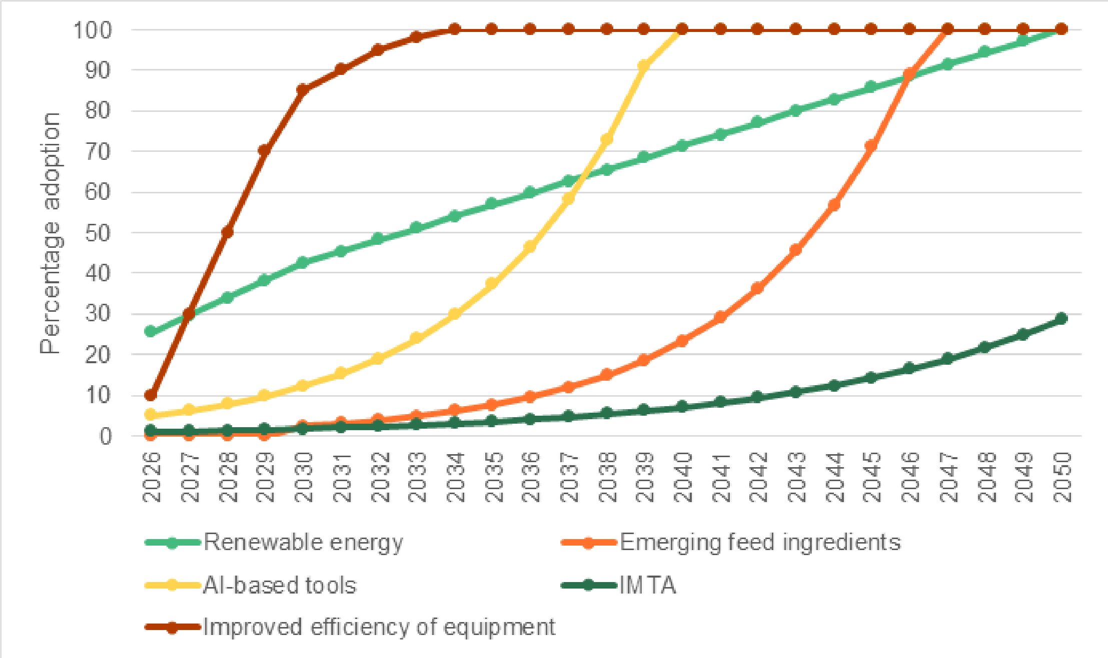


6.4.1.5 Proposed reduction pathway for RAS

The proposed reduction pathway for cage aquaculture (Figure 19) includes:

- Adoption of renewable energy sources in line with the EU's progress and ambitions.
- Rapid adoption of the tool improved efficiency of equipment, with a 100% adoption rate in 2034.
- An assumed adoption of AI-based tools of 5% in 2026, growing by 25% annually. In 2040, adoption rate is then 100%.
- Taking into account that the production and large-scale use of emerging feed materials is challenging, and could require dedicated breeding programs, it is assumed this tool will start to be implemented in 2030 (2.5%) and grow by 25% annually from there onwards. The 100% adoption mark is reached in 2047.
- IMTA can be used in RAS to increase the productivity while reducing per unit GHG emissions. Given the challenges to develop into a large-scale commercially interesting practice, and in light of the current situation, a 2026 adoption rate of 1% is assumed, growing from there on with 15% per year to reach an adoption rate of 28.6% in 2050.

Figure 18 – Proposed reduction pathway for RAS aquaculture



6.4.2 The cost of the proposed reduction pathway towards carbon neutrality by 2050

This section shows the marginal abatement cost of the pathway for carbon neutrality by 2050, across five production systems, with specific intermediary figures for 2030 and 2040. Marginal abatement costs consider the cost of reducing one unit of an environmental negative, in this case tonnes of CO_2eq. It is important to consider that this value considers the cost of reducing one additional tonnes CO_2eq, and not the cost of reducing emissions per tonne so far. Therefore, if significant emissions reduction measures are already in place, the marginal abatement cost can increase, as the cost of reducing the emissions further becomes more expensive.

The marginal abatement cost required to achieve carbon neutrality across five production systems is illustrated in Figure 19. The non-fed system exhibits a significantly higher MAC compared to the other four systems. Key observations include:

- For most systems, MACs remain relatively stable across the short-term (2026–2030), medium-term (2026–2040), and long-term (2026–2050) periods. However, the non-fed system shows an increase in MAC during 2040 and 2050 compared to 2030, which can be explained by the increasing adoption levels of the system over years.
- While the MAC for pond, raceways, RAS, and cage systems ranges between 46–71 €/t CO_2eq, the non-fed system reaches up to 221 €/t CO_2eq. This discrepancy can be explained by the considerably higher investment costs for adopting tools with higher production volume of the

non-fed system. For instance, by 2040, non-fed production reaches 8.7 million tonnes of LW, exceeding the range of 0.5–5.2 million tonnes of LW observed in other systems. While the emission per tonnes of LW is only 1.1 tonnes CO_2eq/t LW (Figure 20).

- Similarly, the relatively low MAC of the RAS system (46 €/t CO_2eq by 2040) is attributed to its small production volume (512 thousand tonnes LW in 2040) and high emissions intensity (13.4 tonnes CO_2eq/t LW) (Figure 20). This results in lower investment costs of tools per tonnes CO_2eq for emissions reduction.

Figure 19 – Marginal abatement cost for carbon neutrality pathways across five production systems by 2050

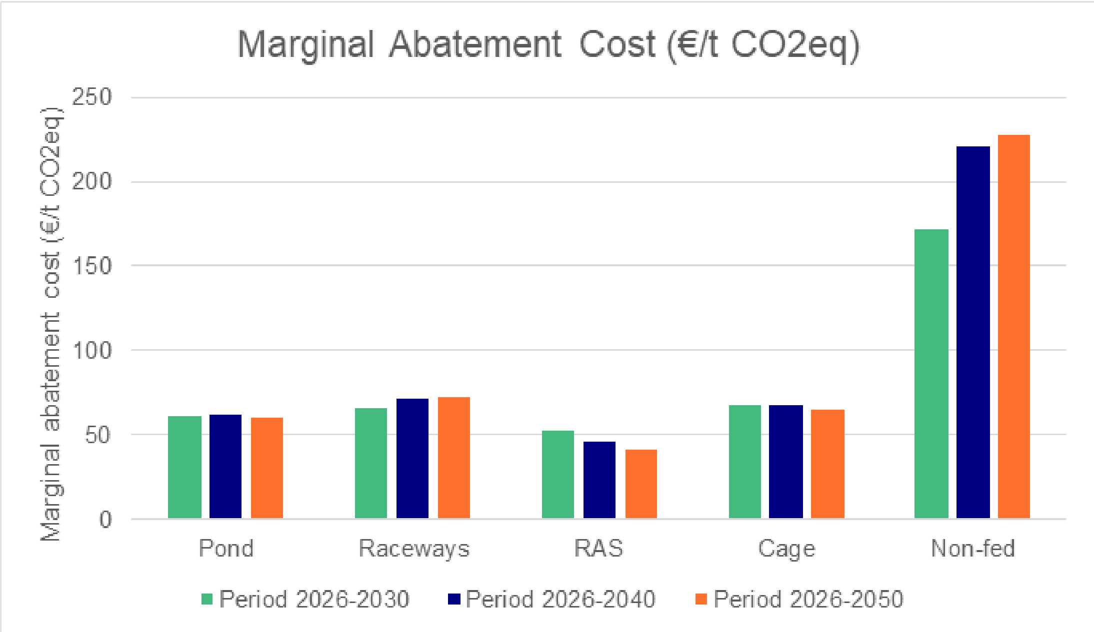


Figure 20 – Average emission per tonnes of LW in the period 2026-2050 across production systems

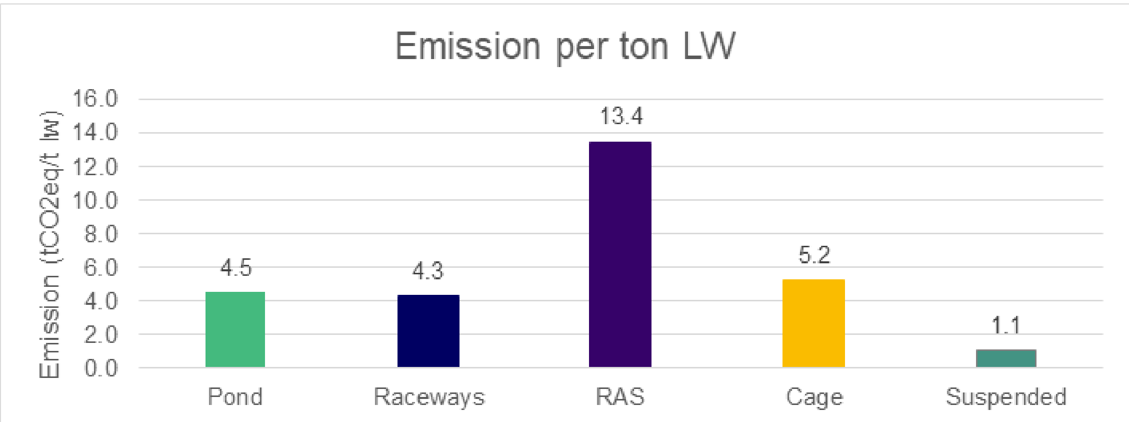
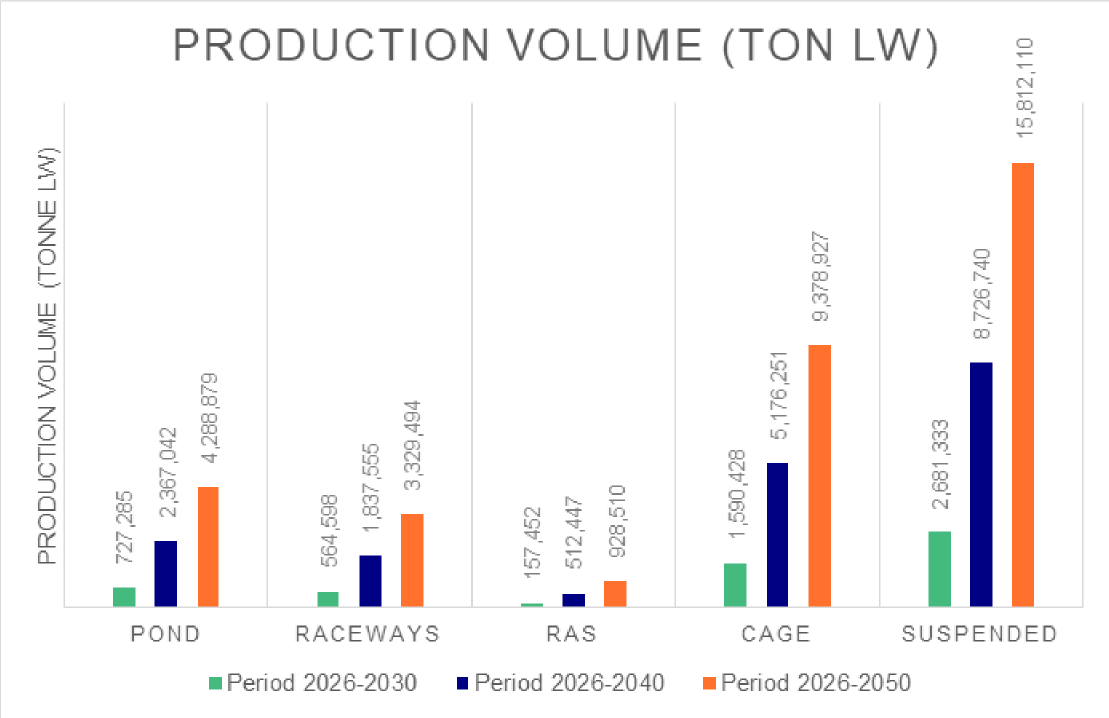
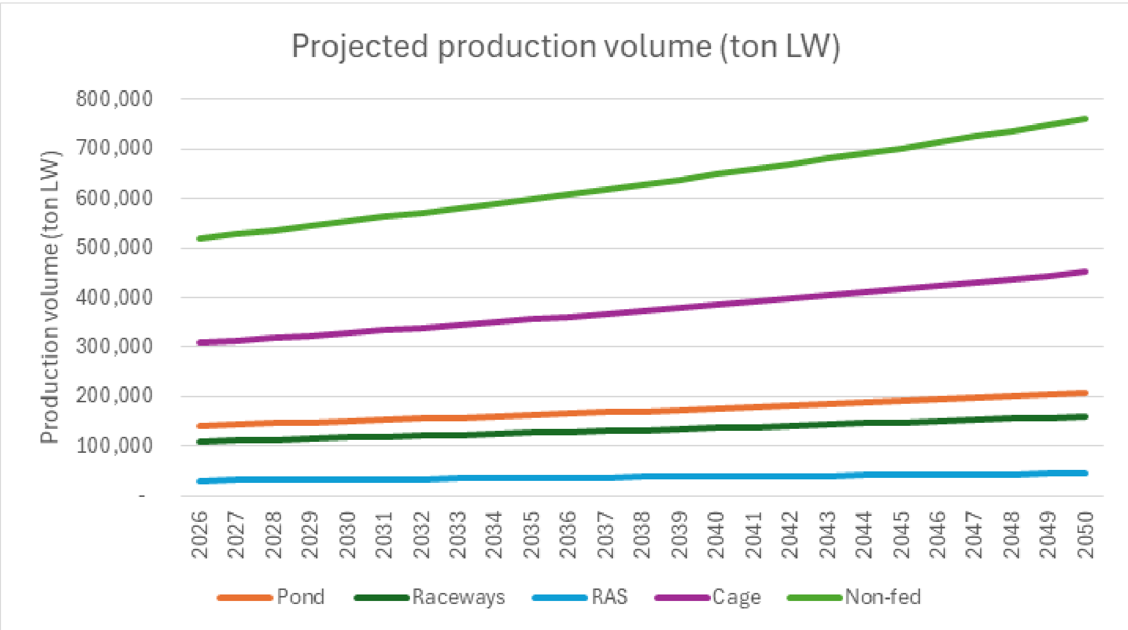


Figure 21 – Production volume by 2050 across production systems

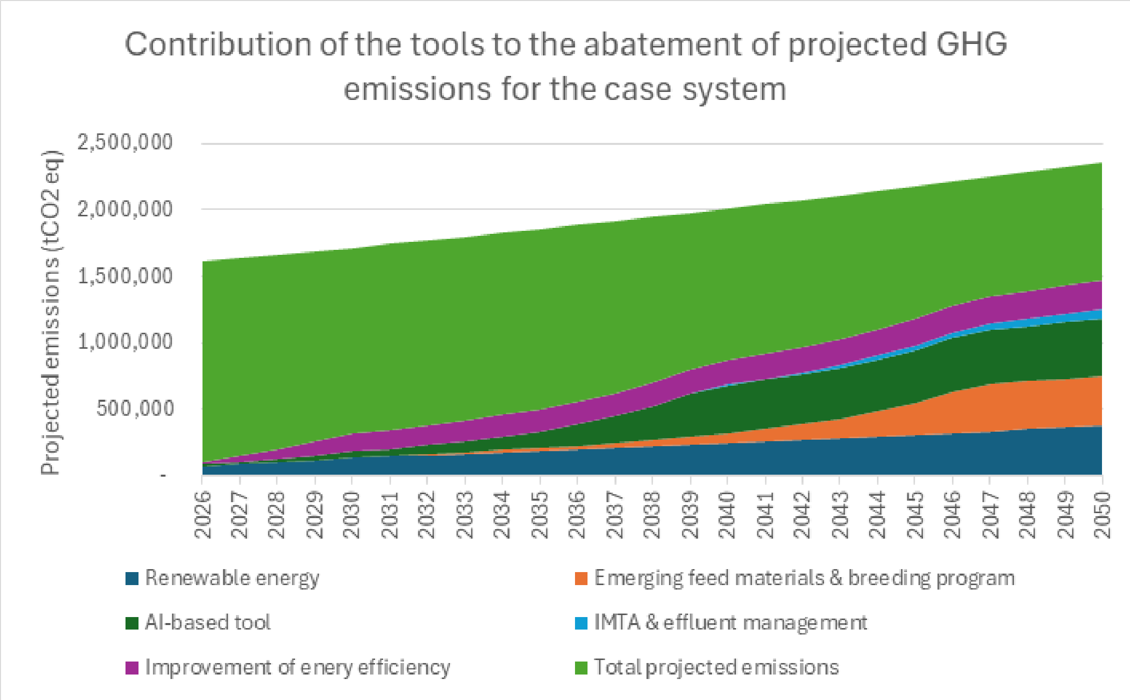




6.4.2.1 Costs for cages

For the cage system, achieving carbon neutrality by 2050 begins with a high reliance on voluntary carbon credits, followed by an increasing adoption of other mitigation tools. By 2050, renewable energy, emerging feed materials and breeding programs, AI, and improvements in energy efficiency contribute to emission reductions, achieving reductions of 379, 373, 430, and 215 thousand tonnes CO_2eq, respectively. In contrast, IMTA and effluent management have a smaller impact, with reductions of only 73 thousand tonnes CO_2eq. Voluntary carbon credits have highest contribution of 887 thousand tonnes CO_2eq.

Figure 22 – Total emission reductions achieved by adopting tools for the cage system



Without voluntary carbon credits, the cage system cannot achieve carbon neutrality, as emissions persist even with tools. Carbon credits play a critical role in 2040, when reduction demands are at their peak. However, reliance on them gradually declines over time, with remaining emissions decreasing from around 1 million tonnes CO_2eq in 2040 to 886,689 tonnes CO_2eq in 2050.

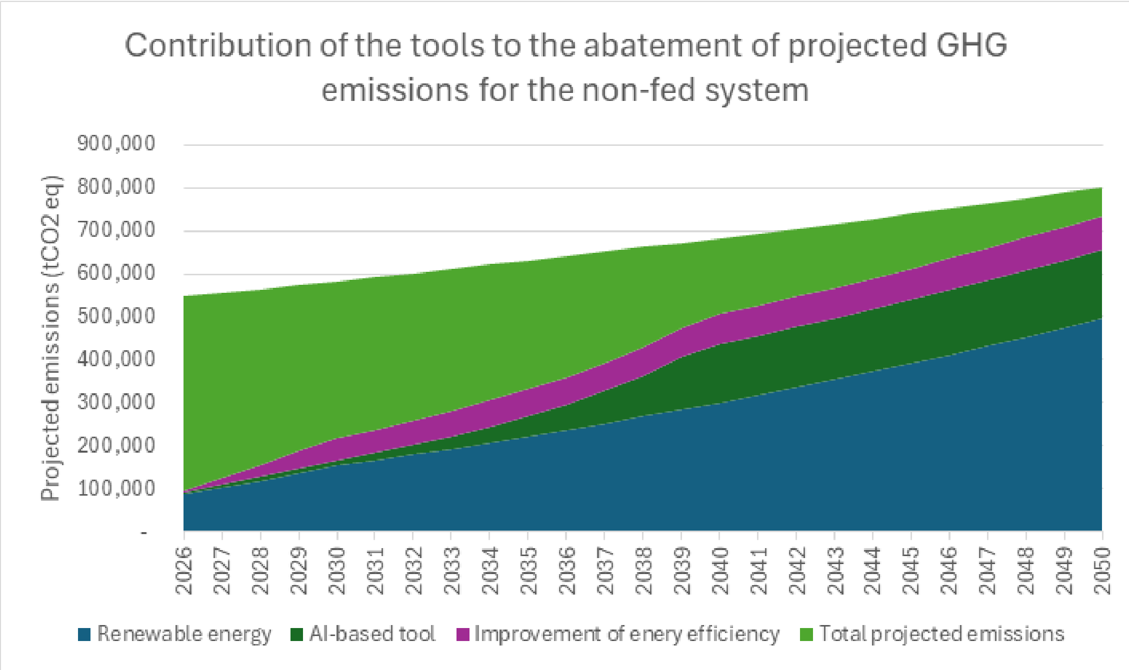
Table 38 – Comparison of emission reduction by adopting tools with reduction target for the cage system

Year	2005 emissions (t CO_2eq)	Reduction target	Emissions cap (t CO_2eq)	Projected emissions without tools (t CO_2eq)	Projected abated emissions (t CO_2eq)	Projected remaining emissions (t CO_2eq)	Additional abatement needed to reach targets (t CO_2eq)
2030	731,651	55%	329 243	1 714 766	314 134	1 400 632	1 071 389
2040	731,651	90%	73 165	2 009 748	868 493	1 141 255	1 068 090
2050	731,651	100%	0	2 355 477	1 468 788	886 689	886 689

6.4.2.2 Costs for non-fed

For the non-fed system, achieving carbon neutrality by 2050 also significantly relies on adopting voluntary carbon credits, then complemented by other tools such as renewable energy, AI, and improvements in energy efficiency. By 2050, the use of renewable energy is responsible for the largest share of emission reductions, while AI and improvement of energy efficiency further enhance reductions. Improvements of energy efficiency make a smaller but notable contribution. In the year of 2050, renewable energy, AI, and improvements in energy achieve reductions of 495, 160, 430, and 80 thousand tonnes CO_2eq, respectively. Voluntary carbon credits contribute on reduction of 66 thousand tonnes CO_2eq.

Figure 23 – Total emission reductions achieved by adopting tools for the non-fed system



Without voluntary carbon credits, the non-fed system cannot achieve carbon neutrality, as emissions persist even with tools. Carbon credits play a critical role in 2040, when reduction demands are highest. However, reliance on them decreases over time as remaining emissions are reduced, dropping from 127 237 tonnes CO_2eq in 2040 to 65 651 tonnes CO_2eq in 2050.

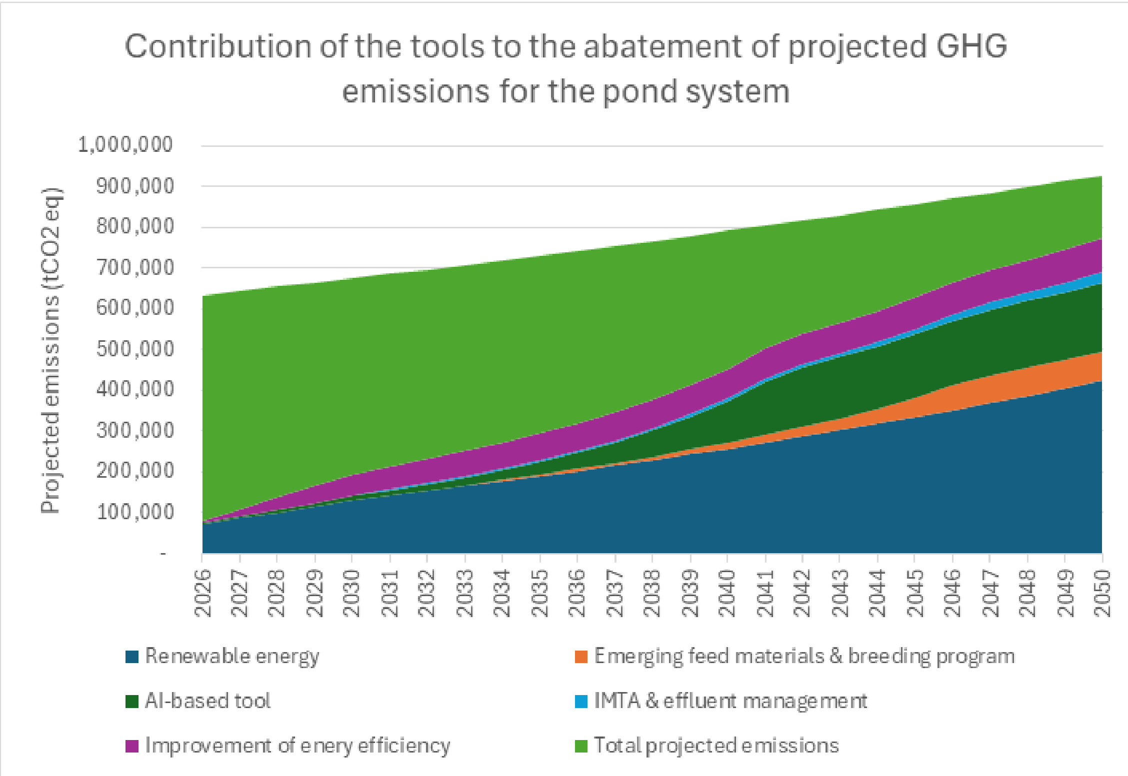
Table 39 – Comparison of emission reduction by adopting tools with reduction target for the non-fed system

Year	2005 emissions (t CO_2eq)	Reduction target	Emissions cap (t CO_2eq)	Projected emissions without tools (t CO_2eq)	Projected abated emissions (t CO_2eq)	Projected remaining emissions (t CO_2eq)	Additional abatement needed to reach targets (t CO_2eq)
2030	502 806	55%	226 263	582 910	216 903	366 007	139 744
2040	502 806	90%	50 281	683 185	505 667	177 518	127 237
2050	502 806	100%	0	800 711	735 060	65 651	65 651

6.4.2.3 Costs for ponds

For the pond system, achieving carbon neutrality by 2050 relies on a combination of mitigation tools, with voluntary carbon credits contributing the largest share of emission reductions which is similar with the cage system. In the year of 2050, renewable energy, emerging feed materials and breeding program, AI, IMTA and effluent management, and improvements of energy efficiency provide significant reductions, achieving reductions of 423, 72, 167, 28, and 83 thousand tonnes CO_2eq, respectively. Furthermore, voluntary carbon credits have a higher impact, with reductions of 153 thousand tonnes CO_2eq.

Figure 24 – Total emission reductions achieved by adopting tools for the pond system



Without voluntary carbon credits, the pond system cannot achieve carbon neutrality, as emissions remain even with tools. The role of carbon credits is crucial in 2040, when emissions reduction demands are highest. Nevertheless, its reliance decreases over time as remaining emissions are reduced, which drop from 281 834 tonnes CO_2eq in 2040 to 152 763 tonnes CO_2eq in 2050.

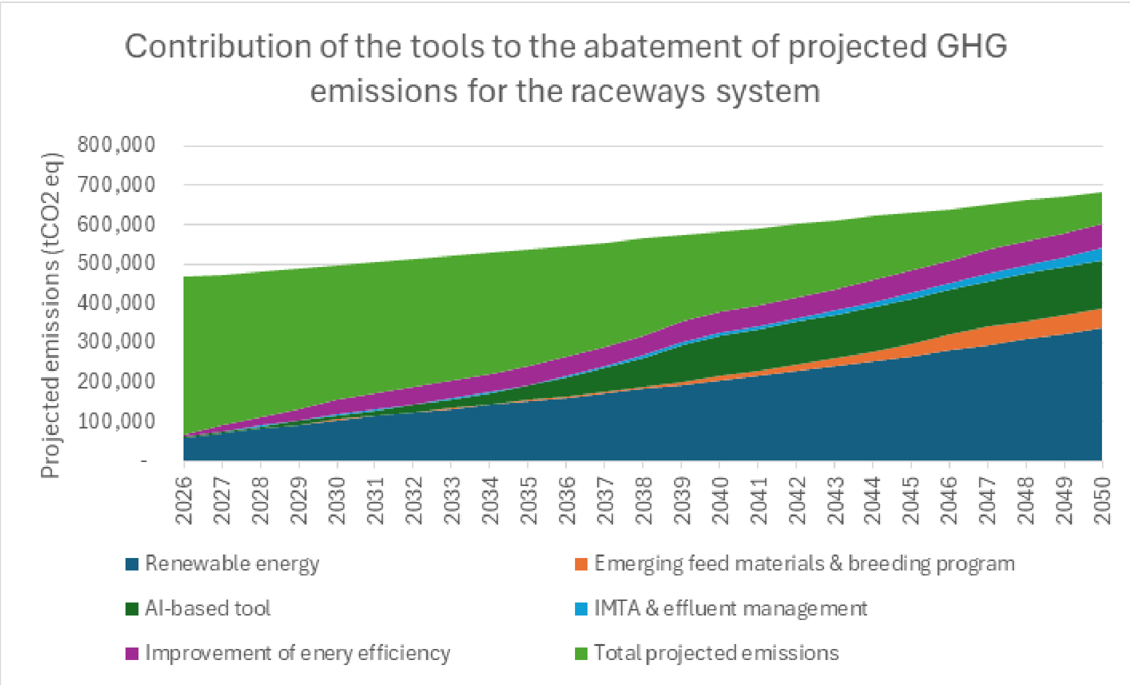
Table 40 – Comparison of emission reduction by adopting tools with reduction target for the pond system

Year	2005 emissions (t CO_2eq)	Reduction target	Emissions cap (t CO_2eq)	Projected emissions without tools (t CO_2eq)	Projected abated emissions (t CO_2eq)	Projected remaining emissions (t CO_2eq)	Additional abatement needed to reach targets (t CO_2eq)
2030	567 737	55%	255 482	675 599	195 010	480 589	225 107
2040	567 737	90%	56 774	791 817	453 209	338 608	281 834
2050	567 737	100%	0	928 030	775 267	152 763	152 763

6.4.2.4 Costs for raceways

For the raceways system, similar with cage and pond systems, achieving carbon neutrality by 2050 also depends on a combination of mitigation tools, with voluntary carbon credits contributing the largest share of emission reductions. By 2050, significant reductions are achieved through renewable energy, emerging feed materials and breeding program, AI, IMTA and effluent management, improvements of energy efficiency: 337, 49, 123, 30, and 62 thousand tonnes CO_2eq respectively. Voluntary carbon credits still have the highest impact, achieving reductions of 82 thousand tonnes CO_2eq in the year 2050.

Figure 25 – Total emission reductions achieved by adopting tools for the raceway system



Similar with other systems, the raceways system cannot achieve carbon neutrality without voluntary carbon credits, as emissions persist even with tools.

Carbon credits are crucial in 2040, when reduction demands are highest. However, reliance on them gradually decreases over time, with remaining emissions dropping from 175 138 tonnes CO_2eq in 2040 to 81 628 tonnes CO_2eq in 2050.

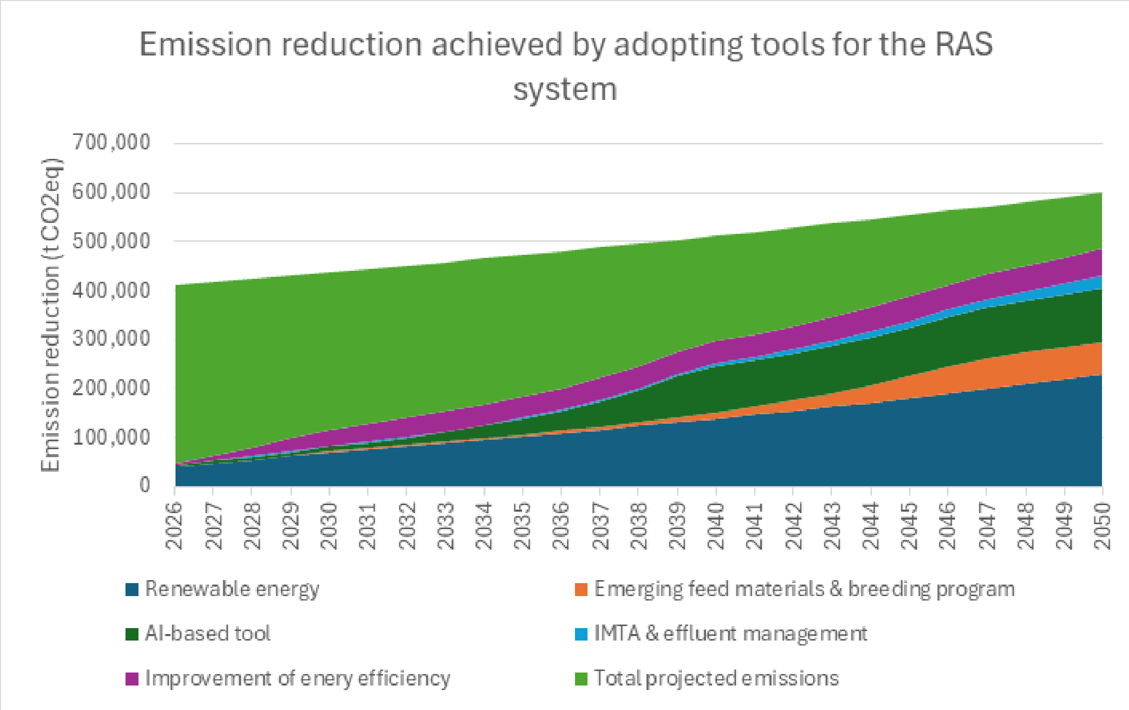
Table 41 – Comparison of emission reduction by adopting tools with reduction target for the raceways system

Year	2005 emissions (t CO_2eq)	Reduction target	Emissions cap (t CO_2eq)	Projected emissions without tools (t CO_2eq)	Projected abated emissions (t CO_2eq)	Projected remaining emissions (t CO_2eq)	Additional abatement needed to reach targets (t CO_2eq)
2030	284 144	55%	127 865	496 866	155 638	341 228	213 363
2040	284 144	90%	28 414	582 340	378 788	203 552	175 138
2050	284 144	100%	0	682 517	600 889	81 628	81 628

6.4.2.5 Costs for RAS

For the RAS system, achieving carbon neutrality by 2050 also requires a combination of mitigation tools, with voluntary carbon credits contributing the largest share of emission reductions, like other systems. By 2050, the tools to provide significant emission reductions include: renewable energy, emerging feed materials and breeding programs, AI, IMTA and effluent management, improvement of energy efficiency. Their emission reductions are 228, 67, 09, 26, 54, and 115 thousand tonnes CO_2eq, respectively. Voluntary carbon credits have achieved reductions of 600 thousand tonnes CO_2eq.

Figure 26 – Total emission reductions achieved by adopting tools for the RAS system



The RAS system also cannot achieve carbon neutrality without voluntary carbon credits, as emissions persist even with tools. Carbon credits are essential in 2040, when reduction demands are at their peak. However, reliance on them decreases over time, with remaining emissions reducing from 158 645 tonnes in 2040 to 115 360 tonnes CO_2eq in 2050.

Table 42 - Comparison of emission reduction by adopting tools with reduction target for the RAS system

Year	2005 emissions (t CO_2eq)	Reduction target	Emissions cap (t CO_2eq)	Projected emissions without tools (t CO_2eq)	Projected abated emissions (t CO_2eq)	Projected remaining emissions (t CO_2eq)	Additional abatement needed to reach targets (t CO_2eq)
2030	388 958	55%	175 031	436 837	116 217	320 620	145 589
2040	388 958	90%	38 896	511 982	296 563	215 419	176 523
2050	388 958	100%	0	600 058	484 698	115 360	115 360

6.4.3 Combined reduction pathway

The analysis reveals that the marginal abatement cost for different scenarios generally follow an increasing trajectory across the implementation periods. Across scenarios, MAC values show a wide range:

- 2026-2030: ranging from 46 to 243 €/t CO_2eq
- 2026-2040: ranging from 65 to 232 €/t CO_2eq
- 2026-2050: ranging from 69 to 228 €/t CO_2eq

In addition to the economic analysis, the wider social, environmental and economic impacts of the scenarios are also evaluated using stakeholder consultation and multi-criteria analysis. All analyses feed into study proposed GHG reduction pathways for the five production systems studied: cage, non-fed, pond, raceways and RAS aquaculture.

The proposed reduction pathways where assessed to see whether they can meet the GHG emission reduction targets for 2030 (55%), 2040 (90%) and 2050 (carbon neutrality). The baseline used here are, as requested in the ToR and aligned with the ESR, the 2005 aquaculture emissions.

Table 43 – Achievement of GHG emission reduction targets under the pathways

	Year	2005 emissions (t CO_2eq)	Reduction target	Emissions cap (t CO_2eq)	Projected emissions without tools (t CO_2eq)	Projected abated emissions (t CO_2eq)	Projected remaining emissions (t CO_2eq)	Additional offsetting needed to reach targets (t CO_2eq)
Cage	2030	731 651	55%	329 243	1 714 766	314 134	1 400 632	1 071 389
	2040	731 651	90%	73 165	2 009 748	868 493	1 141 255	1 068 090
	2050	731 651	100%	0	2 355 477	1 468 788	886 689	886 689
Non-fed	2030	502 806	55%	226 263	582 910	216 903	366 007	139 744
	2040	502 806	90%	50 281	683 185	505 667	177 518	127 237
	2050	502 806	100%	0	800 711	735 060	65 651	65 651
Pond	2030	567 737	55%	255 482	675 599	195 010	480 589	225 107
	2040	567 737	90%	56 774	791 817	453 209	338 608	281 834
	2050	567 737	100%	0	928 030	775 267	152 763	152 763
Raceways	2030	284 144	55%	127 865	496 866	155 638	341 228	213 363
	2040	284 144	90%	28 414	582 340	378 788	203 552	175 138
	2050	284 144	100%	0	682 517	600 889	81 628	81 628
RAS	2030	388 958	55%	175 031	436 837	116 217	320 620	145 589
	2040	388 958	90%	38 896	511 982	296 563	215 419	176 523
	2050	388 958	100%	0	600 058	484 698	115 360	115 360

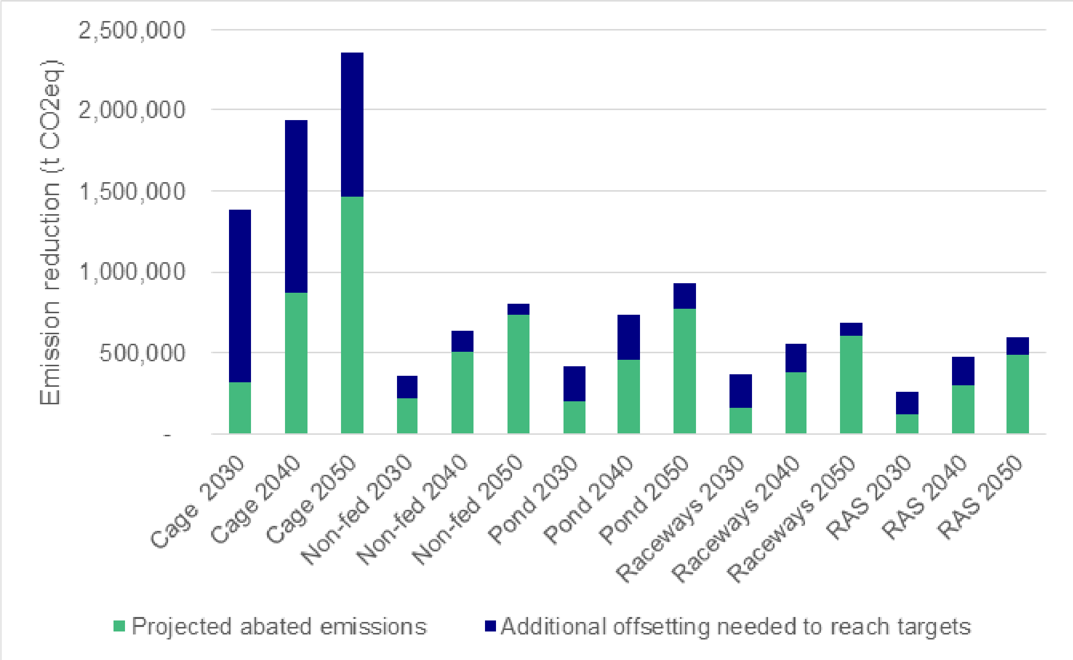
Table 43 above is read as follows:

- Column 1 names the 5 production systems studied
- Column 2 the three years with a GHG emissions reduction target
- Column 3 present the calculated GHG emissions in baseline 2005
- Column 4 the reduction % to be achieved
- Column 5 the emission cap, representing the maximum GHG emissions allowed to reach the reduction % (column 4) compared to the baseline (column 3)
- Column 6 the projected GHG emissions if no tools are taken (results of Scenario 1 analysis)
- Column 7 the projected abated emissions, adopting the tools according to the pathways identified in the project)
- Column 8 the remaining GHG emissions (column 6 minus column 7)
- Column 9 the GHG emissions needed to be abated ensure total remaining GHG emissions are below the cap (column 5)

The study concludes that the target of carbon neutrality can only be reached if offsetting measures are taken. There are two main reasons for this: (1) all energy production, transport and construction come with residual GHG emissions that are not offset by aquaculture practices; and (2) the inclusion of feed-related emissions in the carbon footprint of aquaculture implies that achieving carbon neutrality in fed aquaculture requires achieving carbon neutrality in agriculture.

The extent to which offsetting measures are needed to reach the climate targets differs per production type and over time (see Figure 27). The aquaculture sector is expected to need more offsetting measures to reach the 2030 and 2040 target, than needed to reach the 2050 target. This is explained by the fact that various tools are not ready to implement at large-scale in the next years and the expected adoption rates increases largely in the period 2040-2050.

Figure 27 – Emission reduction needed to achieve 2030, 2040, and 2050 targets



The effectiveness of GHG emissions offsetting is not undisputed, with debates centring around credibility, additionality and reliable certification. Concerns are addressed in the Carbon Removals and Carbon Farming (CRCF) Regulation (EU/2024/3012) ([18]), the first EU-wide voluntary framework for certifying carbon removals, carbon farming and carbon storage in products across Europe.

The European Union's ambition is to grow the EU aquaculture sector, reduce dependency on imported seafood and contribute to improved marine ecosystem quality. Furthermore, as emissions from aquaculture and fisheries fall under the ESR (Regulation (EU) 2023/857), a reduction of GHG emissions from the aquaculture sector is needed. The analysis presented above concludes that this is a highly demanding objective, which can only be achieved by strong governance support at both EU and Member State level, GHG emissions in the whole aquaculture supply chain and the use of offsetting.

6.5 Sensitivity analysis

6.5.1 A higher carbon price

In this analyses, the impact of higher prices for carbon is assessed. Carbon price presented in Table 44 are in alignment with the study on "Greenhouse

([18]) OJ L, 2024/3012, ELI: http://data.europa.eu/eli/reg/2024/3012/oj

Gas Emission (GHG) Reduction Costs, Scenarios and Pathways for EU Fisheries to achieve Net Zero by 2050".

Table 44 – Carbon prices used for sensitivity analysis

Year	2030	2040	2050
Median	195	252	495

When comparing the new carbon value against the base carbon value (i.e., derived from the voluntary market with prices averaging approximately 56 Euro/t CO2eq), there is a significant increase in the Marginal Abatement Cost (MAC) across all production systems (Figure 28). This increase is largely driven by the reliance of each system on offsetting mechanisms to abate remaining emissions and achieve carbon neutrality. The sensitivity of the MAC to these pricing changes varies by system: RAS shows the highest sensitivity, followed by cage, pond, raceways, and non-fed systems, respectively.

These MAC values for the entire period are discounted to 2026 prices, meaning they account for the time value of money and express all future costs in terms of their equivalent value in the base year (2026).

Figure 28 – Impact of new carbon values on abatement cost over periods

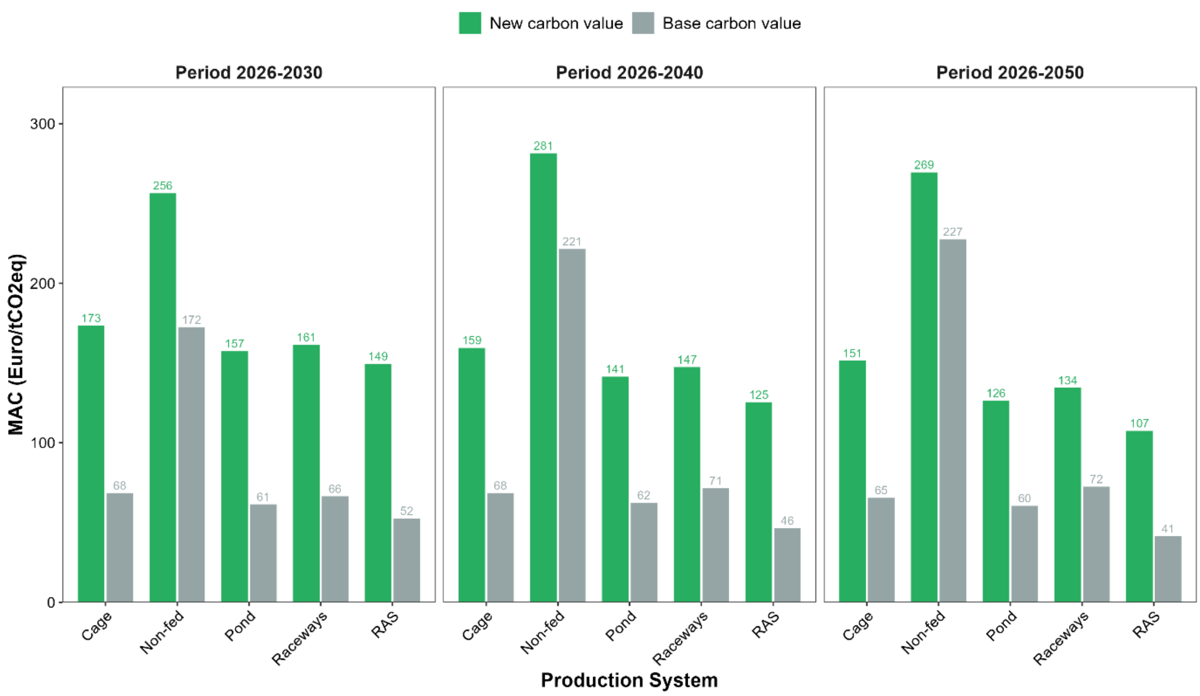
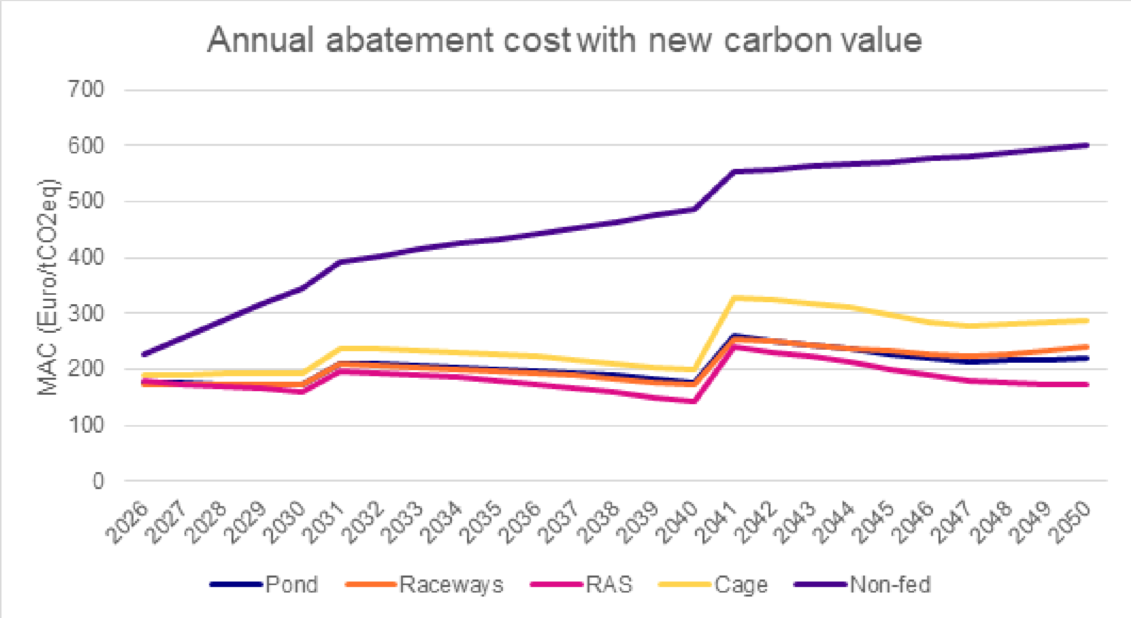


Figure 29 shows the MAC for each individual year - the cost per tonne changes annually from 2026 to 2050. Non-fed systems show the highest MAC, reaching approximately 600 Euro/t CO_2eq by 2050.

Figure 29 – Annual Marginal Abatement Costs with new carbon values



6.5.2 Without feed emission

Figure 30 confirms the major emissions in fed aquaculture comes from feed. In 2026, the inclusion of feed emissions increases total emissions from approximately 1.8 million to 2.8 million t CO2eq. The figure further reveals that aquaculture industry is projected to have significant emission reductions by 2050. The non-fed aquaculture sector follows a pathway that reaches nearly zero emissions, whilst fed aquaculture emissions remain above zero.

Figure 31 presents the projected annual abatement costs excluding feed emissions. Suspended and cage systems become the most expensive pathways, largely due to the high upfront capital investment required for electric boats, peaking approximately 600 €/t CO_2eq in 2050. Pond, raceways, and RAS systems exhibit a lower and similar cost pattern.

Figure 30 – Projected remaining emissions with and without feed emissions

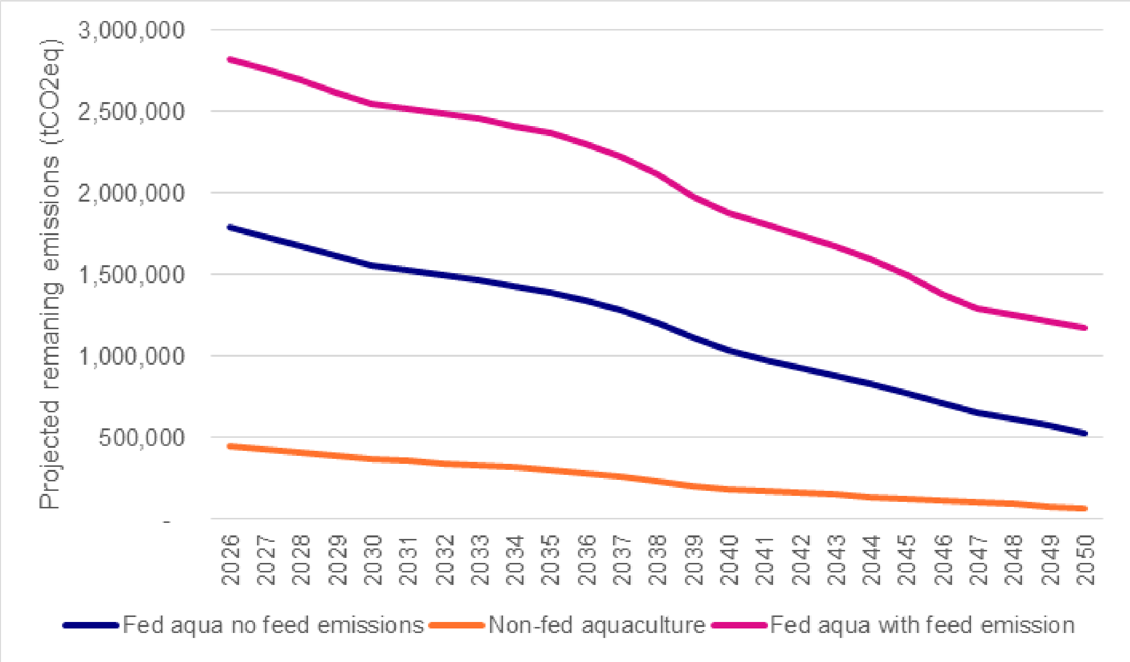
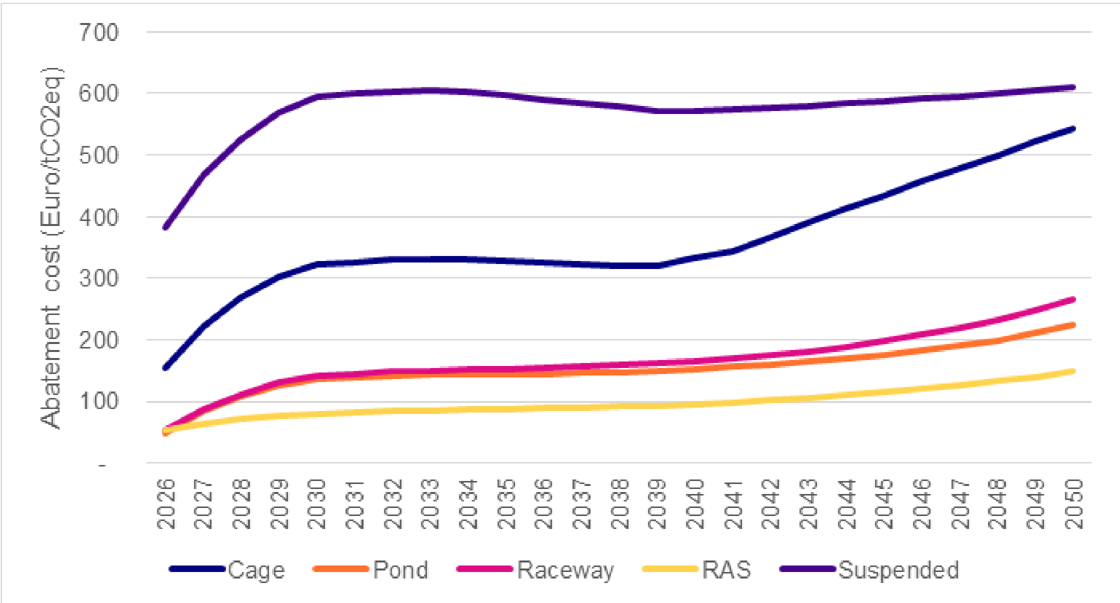


Figure 31 – Annual abatement cost without feed emission



6.6 Recommendations for carbon neutrality in European aquaculture

This section formulates policy recommendations along eight lines. The following key observations underline the formulation of policy recommendations:

- Aquaculture is a key sector food producing sector in the European Union and the objective is to grow the sector in the next decades.
- Achieving carbon neutrality in the aquaculture sector is a complex challenge that requires actions across the entire value chain, considering both technological readiness and economic feasibility.
- Given the fact that emissions stemming from the production of feed are allocated to the aquaculture sector, achieving carbon neutrality in aquaculture requires achieving carbon neutrality as well in agriculture, unless compensatory measures are taken.
- Policy must acknowledge that focusing exclusively on carbon footprint reduction may create trade-offs with other environmental, social, and economic objectives, such as freshwater use, land space, marine resource use and food security.
- Aquaculture is a source of food protein and has a relative lower carbon footprint compared to pork and beef production. Dietary changes can support the move towards low carbon production (including low-trophic aquaculture) but can also mean a shift towards high carbon footprint animal products.

6.6.1 Drive energy efficiency and digitalization

Improving energy management offers accessible "low-hanging fruit" for cost savings and immediate GHG reductions, particularly in land-based and short-haul marine operations. Many small and micro-sized aquaculture enterprises (which constitute 80% of producers in some regions) lack the resources or knowledge to adopt new technologies. AI-based tools offer promising tools to reduce GHG emissions, at farm-level and by forecasting ecosystem changes that negatively affect producers.

To this end, it is proposed to:

- **Mandate and incentivize energy audits.** Support energy audits and regular efficiency checks for aquaculture farms, providing subsidies or grants for associated operational improvements. Many traditional farms do not measure their electricity use per device, meaning significant energy savings are being missed.
- **Promote AI and IoT uptake.** Policy should support the widespread adoption of Artificial Intelligence (AI) and Internet of Things (IoT) equipment. AI tools are seen as one of the most promising short-term improvements as they help optimize feeding, reduce feed conversion

ratios (FCRs) by minimizing waste, and provide early warning systems to prevent fish mortality due to environmental changes or disease.
- **Targeted Training and Support for energy efficiency and digitalization:** Establish training and knowledge transfer programs—delivered in national languages and practical, accessible terms (e.g., using simple apps or demonstration farms)—to increase farmer awareness and acceptance of AI, IoT, and renewable energy technologies. Support existing Producer Organizations (POs) to act as hubs for technical assistance and collective purchasing of services for micro-SMEs.

6.6.2 Support decarbonization of feed and raw materials

Feed materials represent the largest contributor to GHG emissions in fed aquaculture. Policy action in this area is paramount. The transition to emerging feed materials faces challenges related to cost, scalability, and regulatory constraints.

To this end, it is proposed to:

- **Review and adapt food safety and feed marketing regulations to remove bottlenecks.** As of now, regulatory bottlenecks that prohibit the use of potential circular biomass streams, such as sludge (faeces and urine) from fish production effluent for feeding insects or polychaetes.
- **Support R&D and scaling investment for emerging feed materials.** Further public and private investment is necessary to fund research and development (R&D) into scaling emerging ingredient production, particularly microalgae and single-cell proteins, to make them economically competitive with conventional crops. Current data on the GHG footprint of emerging feed materials often derives from small-scale pilots, requiring validation at industrial scale.
- **Explore unexploited resources as potential feed ingredient.** Policy should support research into developing and sustainably exploiting underexploited marine resources, such as zooplankton (*Calanus finmarchicus*) and Arctic krill, which offer significant biomass potential and avoid agricultural land use impact. Technologies for capturing these resources (e.g., slow trawls, electric vessels) should be supported.
- **Support animal byproducts utilization:** Marine-sourced materials (like fish meal and oil) that come from trimmings or certified sustainable stocks already have a low carbon footprint compared to agricultural raw materials. Policy frameworks should ensure that animal byproducts (including fish meal, fish oil, and poultry byproducts) continue to be efficiently integrated into feed to avoid waste.

6.6.3 Accelerate the energy transition for transport and operations

While feed is the primary GHG source, transitioning energy use on farms and in vessels is technically feasible.

To this end, it is proposed to:

- **Continue to finance the energy transition of fisheries and aquaculture:** Implement financing mechanisms (e.g., tax breaks, subsidies, grants) to cover the high capital investment required for renewable energy, especially for electric vessels (boats and trucks). This is critical since electric transport is currently deemed too risky in some regions due to infrastructure challenges. The *Guide on financing the green energy transition of fisheries and aquaculture* ([19]) is credited for providing insight into the available instruments.
- **Support hybrid and intermediate fuels:** Policy can support the use and incentivization of intermediate or transition fuels, such as hydrotreated vegetable oil (HVO), to bridge the gap until electric vessels are widely adopted (expected timeline: post-2035/2040).
- **Renewables Infrastructure:** Aquaculture producers make use of on-site renewable energy sources (solar panels, wind turbines) to meet electricity demands. The regulatory frameworks in place vary between countries yet addressing infrastructure constraints, such as the limit on photovoltaic installation size based on connection power, can accelerate the adoption of renewable energy production.

6.6.4 Support breeding programs for resilience and efficiency

Breeding is a highly effective, ongoing method that can be managed internally and is cheaper than new equipment.

To this end, it is proposed to:

- **Support breeding programs focused on FCR and Growth Rate:** Invest in breeding programs that target increased feed conversion ratio (FCR) efficiency, reduced growth periods, and minimized growth failures. Reducing the growth period from 16–18 months to 12–13 months can improve efficiency by over 30%.
- **Breed for climate adaptation:** Support breeding efforts focused on increasing fish robustness and resilience to climate change impacts,

([19]) https://op.europa.eu/en/publication-detail/-/publication/49590638-8e76-11ee-8aa6-01aa75ed71a1 such as higher temperatures and changes in water quality (pH fluxes, ammonia levels). Reduced fish mortality contributes directly to a lower GHG footprint per unit produced.

6.6.5 Continue support for IMTA

IMTA is conceptually attractive but generally not yet commercially viable for most of Europe due to added complexity, cost, and market limitations.

To this end, it is proposed to:

- **Focus support and incentives on land-based IMTA and polyculture systems.** This includes systems such as freshwater duckweed/carp systems or RAS, where nutrient and energy cycles are controllable and economically feasible demonstration sites exist.
- **Review marine IMTA licensing.** Incentivize Member States to review existing regulations and licensing barriers that hinder the co-location of multiple species (e.g., seaweed and finfish/mussels) in marine environments, where site-specific hydrodynamics are often an issue.
- **Support regulatory frameworks** that allow producers to increase production volume on the same site if they implement IMTA systems that demonstrably reduce environmental impact.

6.6.6 Develop recognized methods for carbon offsetting

Acknowledging that there are hard-to-abate emissions from aquaculture, carbon offsetting is a key instrument to achieve carbon neutrality by 2050. The voluntary carbon credit market offers possibilities, yet the Carbon Removals and Carbon Farming Regulation does not currently provide a specific eligibility route for most aquaculture activities (except possibly some seaweed-based activities) but it is believed that a stronger link between the aquaculture and the marine ecosystem can be made and help create support for carbon offsetting.

To this end, it is proposed to:

- **Develop offsetting through low-trophic aquaculture.** Prioritize the development of clear and credible methodologies for calculating carbon credits (or compensation) derived from low-trophic species aquaculture such as macroalgae to facilitate transparent offsetting between farms.
- **Establish a link between ecosystem conservation and restoration support and aquaculture.** Further investigate the potential of ecosystem conservation and restoration to act as carbon sink. This can lead up to reliable offsetting where the aquaculture sector supports ecosystem conservation and restoration activities.

6.6.7 Stimulate market development and consumer awareness for low-carbon products

Aquaculture already has a significantly lower GHG footprint than other livestock sectors and there is potential to grow the aquaculture sector while reducing GHG emissions. Limited consumer demand for low carbon footprint aquaculture products (such as mussels and grass carp) is an impediment to growth. A market pull for low-carbon products can support the aquaculture producers with the financial means to invest in renewable energy production, increasing energy use efficiency and new production methods.

To this end, it is proposed to:

- **Continue efforts to increase consumer awareness.** Launch and/or continue education and communication campaigns to inform consumers about the relatively low carbon footprint of farmed fish compared to terrestrial meats, while addressing pre-existing concerns regarding welfare and antibiotic use. Examples of previous campaigns include "EU Aquaculture – we work for you with passion" ([20]).
- **Support market development for low carbon footprint species.** Support product innovation and market development to increase consumer acceptance of highly sustainable, but currently underutilized, low-trophic fish species, like carp and mullet, which is often hampered by issues such as public perception.
- **Explore options to introduce clear carbon footprint labelling for aquaculture products.** Such labels, similar to the Nutri-Score of energy-efficiency labels, can enable consumers to make informed choices and helping to reward sustainability investments made by producers.

6.6.8 Reinforce EU Aquaculture policy and streamline licensing

Aquaculture is currently a shared competence of the European Union and Member States, and the sector currently relies heavily on EU agricultural and EU fisheries policies and the strategic guidelines, which hinders progress, create gaps and inconsistencies, hinder stakeholder understanding, and limit the adoption of emerging solutions.

To this end, it is proposed to:

- **Reinforce existing regulatory frameworks to support long-term investments:** The challenge to achieve carbon neutrality by 2050 requires a strong regulatory framework and cooperation among the

([20]) EU Aquaculture - We work for you with passion - EU Aquaculture producers and Member States. It is therefore recommended that the European Commission should reinforce existing, Aquaculture Policy to replace the current reliance on non-binding guidelines, providing a stable regulatory framework for long-term investments in developing a carbon neutral aquaculture sector.

- **Streamline licensing and reduce investment uncertainty**: Member States must urgently streamline and clarify the aquaculture licensing and renewal process. Delays in licensing create uncertainty for financing and innovation, hampering the necessary capital investment in new, low-carbon equipment such as renewable energy and electric vessels.
- **Conduct GHG Baseline measurement and monitoring:** Policies should support the establishment of solid GHG inventories across all Member States, utilizing standardized measurement methods such as the Product Environmental Footprint Category Rules (PEF CR). Without clear baselines, monitoring and reporting, measuring progress in reaching objectives is not possible.

7 Conclusions

The study concludes that the target of carbon neutrality can only be reached if offsetting measures are taken. There are two main reasons for this: (1) all energy production, transport and construction comes with residual GHG emissions that are not offset by aquaculture practices; and (2) the inclusion of feed-related emissions in the carbon footprint of aquaculture implies that achieving carbon neutrality in fed aquaculture requires achieving carbon neutrality in agriculture.

This study is based on the premise that the aquaculture sector has to abate scope 1 (direct emissions), scope 2 (purchased energy with emissions decreasing to 2050) and scope 3 emissions (feed production and feed transport). This is not to say that the costs related to reducing these emissions should be borne by the aquaculture sector alone, and indeed under the climate law the responsibility to reduce emissions falls to the relevant sector.

The extent to which offsetting measures are needed to reach the climate targets differs per production type and over time. The aquaculture sector is expected to need more offsetting measures to reach the 2030 and 2040 target, than needed to reach the 2050 target. This is explained by the fact that various tools are not ready to implement at large-scale in the next years and the expected adoption rates increases largely in the period 2040-2050.

The effectiveness of GHG emissions offsetting is not undisputed, with debates centring around credibility, additionality and reliable certification. Concerns are addressed in the Carbon Removals and Carbon Farming (CRCF) Regulation (EU/2024/3012), the first EU-wide voluntary framework for certifying carbon removals, carbon farming and carbon storage in products across Europe. Removal through aquaculture activities is not currently eligible under the CRCF but the industry can make use of the broader market to offset emissions that fall outside of targets.

The European Union’s ambition is to grow the EU aquaculture sector, reduce dependency on imported seafood and contribute to improved marine ecosystem quality. Furthermore, as emissions from aquaculture and fisheries fall under the ESR (Regulation (EU) 2023/857), a reduction of GHG emissions from the aquaculture sector is needed. The analysis presented above concludes that this is a highly demanding objective, which can only be achieved by strong governance support at both EU and member state level, GHG emissions in the whole aquaculture supply chain and the use of offsetting.

The study was explicitly designed to assess how the aquaculture sector can move towards carbon neutrality in a context where upstream agriculture remains significantly emissive.

References

Abaho, I., Kwikiriza, G., Atukwatse, F., Izaara, A.A., Ekwangu, J., Baguma, S.D., Kubiriba, J., Kasozi, N. (2025). Selective Breeding for Genetic Improvement of Nile tilapia (Oreochromis niloticus Linnaeus, 1758) in Uganda: Current Status, Challenges, and Future Perspectives. Animals. 2025; 15(2):142. https://doi.org/10.3390/ani15020142.

Al Eissa, A., Chen, P., Brown, P. B., & Huang, J. Y. (2022). Effects of feed formula and farming system on the environmental performance of shrimp production chain from a life cycle perspective. Journal of Industrial Ecology, 26(6), 2006-2019.

Alam, M. M., Jørgensen, N. O. G., Bass, D., Santi, M., Nielsen, M., Rahman, M. A., Hasan, N. A., Bablee, A. L., Bashar, A., Hossain, M. I., Hansen, L. H., & Haque, M. M. (2024). Potential of integrated multitrophic aquaculture to make prawn farming sustainable in Bangladesh. Frontiers in Sustainable Food Systems, 8. https://doi.org/10.3389/fsufs.2024.1412919

Alotaibi, E., & Nassif, N. (2024). Artificial intelligence in environmental monitoring: in-depth analysis. *Discover Artificial Intelligence*, *4*(1), 84.

Aubin, J., Fontaine, C., Callier, M., & Roque d'orbcastel, E. (2018). Blue mussel (Mytilus edulis) bouchot culture in Mont-St Michel Bay: potential mitigation effects on climate change and eutrophication. The International Journal of Life Cycle Assessment, 23(5), 1030-1041.

Aubin, J., Papatryphon, E., Van der Werf, H. M. G., & Chatzifotis, S. (2009). Assessment of the environmental impact of carnivorous finfish production systems using life cycle assessment. Journal of Cleaner production, 17(3), 354-361.

Ayer, N. W., & Tyedmers, P. H. (2009). Assessing alternative aquaculture technologies: Life cycle assessment of salmonid culture systems in Canada. Journal of Cleaner Production, 17(3), 362–373. https://doi.org/10.1016/j.jclepro.2008.08.002

Ayisi, C. L., Alhassan, E. H., Addo, D., Agyei, B. O., & Apraku, A. (2016). Aquaculture extension services: A case study of fish farms in the eastern region of Ghana.

Badiola, M., Basurko, O. C., Piedrahita, R., Hundley, P., & Mendiola, D. (2018). Energy use in recirculating aquaculture systems (RAS): a review. Aquacultural engineering, 81, 57-70.

Bava, L., Jucker, C., Gislon, G., Lupi, D., Savoldelli, S., Zucali, M., & Colombini, S. (2019). Rearing of Hermetia Illucens on Different Organic By-Products:

Influence on Growth, Waste Reduction, and Environmental Impact. Animals, 9(6), 289. https://doi.org/10.3390/ani9060289

Bergman, K., Henriksson, P. J. G., Hornborg, S., Troell, M., Borthwick, L., Jonell, M., Philis, G., & Ziegler, F. (2020). Recirculating aquaculture is possible without major energy trade-off: Life cycle assessment of warmwater fish farming in Sweden. Environmental Science & Technology, 54(24), 16062–16070. https://doi.org/10.1021/acs.est.0c01100.

Besson, M., Aubin, J., Komen, H., Poelman, M., Quillet, E., Vandeputte, M., van Arendok, J. A. M., & De Boer, I. J. M. (2016). Environmental impacts of genetic improvement of growth rate and feed conversion ratio in fish farming under rearing density and nitrogen output limitations. Journal of cleaner production, 116, 100-109.

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, 404-415.

Billing, S.-L., Rostan, J., Tett, P., & Macleod, A. (2021). Is social license to operate relevant for seaweed cultivation in Europe? Aquaculture, 534, 736203. https://doi.org/10.1016/j.aquaculture.2020.736203

Bohnes, F. A., Hauschild, M. Z., Schlundt, J., & Laurent, A. (2019). Life cycle assessments of aquaculture systems: A critical review of reported findings with recommendations for policy and system development. Reviews in Aquaculture, 11(4), 1061–1079. https://doi.org/10.1111/raq.12280.

Bolstad, G. H., Karlsson, S., Hagen, I. J., Fiske, P., Urdal, K., Sægrov, H., Larsen, B., F., Solien, V. P., Østborg, G., Diserud, O. H., Jensen, A. J., & Hindar, K. (2021). Introgression from farmed escapees affects the full life cycle of wild Atlantic salmon. Science Advances, 7(52), eabj3397.https://doi.org/10.1126/sciadv.abj3397

Bosma, R. H., & Verdegem, M. C. (2011). Sustainable aquaculture in ponds: Principles, practices and limits. *Livestock science*, *139*(1-2), 58-68.

Bosma, R., Anh, P. T., & Potting, J. (2011). Life cycle assessment of intensive striped catfish farming in the Mekong Delta for screening hotspots as input to environmental policy and research agenda. The International Journal of Life Cycle Assessment, 16(9), 903-915.

Boxman, E, S., Zhang, Q., Bailey, D., Trotz, A, Maya. (2016) Life Cycle Assessment a Commercial-Scale Freshwater Aquaponic System. Environmental Engineering Science. 2016;34(5):299-311. doi:10.1089/ees.2015.0510

Boyd, C. E., Wood, C. W., Chaney, P. L., & Queiroz, J. F. (2010). Role of aquaculture pond sediments in sequestration of annual global carbon emissions. Environmental pollution, 158(8), 2537-2540.

Brown, A. R., Wilson, R. W., & Tyler, C. R. (2024). Assessing the Benefits and Challenges of Recirculating Aquaculture Systems (RAS) for Atlantic Salmon Production. Reviews in Fisheries Science & Aquaculture, 33(3), 380–401. https://doi.org/10.1080/23308249.2024.2433581.

Buck, B. H., Troell, M. F., Krause, G., Angel, D. L., Grote, B., & Chopin, T. (2018). State of the art and challenges for offshore integrated multi-trophic aquaculture (IMTA). Frontiers in Marine Science, 5, 165. https://doi.org/10.3389/fmars.2018.00165

Bujas, T., Koričan, M., Vukić, M., Soldo, V., Vladimir, N., & Fan, A. (2022). Review of energy consumption by the fish farming and processing industry in Croatia and the potential for zero-emissions aquaculture. Energies, 15(21), 8197.

Campos, I., Pinheiro Valente, L. M., Matos, E., Marques, P., & Freire, F. (2020). Life-cycle assessment of animal feed ingredients: Poultry fat, poultry by-product meal and hydrolyzed feather meal. Journal of Cleaner Production, 252, 119845.

Capetillo-Contreras, O., Pérez-Reynoso, F. D., Zamora-Antuñano, M. A., Álvarez-Alvarado, J. M., & Rodríguez-Reséndiz, J. (2024). Artificial Intelligence-Based Aquaculture System for Optimizing the Quality of Water: A Systematic Analysis. Journal of Marine Science and Engineering, 12(1), 161. https://doi.org/10.3390/jmse12010161

Carnell, P. E., Whiteoak, K., Young, M., Critchell, K., Swearer, S., Macreadie, P. I., McIntyre, J., & Treml, E. A. (2025). Prioritising investment in kelp forest restoration: A spatially explicit benefit-cost analysis in southern Australia. Ecosystem Services, 74, 101739.

Chang, CC., Wang, JH., Wu, JL. et al. (2021). Applying Artificial Intelligence (AI) Techniques to Implement a Practical Smart Cage Aquaculture Management System. J. Med. Biol. Eng. 41, 652–658. https://doi.org/10.1007/s40846-021-00621-3.

Chen, F., Sun, M., Du, Y., Xu, J., Zhou, L., Qiu, T., & Sun, J. (2022). Intelligent feeding technique based on predicting shrimp growth in recirculating aquaculture system. Aquaculture Research, 53(12), 4401-4413.

Chen, G., Bai, J., Bi, C., Wang, Y., & Cui, B. (2023). Global greenhouse gas emissions from aquaculture: A bibliometric analysis. Agriculture, Ecosystems & Environment, 348, 108405.

Collins, N., Mediboyina, M. K., Cerca, M., Vance, C., & Murphy, F. (2022). Economic and environmental sustainability analysis of seaweed farming: Monetizing carbon offsets of a brown algae cultivation system in Ireland. Bioresource Technology, 346, 126637.

Cooney, R., Tahar, A., Kennedy, A., & Clifford, E. (2021). The dilemma of opportunity in developing a life cycle assessment of emerging aquaculture systems-a case study of a Eurasian perch (Perca fluviatilis) hatchery recirculating aquaculture system. Aquaculture, 536, 736403.

Cottrell, R. S., Blanchard, J. L., Halpern, B. S., Metian, M., & Froehlich, H. E. (2020). Global adoption of novel aquaculture feeds could substantially reduce forage fish demand by 2030. Nature Food, 1(5), 301-308.

Cusimano, Giovanni Marco, Pablo Sánchez Cueto, Salvador Lladó, Simona Paolacci, Jui-Che Chiang, Natalie E. Panasiak, Radu Ghemis et al. (2025) "Effect of water salinity and dietary supplementation with Microchloropsis gaditana on growth, health, quality and microbiota of Barramundi Lates calcarifer." Open Research Europe 5: 58.

D'Agaro, E., Favaro, A., Matiussi, S., Gibertoni, P. P., & Esposito, S. (2021). Genomic selection in salmonids: new discoveries and future perspectives. Aquaculture International, 29(5), 2259-2289.

da Silva, E. G., Castilho-Barros, L., & Henriques, M. B. (2022). Economic feasibility of integrated multi-trophic aquaculture (mussel Perna perna, scallop Nodipecten nodosus and seaweed Kappaphycus alvarezii) in Southeast Brazil: A small-scale aquaculture farm model. Aquaculture, 552, 738031.uDanovaro, R., Aronson, J., Bianchelli, S., Boström, C., Chen, W., Cimino, R., Corinaldesi, C., Cortina-Segarra, J., D'Ambrosio, P., Gambi, C., Garrabou, J., Giorgetti, A., Grehan, A., Hannachi, A., Mangialajo, L., Morato, T., Orfanidis, S., Papadopoulou, N., Ramirez-Llodra, E., … Fraschetti, S. (2025). Assessing the success of marine ecosystem restoration using meta-analysis. Nature Communications, 16(1), 3062.

Danovaro, R., Aronson, J., Bianchelli, S., Boström, C., Chen, W., Cimino, R., Corinaldesi, C., Cortina-Segarra, J., D'Ambrosio, P., Gambi, C., Garrabou, J., Giorgetti, A., Grehan, A., Hannachi, A., Mangialajo, L., Morato, T., Orfanidis, S., Papadopoulou, N., Ramirez-Llodra, E., … Fraschetti, S. (2025). Assessing the success of marine ecosystem restoration using meta-analysis. Nature Communications, 16(1), 3062. https://doi.org/10.1038/s41467-025-57254-2

De Groot, R. S., Blignaut, J., Van Der Ploeg, S., Aronson, J., Elmqvist, T., & Farley, J. (2013). Benefits of investing in ecosystem restoration. Conservation Biology, 27(6), 1286-1293.

de Vet, Jan M., Hugh Gardner, Manuel Sala Pérez, David Matheus, Marta Mirambell Huguet, Anna Bessin, Maria Reyes et al. (2024). Techno-economic analysis for the renewable energy of the EU fisheries and aquaculture sector. Publications Office of the European Union, 2024.

Diken, G. (2023). Carbon footprint (kg CO2 e) expended in the aquaculture: An assessment of concrete pond rainbow trout farming from Türkiye. Journal of Water and Climate Change, 14(3), 878-899.

EMBER. (2025). Wind sector challenges are blowing over. European Electricity Review 2025. Retrieved from: https://ember-energy.org/latest-insights/european-electricity-review-2025/wind-sector-challenges-are-blowing-over/#:~:text=In%20Germany%2C%20for%20example%2C%20the,%E2%82%AC76/MWh%20in%202024.

European Commission (2021) Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030. Publications Office of the European Union, 2021

European Commission (2023). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. On the Energy Transition of the EU Fisheries and Aquaculture sector. Brussels, 21.2.2023. 27 pp.

European Commission (2024a): European Climate, Infrastructure and Environment Executive Agency, BlueFarm, CE Delft, ECORYS and SML, Techno-economic analysis for the energy transition of the EU fisheries and aquaculture sector, Publications Office of the European Union, 2024, https://data.europa.eu/doi/10.2926/425550

European Commission (2024b) European Commission Working Document: Implementing the Strategic Guidelines on EU Aquaculture - Renewable energy in the EU aquaculture sector. 2024 SWD(20224)0280

European Commission. (2020a). Energy costs, taxes and the impact of government interventions on investments. Retrieved from: https://energy.ec.europa.eu/system/files/2020-10/final_report_levelised_costs_0.pdf

European Commission. (2020b). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system* (COM (2020) 381 final; CELEX No. 52020DC0381). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0381

European Commission. (2025). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social*

Committee and the Committee of the Regions: The European Ocean Pact (COM (2025) 281 final). https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=comnat:COM_2025_0281_FIN

European Court of Auditors. (2023). Special report 25/2023: EU aquaculture policy: Stagnating production and unclear results despite increased EU funding (SR-2023-25). https://www.eca.europa.eu/ECAPublications/SR-2023-25/SR-2023-25_EN.pdf

European Market Observatory for Fisheries and Aquaculture Products (EUMOFA). (2021). Country profiles: Freshwater aquaculture in the EU – Annex 1

European Market Observatory for Fisheries and Aquaculture Products (EUMOFA). (2020). Recirculating aquaculture systems (RAS) in the EU.

EUROSTAT (2025) Complete Energy Balances. nrg_bal_c. DOI: 10.2908/nrg_bal_c

EY. (2025). Essential and still evolving: The global voluntary carbon market outlook 2024.

Falconer, L., Cutajar, K., Krupandan, A., Capuzzo, E., Corner, R.A., Ellis, T., Jeffery, K., Mikkelsen, E., Moore, H., O'beirn, F.X. and O'donohoe, P., 2023. Planning and licensing for marine aquaculture. Reviews in Aquaculture, 15(4), pp.1374-1404.

FAO. (2024). The State of World Fisheries and Aquaculture 2024 – Blue Transformation in action. Retrieved from: https://openknowledge.fao.org/items/06690fd0-d133-424c-9673-1849e414543d

FAO. 2025. FishStat: Global aquaculture production 1950-2023. [Accessed on 28 March 2025]. In: FishStatJ. Retrieved from: www.fao.org/fishery/en/statistics/software/fishstatj. Licence: CC-BY-4.0.

Fernandes, S., & Dmello, A. (2025). Artificial intelligence in the aquaculture industry: Current state, challenges and future directions. Aquaculture, 598, 742048.

Fernández Sánchez, J. L., Basurco, B., & Aguilera, C. (2023). Economic assessment of investment in automatic feeding systems for sea bass grow-out farms of different sizes. Journal of the World Aquaculture Society, 54(3), 625–634.

Garcia, G.B., Jimenez, R, C., Aguado-Gimenez, F., Garcia, G, B. (2019). Life Cycle Assessment of Seabass (Dicentrarchus labrax) Produced in Offshore Fish Farms: Variability and Multiple Regression Analysis. Sustainability, 11, 3523.

Gasco, L., Gai, F., Maricchiolo, G., Genovese, L., Ragonese, S., Bottari, T., & Caruso, G. (2018). Fishmeal alternative protein sources for aquaculture feeds. In Feeds for the aquaculture sector: current situation and alternative sources (pp. 1-28). Cham: Springer International Publishing.

Georgopoulos, V. P., Gkikas, D. C., & Theodorou, J. A. (2023). Factors influencing the adoption of artificial intelligence technologies in agriculture, livestock farming and aquaculture: A systematic literature review using PRISMA 2020. Sustainability, 15(23), 16385.

Gjedrem, T., & Baranski, M. (2009). The success of selective breeding in aquaculture. In *Selective Breeding in Aquaculture: An Introduction* (pp. 13-23). Dordrecht: Springer Netherlands.

Gjedrem, T., & Robinson, N. (2014). Advances by selective breeding for aquatic species: A review. Aquaculture, 420–421, 1–7. http://dx.doi.org/10.4236/as.2014.512125

Gjedrem, T., & Rye, M. (2018). Selection response in fish and shellfish: a review. Reviews in Aquaculture, 10(1), 168-179. https://doi.org/10.1111/raq.12154.

Gjedrem, T., Robinson, N., & Rye, M. (2012). The importance of selective breeding in aquaculture to meet future demands for animal protein: A review. Aquaculture, 350–353, 117–129. https://doi.org/10.1016/j.aquaculture.2012.04.008.

Glencross, B. D. (2020). A feed is still only as good as its ingredients: an update on the nutritional research strategies for the optimal evaluation of ingredients for aquaculture feeds. Aquaculture Nutrition, 26(6), 1871-1883. https://doi.org/10.1111/anu.13138.

Glover, K. A., Solberg, M. F., McGinnity, P., Hindar, K., Verspoor, E., Coulson, M. W., Hansen, M. M., Araki, H., & Svåsand, T. (2017). Half a century of genetic interaction between farmed and wild Atlantic salmon: status of knowledge and unanswered questions. Fish and Fisheries, 18(5), 890-927. https://doi.org/10.1111/faf.12214

Gold Standard. (2025). The Gold Standard Marketplace. https://marketplace.goldstandard.org/collections/projects?srsltid=AfmBOoqP2mpgtE-owwpj24xWwK4zAvV7_fmwMb0EFIfjzctCCpbMItrb

Guillen, J., Asche, F., Carvalho, N., Druon, J. N., Llorente, I., Sciberras, A., ... & Vukov, I. (2024). How sustainable is tuna aquaculture? A methodology to assess the sustainability of seafood production systems. Frontiers in Aquaculture, 3, 1422372.

Guillen, J., Asche, F., Carvalho, N., Druon, J.N., Llorente, I., Sciberras, A., Višnić Novaković, S. and Vukov, I., 2024. How sustainable is tuna aquaculture? A methodology to assess the sustainability of seafood production systems. *Frontiers in Aquaculture*, *3*, p.1422372.

Gurel, E., & Tat, M. (2017). SWOT Analysis: A Theoretical Review. The Journal of International Social Research, 10, 994-1006.

He, P., Davy, D., Sciortino, J., Beveridge, M. C., Arnason, R., & Gudmundsson, A. (2018). Countering climate change: measures and tools to reduce energy use and greenhouse gas emission in fisheries and aquaculture. Impacts of climate change on fisheries and aquaculture, 585.

Hossain, A., Senff, P., & Glaser, M. (2022). Lessons for Coastal Applications of IMTA as a Way towards Sustainable Development: A Review. Applied Sciences, 12(23), 11920. https://doi.org/10.3390/app122311920.

Hossain, M. S., Small, B. C., Kumar, V., & Hardy, R. (2024). Utilization of functional feed additives to produce cost-effective, ecofriendly aquafeeds high in plant-based ingredients. Reviews in Aquaculture, 16(1), 121-153.

Houston, R.D., Bean, T.P., Macqueen, D.J. et al. (2020). Harnessing genomics to fast-track genetic improvement in aquaculture. Nat Rev Genet 21, 389–409 (2020). https://doi.org/10.1038/s41576-020-0227-y

Huang, S. K., Kuo, L., & Chou, K.-L. (2016). The applicability of marginal abatement cost approach: A comprehensive review. Journal of Cleaner Production, 127, 59–71.

Huang, Y. P., et al. (2025). Artificial Intelligence of Things (AIoT) advances in aquaculture. Processes, 13(1), 73. https://doi.org/10.3390/pr13010073

Huntington, T.C. & Hasan, M.R. 2009. Fish as feed inputs for aquaculture – practices, sustainability and implications: a global synthesis. In M.R. Hasan and M. Halwart (eds.). Fish as feed inputs for aquaculture: practice, sustainability and implications, pp. 1–61.FAO Fisheries and Aquaculture Technical Paper. No. 518. Rome, FAO.

Institute for Environment and Sustainability (Joint Research Centre), Dietzel, A., & Maes, J. (2015). Costs of restoration measures in the EU based on an assessment of LIFE projects. Publications Office of the European Union.

Institute, M., & Mhara, B. I. (2024). Shellfish Stocks and Fisheries Review 2023: An assessment of selected stocks [Technical Report]. Marine Institute.

Iribarren, D., Moreira, M. T., & Feijoo, G. (2010). Revisiting the Life Cycle Assessment of mussels from a sectorial perspective. Journal of Cleaner Production, 18(2), 101–111.

Isaac, E. A. (2025). Integrating Renewable Energy Sources in Aquaculture Operations: Opportunities and Challenges. Journal of Built Environment and Geological Research.

Janssen, K., Saatkamp, H., & Komen, H. (2018). Cost-benefit analysis of aquaculture breeding programs. Genetics Selection Evolution, 50(1), 2.

Jean, A. B., & Brown, R. C. (2024). Techno-economic analysis of gas fermentation for the production of single cell protein. Environmental Science & Technology, 58(8), 3823–3829.

Joensen, B., & Bingham, H. B. (2024). Economic feasibility study for wave energy conversion device deployment in Faroese waters. Energy, 295, 130869.

Jolly, C.M., Nyandat, B., Yang, Z., Ridler, N., Matias, F., Zhang, Z., Murekezi, P. and Menezes, A., 2023. Dynamics of aquaculture governance. Journal of the World Aquaculture Society, 54(2), 427-481.

Kallistis, E., Korre, A., Mousamas, D., & Avramidis, P. (2020). Environmental life cycle assessment of mediterranean sea bass and sea bream. Sustainability, 12(22), 9617.

Kreibich, N. (2024). Toward global net zero: The voluntary carbon market on its quest to find its place in the post-Paris climate regime. WIREs Climate Change, 15(5), e892.

Kružić, Nikolina, Bosiljka Mustać, Ivan Župan, and Slavica Čolak (2016) "Meagre (Argyrosomus regius Asso, 1801) aquaculture in Croatia." Croatian Journal of Fisheries: Ribarstvo 74, no. 1: 14-19.

Kyule, D., Munguti, J., Muthoka, M., Ogello, E., Opiyo, M., & Abwao, J. (2025). Historical Origin of Trout Farming in Kenya: Current Status, Challenges, and Future Prospects. Aquaculture Research, 2025(1), 8816761.

Leys, C., Ley, C., Klein, O., Bernard, P., & Licata, L. (2013). Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median. Journal of Experimental Social Psychology, 49(4), 764–766.

Li, Y., Wang, H., Zhang, X., Liu, L., & Chen, Z. (2025). Insight into greenhouse gas emission in freshwater aquaculture ponds in Jiangsu Province: Variation due to species used and pond management practice. Journal of Environmental Sciences. https://doi.org/10.1016/j.jes.2025.03.042.

Lu, H. Y., Cheng, C. Y., Cheng, S. C., Cheng, Y. H., Lo, W. C., Jiang, W. L., ... & Ubina, N. A. (2022). A low-cost AI buoy system for monitoring water quality at offshore aquaculture cages. Sensors, 22(11), 4078.

Ma, F., Fan, Z., Nikolaeva, A., & Bao, H. (2025). Redefining Aquaculture Safety with Artificial Intelligence: Design Innovations, Trends, and Future Perspectives. *Fishes*, *10*(3), 88.

MacLeod, M. J., Hasan, M. R., Robb, D. H., & Mamun-Ur-Rashid, M. (2020). Quantifying greenhouse gas emissions from global aquaculture. Scientific reports, 10(1), 11679.

Martini, A., Napolitano, R., Capoccioni, F., Martinoli, M., Tonachella, N., Aguiari, L., Piva, P., Rossetti, E., & Pulcini, D. (2025). Prefacing the challenge – Assessment of the environmental efficiency of Manila clam (Ruditapes philippinarum) production based on hatchery-produced and wild seed. Aquaculture, 595, 741474.

McDonald, N., Lovric, K., & Cosby, A. (2024). Skill Development in Current and Future Workers to Thrive in the Digital Aquaculture Industry. Aquaculture Journal, 4(1), 15-27.

Mhara, B. I. (2024). Shellfish Stocks and Fisheries Review 2023: an assessment of selected stocks.

MOA, Department of Fisheries and Marine Research, Overview- Cyrpus Aquaculture 2024. Retrieved from: https://www.moa.gov.cy/moa/dfmr/dfmr.nsf/All/CF42DB069283278342257E960035E13B/$file/Cypriot%20Aquaculture%202024.pdf

Modahl, I. S., & Brekke, A. (2022). Environmental performance of insect protein: A case of LCA results for fish feed produced in Norway. SN Applied Sciences, 4(6), 183.

Navarro Forner, P. (2021). Plan de empresa dedicada al cultivo y transformación de macroalgas para consumo humano. Universitat Politècnica de València.

Nguyen, N. H. (2016). Genetic improvement for important farmed aquaculture species: A review. Aquaculture, 465, 153–161. https://doi.org/10.1111/faf.12122

Niyonsaba, H. H., Groeneveld, I. L., Vermeij, I., Höhler, J., Van der Fels-Klerx, H. J., & Meuwissen, M. P. M. (2023). Profitability of insect production for T. molitor farms in The Netherlands. Journal of Insects as Food and Feed, 10(6), 895–902.

Nunes, A. J., Yamamoto, H., Simões, J. P., Pisa, J. L., Miyamoto, N., & Leite, J. S. (2023). The black soldier fly (Hermetia illucens) larvae meal can cost-effectively replace fish meal in practical nursery diets for post-larval Penaeus vannamei under high-density culture. Fishes, 8(12), 605.

Olesen, I., Gjedrem, T., Bentsen, H. Á., Gjerde, B., & Rye, M. (2003). Breeding programs for sustainable aquaculture. Journal of Applied Aquaculture, 13(3-4), 179-204.

Oliveira-Pinto, S., & Stokkermans, J. (2020). Assessment of the potential of different floating solar technologies – Overview and analysis of different case studies. Energy Conversion and Management, 211, 112747. https://doi.org/10.1016/j.enconman.2020.112747.

Panda, R. K., & Baral, D. (2023). Adoption of AI/ML in Aquaculture: a study on Pisciculture. J Surv Fish Sci, 228-233.

Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjö, A., Kruse, S., Cancino, B., & Silverman, H. (2009). Not all salmon are created equal: Life cycle assessment of global salmon farming systems. Environmental Science & Technology, 43(23), 8730–8736. https://pubs.acs.org/doi/pdf/10.1021/es9010114.

Publications Office of the European Commission. (2021). Freshwater aquaculture in the EU. Publications Office. https://data.europa.eu/doi/10.2771/594002

Publications Office of the European Union. (2022). Study on state-of-the-art scientific information on the impacts of aquaculture activities in Europe: Final report. Publications Office. https://data.europa.eu/doi/10.2926/929238

Ragab, S., et al. (2024). Overview of Aquaculture Artificial Intelligence (AAI) applications. Aquaculture & Aquatic Sciences. https://doi.org/10.2478/aoas-2024-0075

Rana, K. J., Siriwardena, S., & Hasan, M. R. (2009). Impact of rising feed ingredient prices on aquafeeds and aquaculture production. FAO Fisheries and Aquaculture Technical Paper No. 541.

Rather, M. A., Ahmad, I., Shah, A., Hajam, Y. A., Amin, A., Khursheed, S., ... & Rasool, S. (2024). Exploring opportunities of Artificial Intelligence in aquaculture to meet increasing food demand. Food Chemistry: X, 22, 101309.

Ridler, N., Wowchuk, M., Robinson, B., Barrington, K., Chopin, T., & Robinson, S. (2007). Integrated multi-trophic aquaculture (IMTA): A potential strategic choice for farmers. Aquaculture Economics & Management, 11(1), 99–110. https://doi.org/10.1080/13657300701202767.

Rumbos, C. I., Mente, E., Karapanagiotidis, I. T., Vlontzos, G., & Athanassiou, C. G. (2021). Insect-Based Feed Ingredients for Aquaculture: A Case Study for Their Acceptance in Greece. Insects, 12(7), 586. https://doi.org/10.3390/insects12070586.

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.

Samuelsson, S. (2022). A comprehensive review of the factors influencing the environmental impact of different species bred in closed land-based recirculating aquaculture system. Bachelor thesis Environmental Science. Lund University. Lund University Library.

Schade, S., & Meier, T. (2021). Techno-economic assessment of microalgae cultivation in a tubular photobioreactor for food in a humid continental climate. Clean Technologies and Environmental Policy, 23(5), 1475-1492.

Scientific Technical and Economic Committee for Fisheries (STECF) – The 2024 Aquaculture Economic Report (STECF 24-14), NIELSEN, R., LLORENTE, I., VIRTANEN, J. and GUILLEN, J. editor(s), Publications Office of the European Union, Luxembourg, 2025, https://data.europa.eu/doi/10.2760/5049952, JRC140767.

Scroggins, R. E., Fry, J. P., Brown, M. T., Neff, R. A., Asche, F., Anderson, J. L., & Love, D. C. (2022). Renewable energy in fisheries and aquaculture: Case studies from the United States. Journal of Cleaner Production, 376, 134153.

Serra, V., Pastorelli, G., Tedesco, D. E. A., Turin, L., & Guerrini, A. (2024). Alternative protein sources in aquafeed: Current scenario and future perspectives. Veterinary and Animal Science, 25, 100381. https://doi.org/10.1016/j.vas.2024.100381

Song, X., Liu, Y., Pettersen, J.B., Brandao, M., Ma, X., Roberg, S., Frostell, B. (2019) Life Cycle Assessment of recirculating aquaculture systems. A case of Atlantic salmon farming in China. Journal of industrial ecology.

Sun, W. (2009). Life cycle assessment of indoor recirculating shrimp aquaculture system (Doctoral dissertation).

Tamburini, E., Turolla, E., Fano, E. A., & Castaldelli, G. (2020). Sustainability of mussel (Mytilus galloprovincialis) farming in the Po river delta, northern Italy, based on a life cycle assessment approach. Sustainability, 12(9), 3814.

Tian, XL., Dong, SL. (2023). Land-Based Intensive Aquaculture Systems. In: Dong, SL., Tian, XL., Gao, QF., Dong, YW. (eds) Aquaculture Ecology. Springer, Singapore. https://doi.org/10.1007/978-981-19-5486-3_10.

Tölgyesi, C., Csikós, N., Temperton, V. M., Buisson, E., Silveira, F. A. O., Lehmann, C. E. R., Török, P., Bátori, Z., & Bede-Fazekas, Á. (2025). Limited carbon sequestration potential from global ecosystem restoration. Nature Geoscience, 18(8), 761–768. https://doi.org/10.1038/s41561-025-01742-z.

Tsakiridis, A., O'Donoghue, C., Hynes, S., & Kilcline, K. (2020). A comparison of environmental and economic sustainability across seafood and livestock product value chains. Marine Policy, 117, 103968. https://doi.org/10.1016/j.marpol.2020.103968

Ullah, F., Saqib, S. & Xiong, YC. (2025). Integrating artificial intelligence in biodiversity conservation: bridging classical and modern approaches. Biodivers Conserv 34, 45–65 (2025). https://doi.org/10.1007/s10531-024-02977-9

Van Riel, A., Nederlof, M. A. J., Chary, K., Wiegertjes, G. F., & De Boer, I. J. M. (2023). Feed-food competition in global aquaculture: Current trends and prospects. Reviews in Aquaculture, 15(3), 1142-1158. https://doi.org/10.1111/raq.12804

Vázquez-Romero, B., Villar-Navarro, E., Perales, J. A., Garrido-Pérez, C., & Ruiz, J. (2024). Techno-economic analysis of using microalgae to treat streams from fish RAS farming and replace fish meal: A case study. Journal of Water Process Engineering, 59, 104904. https://doi.org/10.1016/j.jwpe.2024.104904.

Vielma, J., Kankainen, M., & Setälä, J. (2022). Current status of recirculation aquaculture systems (RAS) and their profitability and competitiveness in the Baltic Sea area. https://urn.fi/URN:ISBN:978-952-380-504-0.

Vo, T. T. E., Ko, H., Huh, J. H., & Park, N. (2021). Overview of solar energy for aquaculture: The potential and future trends. Energies, 14(21), 6923.

Vodounnou, J. V., Iko, R., Okou, G., Kpogue, D., Ahouansou Montcho, S., & Micha, J.-C. (2025). Complete substitution of fish meal with black soldier flies Hermetia illucens (L. 1758) larvae meal at varying incorporation rates for feeding Oreochromis niloticus raised in captivity. Aquaculture Science and Management, 2(1), 1.

Wang, C., Li, Z., Wang, T. et al. (2021). Intelligent fish farm—the future of aquaculture. Aquacult Int 29, 2681–2711 (2021). https://doi.org/10.1007/s10499-021-00773-8

Wind, T., Schumann, M., Hofer, S., Schulz, C., & Brinker, A. (2022). Life cycle assessment of rainbow trout farming in the temperate climate zone based on the typical farm concept. Journal of Cleaner Production, 380, 134851.

World Bank. (2020, May). State and trends of carbon pricing 2020. International Bank for Reconstruction and Development / The World Bank.

Yacout, D. M., Soliman, N. F., & Yacout, M. M. (2016). Comparative life cycle assessment (LCA) of Tilapia in two production systems: semi-intensive and intensive. The International Journal of Life Cycle Assessment, 21(6), 806-819.

Yu, L., Ren, A., Han, F., Jia, F., Li, S., Guan, J., ... & Liu, Y. (2024). Optimization Analysis of Yellowtail Kingfish (Seriola aureovittata) Land–Sea

Relay Farming Based on Life Cycle Environment and Cost Assessment in Dalian, China. Sustainability, 16(15), 6452.

Zhang, Z., Liu, H., Jin, J., Zhu, X., Han, D., & Xie, S. (2024). Towards a low-carbon footprint: Current status and prospects for aquaculture. Water Biology and Security, 3(4), 100290.

European Legislation

Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (‘European Climate Law’)

Regulation (EU) 2023/857 of the European Parliament and of the Council of 19 April 2023 amending Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement, and Regulation (EU) 2018/1999

Regulation (EU) 2024/3012 of the European Parliament and of the Council of 27 November 2024 establishing a Union certification framework for permanent carbon removals, carbon farming and carbon storage in products

Annex 1: Project methodology

Description of method for baseline analysis

Data Collection and system boundaries for finfish

The first phase of the work consisted in the collection of aquaculture production data in EU countries from 2005 to 2025 extracted from the FAO's database FishStatJ (FAO, 2025). FishStatJ was chosen as the data source for all years as the data available on the EUMOFA website only goes back as far as 2010 and a single source was preferred for consistency. As the database contains annual data detailed at species level, species belonging to the same family and the same environment (fresh water and marine) were grouped together. As production data for 2024 were not available, production for this was assumed to be the production volumes from 2023 + 1.6% ([21]).

The aquaculture production systems analysed were cages, recirculating aquaculture systems (RAS), ponds, raceways, and the non-fed aquaculture (a.k.a. culture of bivalves including *bouchot*). A description of the production systems is provided in Annex 8. The proportion that each of these systems contributed to the production of each different species in each country was also incorporated into the database. For most countries, two sources were used to identify the production methods adopted and their proportional contribution to production volumes. For freshwater species, annex 1 of the European Market Observatory for Fisheries and Aquaculture (EUMOFA) report in 2021 'Freshwater Aquaculture in the EU' was used, while for marine species data were collected from the website of the EU Aquaculture Assistance Mechanism, managed by the European Climate, Infrastructure and Environment Executive Agency (CINEA) on behalf of Directorate-General for Maritime Affairs and Fisheries (DG MARE) ([22]).

As historical data about the change in production systems in the last 20 years were not available, it was assumed that the systems indicated in the sources mentioned above did not change substantially in the study period considered (2005-2024).

([21]) 1.6% is the predicted average annual growth of the aquaculture industry according to FAO 2024

([22]) https://aquaculture.ec.europa.eu/country-information

While in some cases variations in the production systems used have occurred in some Member States during the last 20 years, it is reasonable to assume that the magnitude of shifts from one production system to another is not considerable. The only exception is Recirculating Aquaculture Systems (RAS), which increased significantly in the last 10 years. However, the use of this system is still minor compared to other production methods and such assumption does not have a significant impact on the overall estimation of emissions.

Figure 32 shows an example of the organisation of species, annual production and production methods from 2005 to 2024 in the final database.

Figure 32 – Example of annual production data for different production methods as organised in the database

Species	Environment	Year	Production System (PS)	% PS Used	Production per sytems (tonnes)	Total production (Tonnes)
Salmonoids	Freshwater	2005	Ponds	90.5	2219.06	2452
	Freshwater		Raceways	9.5	232.94	
	Freshwater	2006	Ponds	90.5	2894.19	3198
	Freshwater		Raceways	9.5	303.81	
	Freshwater	2007	Ponds	90.5	2559.34	2828
	Freshwater		Raceways	9.5	268.66	
	Freshwater	2008	Ponds	90.5	3111.39	3438
	Freshwater		Raceways	9.5	326.61	
	Freshwater	2009	Ponds	90.5	2362.05	2610
	Freshwater		Raceways	9.5	247.95	
	Freshwater	2010	Ponds	90.5	2463.41	2722
	Freshwater		Raceways	9.5	258.59	
	Freshwater	2011	Ponds	90.5	1732.0795	1913.9
	Freshwater		Raceways	9.5	181.8205	
	Freshwater	2012	Ponds	90.5	1783.09435	1970.27
	Freshwater		Raceways	9.5	187.17565	
	Freshwater	2013	Ponds	90.5	1824.9325	2016.5
	Freshwater		Raceways	9.5	191.5675	
	Freshwater	2014	Ponds	90.5	1460.3985	1613.7
	Freshwater		Raceways	9.5	153.3015	
	Freshwater	2015	Ponds	90.5	1594.791	1762.2
	Freshwater		Raceways	9.5	167.409	
	Freshwater	2016	Ponds	90.5	1488.0915	1644.3
	Freshwater		Raceways	9.5	156.2085	
	Freshwater	2017	Ponds	90.5	1799.7735	1988.7
	Freshwater		Raceways	9.5	188.9265	

The production method used influences emissions through nutrient loading and waste decomposition, which can cause nitrous oxide and methane emissions, but these are typically less significant than emissions due to use of non-renewable sources of energy (Chen et al 2023). Moreover, detailed variations in sources of energy used in the last 20 years are accounted for, and the GHG emissions are calculated by modelling the emissions of the different systems adjusted to account for the different mixes of energy sources that were used during the focus periods. Data about main sources of energy used to produce electricity in different countries were also collected from the EUROSTAT database (EUROSTAT, 2025). EUROSTAT provides data about use of sources of energy for different sectors; however, it does not provide specific data for the aquaculture sector. Hence, use of sources of energy at national level were considered, and it was assumed that these are reflected in the aquaculture sector in the same proportion.

Data on GHG emissions associated with the production of 1 tonne of each aquaculture species, across the different production systems and EU Member States were primarily derived from peer-reviewed Life Cycle Assessment (LCA) studies. The complete list of the studies used is shown in Table 46 (for fish) and Table 47 (for non-fed aquaculture). Both direct and indirect emissions were considered in the calculation of emissions.

The direct emissions are represented by the hatchery-associated emissions and by emissions generated in culture operations such as those generated by on-site fuel use for boats, on-site machinery and equipment and nitrous oxide coming from pond sediments and sludge management in certain systems.

The indirect emissions considered in the study were the ones related to the feed production including ingredients sourcing, processing, transportation and logistics associated with feed delivery.

Once emissions data were obtained from the literature for each species–production system–country combination, total emissions were calculated by multiplying the CO_2-eq. emissions per tonne of LW by the corresponding annual production volumes.

General assumptions were made due to country specific data gaps. Other sources, assumptions and calculations specific for different countries are listed below.

Bulgaria

No data about production methods in Bulgaria were present in the sources used for other countries. The percentages indicated for the different systems were estimated based on the number of times each system was reported in the Scientific, Technical and Economic Committee for Fisheries (STECF) 24-14 Aquaculture economic sector database (STECF, 2024). This database reports data from a sample number of farms that changes depending on the species collected between 2015 and 2020.

Cyprus

The EUMOFA report did not provide data about freshwater production systems. The national aquaculture report was used instead (MOA, 2024).

Estonia

According to 2022 data available in Eurostat, in Estonia, aquaculture production is carried out both in sea and brackish water and in freshwater. Marine and brackish water aquaculture production is mainly carried out using cage methods and a small percentage in ponds, while freshwater aquaculture mainly uses tanks and raceways as production methods. However, no details are available for more than half (55%) of the production ([23]). It was assumed that 100% of the freshwater farms are constituted by tanks and raceway and that 100% of seawater species are farmed in cages.

France

The proportions of the different freshwater production systems indicated were made using data that refer to only 19.5% of the freshwater farms active in the country as the production method for 80.5% of freshwater farms is not specified.

A small number of seabass ponds are present in Northern France, but specific percentage for this system is not available and it is known to be a minor contributor to total production, so it was assumed that 100% of seabass in France is produced in cages.

Germany

The EUMOFA report about freshwater aquaculture indicates that ponds, raceways and RAS are present in the proportion of 39%, 59% and 2% respectively. However, another EUMOFA report about RAS indicates that these systems appeared in Germany in 2016 (EUMOFA, 2020). Hence, for the previous time, it was assumed that Ponds and Raceways were the only two freshwater aquaculture systems used in the proportion of 40% and 60% respectively.

Slovakia

Data about production methods for 43% of the farms were not available, it was assumed that the production systems available for the other farms were used in the same proportion in these farms for which details are not available.

Sweden

Data about RAS system are extracted from Bergman et al (2020). These data took the form of proportions of total production by production system, and these were used to estimate production volumes for each species and system for each year interval.

([23]) https://aquaculture.ec.europa.eu/country-information/estonia

Definition of System Boundaries for finfish

To ensure comparability across different studies, it was necessary to define consistent system boundaries. In LCA, system boundaries delineate which processes are included in the analysis. Given that the different LCAs studied used varying boundaries, 2 specific system boundaries were defined for fin fish aquaculture.

- For analysis of emissions generated in raceways, ponds, and RAS, the system boundaries encompassed (Figure 33):
  - Hatchery
  - Feed production and transportation
  - Feed transportation from production plant to farm
  - On-farm grow-out (including energy used for pumping water, monitoring and managing water quality, and feeding)
- For cage systems, the boundaries included (Figure 34):
  - Hatchery
  - Feed production
  - Feed transportation from production plant to farm
  - Grow-out
  - Emissions associated with boat trips

These boundaries correspond to a cradle-to-gate perspective, excluding post-harvest stages such as packaging and manufacture of fish, waste processing and commercial distribution stages.

The resulting database categorizes emissions according to each defined life cycle stage, across all species, systems, and countries. The following subsections describe each life cycle stage included within the study's defined system boundaries:

Hatchery

This includes all activities required to produce smolts and juveniles in dedicated hatcheries. Two articles were consulted as a source to estimate the contribution of the hatchery stage to overall emissions (Table 45). One reported a contribution between 6 and 10%, while a second one reported a contribution of only 6%. In the present study, a transversal 10% emissions increase was applied transversally to all species and production methods to include the emissions derived from the hatchery stage.

Table 45 – References consulted to estimate the contribution of Hatchery to overall emissions

Study	Species	Country	% Contribution hatchery stage on overall emissions
Smárason, B. Ö., Ögmundarson, Ó., Árnason, J., Bjornsdottir, R., & Davidsdottir, B. (2017). Life cycle assessment of Icelandic arctic char fed three different feed types.	Arctic char	Iceland	6-10%
Grönroos, J., Silvenius, F., Kankainen, M., Silvo, K., & Mäkinen, T. (2012). Life cycle environmental impacts of different fish production alternatives in the Baltic Sea.	Rainbow trout	Finland	6%

Feed Production

This stage includes all processes from the production of feed materials, from sourcing to processing into formulated feed. These data were extracted from available literature.

Feed Transportation

Because many LCAs did not separately report feed transportation emissions, these were estimated independently. This estimation required four steps described below.

- **Identification of average Feed Conversion Ratios (FCRs)**: Species-specific average FCRs were determined through literature review and expert interviews, accounting for environmental conditions such as temperature.
- **Calculation of total feed use**: The total feed consumption per species was calculated by multiplying the FCR by the species' production volume.
- **Estimation of distances**: An average transportation distance (from feed producers to fish farms) of 250 km was assumed. Stakeholders and experts were consulted to estimate the distance. These suggested that most of the feed used in EU fish farms is produced in Europe. The average distance was estimated considering the location of the main feed producers in Europe and the distribution of fish farms in the EU countries.
- **Emissions calculation:** Transportation was modelled in SimaPro using the truck type EURO 6 trucks, with a capacity of 28 tonnes of feed carried per trip. Emissions related to the transportation of 1 tonne of feed were calculated for 250 km was inputted.

For 1 tonne of feed transported, an average of 192 g CO_2eq was emitted by using a 28-t capacity truck for one km. This number was directly calculated by the software considering the capacity of the truck.

Once the emissions related to the transportation of 1 tonne of feed calculated, the data was then multiplied by the total feed consumed per species–system–period.

Grow-out Phase

This stage includes emissions associated with all activities occurring during the rearing of fish. It includes feeding operations, maintenance, and other energy used by equipment like pumps, monitoring systems, oxygen and water quality management and lime input. These emissions are extracted from the available literature (Table 46) and remodelled with SimaPro to adjust them considering the specific sources of energy used in the different countries (detailed methodology explained in section 2.3.8).

Emissions associated with boat trips

For cage aquaculture, the emissions associated with use of vessels to reach the cages were also considered. These were estimated based on the results of the study of Garcia et al. (2019). The authors analysed the LCA of offshore (5 km from the coast) seabass production in Greece. They estimated that the vessels are responsible for the emission of 0.21t CO_2eq /t LW. This value, that includes trips for cage revision, removal of dead fish, maintenance and feeding, was used in the present study for all the cage aquaculture production.

Adjustments of the different LCA studies' boundaries

To standardize emissions data, adjustments were made when original LCA studies extended beyond the defined system boundaries (Figure 33 and Figure 34). For example, if reported emissions included downstream stages such as packaging or commercial transportation, the proportional contribution of these stages was deducted. When studies reported emissions from additional minor sub-processes (e.g., internal logistics, specific material use), their emissions were aggregated into an "Other" category to reduce data fragmentation and enhance comparability. This harmonisation ensured consistency in the scope of emissions considered across all species, systems, and Member States.

Table 46 – Reference and assumption used for finfish aquaculture

Source	Species	Production System	Country original study	Notes and Assumptions
(Diken et al., 2023)	Salmonids	Ponds	Germany	Trout production in ponds
	Perches			
	Catfish			
	Cyprinids	Ponds	Vietnam	Carp production in ponds

Source	Species	Production System	Country original study	Notes and Assumptions
(Biermann & Geist, 2019)	Eels Pikes Sturgeons Flatfish Tilapias			
(Boyd et al., 2012)	Catfish	Ponds	USA	Catfish production in ponds and RAS
(Yacout et al., 2016)	Tilapias	Ponds	Egypt	Tilapia production in ponds
(Al Eissa et al., 2022)	Malacostracans	Ponds	USA	Shrimp production in ponds
(Wind et al., 2022)	Salmonids Perch Catfish	Raceways	Germany	Trout production in raceways
(Biermann & Geist, 2019)	Cyprinids Eels Pikes Sturgeons Flatfish Tilapias	Raceways	Vietnam	Carp production in ponds
(Song et al., 2019)	salmonids	RAS	Denmark	Trout production in RAS (Song et al., 2019)
(Samuel-Fitwi et al., 2013)	salmonids	RAS	China	Salmon production in RAS (Samuel-Fitwi et al., 2013)
(Bergman et al., 2020)	 Tilapias Cyprinids	RAS	Sweden	Tilapias and Clarias production in RAS (Bergman et al., 2020)
(Boxmann et al., 2016)	Eels Pikes	RAS	Virgin Islands	Tilapias farmed in RAS (Boxman et al., 2016)
(Samuelsson, 2022)	Sturgeons	RAS	Sweden	GHG emissions repartition between life cycle phases for different species bred in RAS, including tilapias. (Samuelsson, 2022)
(Besson et al., 2016)	Catfish	RAS	Netherlands	Catfish production in RAS (Besson et al., 2016)
(Samuel-Fitwi et al., 2013	Catfish	RAS	Netherlands	Salmon production in RAS (Samuel-Fitwi et al., 2013)
(Aubin et al., 2009)	Flatfish	RAS	France Global/Europe	Turbot production in RAS (Aubin et al., 2009) Multi species production in RAS (Badiola et al., 2018)
(Badiola et al., 2018)	Flatfish	RAS		
(Sun et al., 2009)	Malacostracans	RAS	Vietnam	Shrimp production in RAS

Source	Species	Production System	Country original study	Notes and Assumptions
(Yu et al., 2024)	Seriola	RAS	China	Seriola production in RAS
(Cooney et al, 2021)	Perch	RAS	Ireland	Seriola production in cages
(Bord Iascaigh Mhara., 2023)	Salmonids	Cages	Ireland	Salmon production in cage
	Sturgeons			
(Kallistis et al., 2020)	Seabream	Cages	Greece	Seabream and Seabass production in Greece (Kallistis et al., 2020)
	Flatfish			
(Garcia et al., 2019)	seabass		Spain	Seabass production in Spain (Garcia et al., 2019)
	Meagre			
(Guillen et al., 2024)	Tuna	Cages	Malta	Tuna production in cages

Figure 33 – System boundaries (red square) considered in the study for the LCA of aquaculture in pond, raceway and RAS

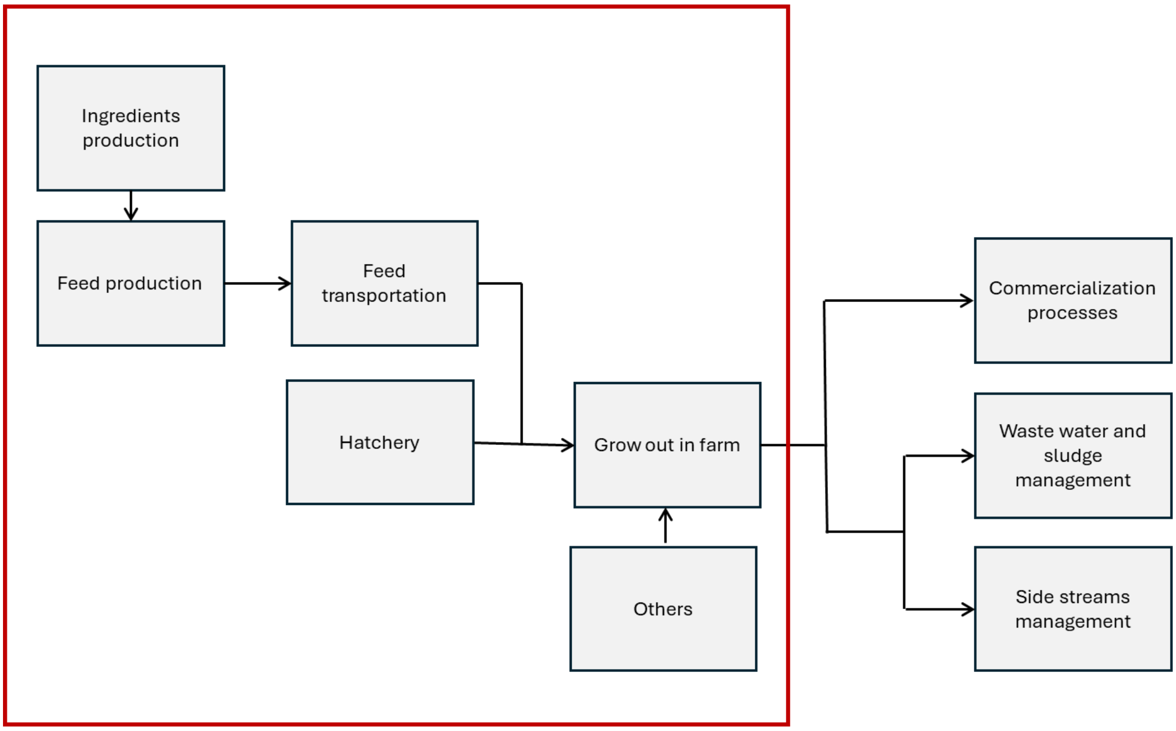
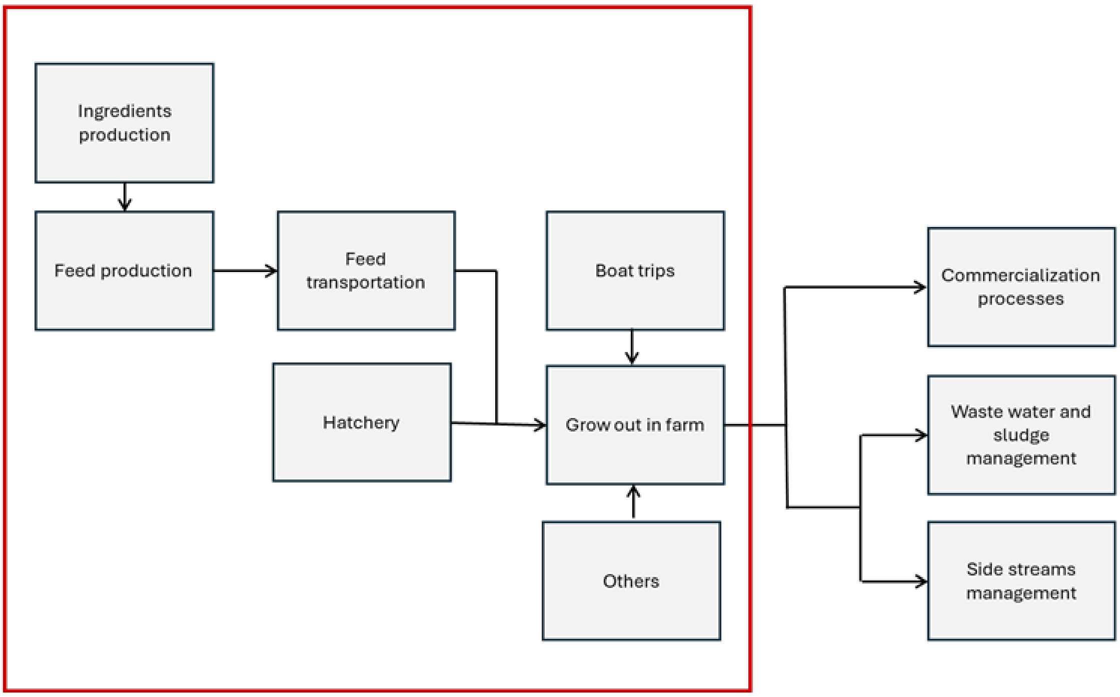


Figure 34 – System boundaries (red square) considered in the study for the LCA of aquaculture in cage



Calculation of the CO_2eq emissions

To estimate the emissions associated with each life cycle stage, the percentage of contribution of that stage to the total emissions (included in the boundaries) was derived from the LCA studies reported in Table 46and Table 47. This percentage was then applied to the total CO_2 equivalent emissions per year for the same species and production system.

For example, if feed accounted for 72% of the total emissions within a system boundary, the emissions attributable to feed alone were calculated as:

$$(72 / 100) \times \text{total } CO_2\text{eq. emissions}$$

As a result, the formulas in the database used to calculate emissions associated with different categories report different percentages for different species and production systems.

Trophic-level-based data assumptions for missing species-specific LCA data

Species-specific LCA data were not available for all species across all systems and countries. In such cases, emissions data were calculated based on studies that included species of similar trophic levels.

For example, GHG emissions data for meagre in cage systems, were unavailable. To estimate emissions for this species, data from seabream were used. These species share similar trophic levels, are often reared in comparable environmental conditions, and are farmed in similar production systems. This approach helped maintain ecological and methodological consistency while bridging key data gaps.

Data Collection and system boundaries for non-fed aquaculture

Data about non-fed aquaculture production were also collected from the FAO’s database FishStatJ, aggregated at family level, and separated in different production systems. Emissions were estimated based on existing literature (Table 3). The production systems considered for shellfish production in this study included on-bottom, bouchot, off-bottom longline, and raft systems (see annex 8 for description of the different systems).

Definition of System Boundaries for non-fed aquaculture

As shellfish production does not involve feed inputs, the system boundaries defined for this study focus on two main stages: grow-out in the farm and harvesting. Where appropriate, hatchery stage and boat trips were included in the study boundaries. The subsections below explain in detail each life cycle stage included within the scope of the study.

Hatchery

This includes all activities required to produce seeds in dedicated hatcheries. Hatchery seed production was considered for all species except for mussel, as natural seed is overall used irrespective of the production system (e.g., longline, raft, *bouchot*).

Grow-Out in Farm

This stage considers all on-farm activities during the rearing phase. It includes the impact of the use of auxiliary materials and gears (e.g., cotton socks for mussel cultivation) as well as boat operations for site maintenance and stock monitoring.

Emissions associated with boat trips

For the production systems that require boat travelling, the emissions for this activity were included in the study boundary.

These include the emissions that results from the fuel used in boat transports to and from the farm for the various activities conducted over the life cycle (stocking, inspections, harvesting etc).

This stage includes all processes related to the harvesting of shellfish following the grow-out period.

Table 47 – Reference and assumption table for shellfish/non-fed aquaculture

Source	Species	Production system	Country original study	Notes and Assumptions
(Institute & Mhara, 2024)	Mussels	On-bottom	Ireland	Used for all countries
(Tamburini et al., 2020)	Mussels	Longline	Italy	Used for all countries
(Iribarren et al., 2010)	Mussels	Raft	Spain	Used for all countries

Source	Species	Production system	Country original study	Notes and Assumptions
(Aubin et al., 2018)	Mussels	Bouchot	France	
(Tamburini et al., 2020)	Oysters	Longline	Italy	Used for all countries
(Martini et al., 2025)	Clams Cockles Carpet shells Scallop	On-bottom	Italy	The study was on clams intertidal farm, used also for Cockles, carpet shell and scallop in all countries

Addressing Data Gaps and Uncertainty for non-fed aquaculture

Given the heterogeneity of the aquaculture sector and the limited availability of comprehensive LCA data, several assumptions were made to address data gaps and maintain methodological consistency across species, production systems, and EU Member States. The following subsections outline the primary methods and assumptions used.

Proxy data for ecologically similar species

In cases where specific LCA data were unavailable for a given shellfish species, proxy data were used from ecologically similar species cultivated under identical conditions. In this context, the same data was used for clams, cockles, scallops and carpet shell. Since shellfish production does not include feeding stages, the environmental impact of two species reared under the same production system is considered comparable across the EU.

European data for missing country-specific data

Detailed country-level data on shellfish production practices were not available for the majority of EU Member States. However, unlike fish aquaculture, shellfish production does not typically involve energy-intensive inputs during the grow-out phase. As such, GHG emissions associated with shellfish production were assumed to be consistent across countries. GHG emissions in different countries and different periods, were extracted from the studies indicated in Table 46.

Addressing data gaps and uncertainty for finfish

Due to the heterogeneity of the aquaculture sector and the limited availability of comprehensive Life Cycle Assessment (LCA) studies, several assumptions were made to fill data gaps and ensure consistency across species, production systems, and EU Member States. The following subsections outline the key assumptions and methods used to address data limitations.

Country-Specific adjustment using national energy mix

LCA studies used in this study were conducted for a single species or species group, in a specific production system, within a particular country. In cases where no European LCA data were available, LCA studies from Asia, Africa, or the Americas were used as proxies. To estimate emissions across EU Member States more accurately, electricity-associated emissions were remodelled according to national energy sources used. Since the type and share of energy sources (coal, gas, renewables) used to power aquaculture operations vary between countries and over time, the CO_2-eq. emissions from energy consumption were recalculated using country-specific electricity profiles.

To do so, the methodology focused on two main steps:

- Step 1: Data collection of EU Member States' energy-mix

  The sources of energy used by different countries from 2005 to 2023 were collected from Eurostat for each Member State (EUROSTAT, 2025). Eurostat database reports the use of different sources of energy at national level, as well as for some specific sectors. However, the specific sources of energy used in the aquaculture sector are not available, hence use of different sources at national level was considered and it was assumed that it reflects the sources of energy specifically used for the aquaculture sector.

- Step 2: Calculation of electricity-associated Emissions for different Member State's systems and species studied

  For each study in Table 46, the emissions (t CO_2eq.) and the number of Kilowatt Hour (kWh) associated with electricity consumption to produce 1 tonne of LW were extrapolated. The emissions related to the use of 1 kWh of electricity were then modelled on software SimaPro considering for each country the specific mix of sources of energy used (extracted by EUROSTAT). These emissions of 1 kWh adjusted according to specific energy sources were then multiplied by the number of kWh necessary to produce 1 tonne of LW.

Description of method for scenario development

A list of tools to improve aquaculture efficiency while reducing emissions was identified and for each tool the potential to reduce emissions was estimated. Different tools were then suggested for different scenarios. Five scenarios for the development of the aquaculture sector in Europe in the periods 2025-2030, 2031-2040 and 2041-2050 were agreed with the contracting authority and validated by stakeholders. The scenarios consist in a number of actions (adoption of tools identified) to be taken in the next 25 years to ensure growth of the aquaculture industry in Europe while reducing its environmental impact. The scenarios were selected based on different priorities: to achieve the reduction emissions targets set in EU ESR, to minimise the investment requested, to protect the sector from the negative impact of climate change, and to maximise the reduction of GHG emissions. These scenarios were then compared with a baseline scenario where aquaculture emissions from 2025 to 2050 were estimated assuming that no action to minimise the impact will be taken. For each scenario, different tools at different intensity were suggested based on its focus.

In consultation with CINEA and DG MARE, it has been discussed that hard-to-abate scenarios should be seen as variants of existing scenarios, adding tool to offset hard-to-abate scenario. Subsequently, the study team identified four tools to offset hard-to-abate emissions and formulated two hard-to-abate scenarios.

Data collection for cost of proposed tools

Cost data associated with proposed tools were gathered through literature review and interviews with targeted stakeholders. The literature search began with a focus on peer-reviewed journal articles. Predefined search strings were used, such as “economic” combined with the specific tool name.

The retrieved documents were then screened according to three main criteria. First, they had to provide quantitative economic data, especially figures on capital and operational costs for a specific tool. It is noted that emerging feed materials had to focus on aquafeed, not for cosmetics or pharmaceuticals. Second, the cost data needed had to reflect farm-scale. Third, the documents had to address tools within the European context.

Due to the relatively limited publication of relevant data in peer-reviewed journals, the search was subsequently expanded to include book chapters, reports, and academic theses in order to capture additional information. In instances where relevant information still remained unavailable, interviews with stakeholders were conducted to obtain the necessary insights. These interviews were also useful for validating the information gathered from literature review, where applicable. Cost of a proposed tool is presented in Annex 3.

Stakeholder engagement

The purpose of the targeted stakeholder interviews in task 2 was to gather feedback on the proposed tools, including their characteristics, scenario development, and cost data. The interviews, which lasted approximately 45 minutes each, were conducted online via Microsoft Teams. An official support letter, along with the data management plan and interview guide, was provided prior to the interviews. The interview questions covered the following sections:

Section 1: Tools description

The table below (Table 48) outlines tools identified to support the transition to net zero in the aquaculture sector within the EU by 2050, and their description.

Table 48 - Tool description for targeted interviews

Tools	Description	TRL
Emerging feed materials in aquafeeds to replace fishmeal and soybeans	Insects, microalgae, poultry by-products, single cell protein	5
Breeding program	Focused on selecting breeds that optimise the efficiency of the emerging materials and more resistant to novel pathogens and increased temperature.	9
AI-based tools	To improve FCR, to monitor water parameters and to detect pathogens earlier.	7
Species diversification	Increase production of species currently under-farmed (Meagre, Halibut, Pikeperch, sole, turbot) or lower trophic species (carp, mugil, tilapia)	9
Increase production of non-fed species	Shellfish and seaweed	9
IMTA	Promote co-production of different species at different trophic level	9
Renewable energy	Solar, wind, geothermal, biofuel, hydropower	9
Audits	Upgrade to Energy-Efficient Equipment, regular maintenance	N/A
Logistic and training	Optimize Transportation and Operational Practices	N/A

Tools	Description	TRL
Effluents reutilisation	Aquaponics, bioflocs, use of sludge as fertiliser	9
Carbon credits	Mechanisms of compensation for emissions produced (e.g. trees planting)	N/A

Section 2: Future scenarios briefly described.

Section 3: Feedback on these tools, their characteristics and scenarios. Including GHG emissions reduction potential, Technology Readiness Level, Capital expenditure (CAPEX), Operational expenses (OPEX), Regulatory constraints, Licences/patents, Benefits associated with adopting the tool earlier, Risks associated with delaying the intervention, and Training required.

Initially, three experts for each of the five production systems included in the study were contacted, resulting in a response rate of 33%. Given the low response rate, more experts were contacted, specialised in some or all systems. Nine experts have been interviewed, covering all the production systems. The table below provides details of the final interviewee profiles (Table 49).

Table 49 - List of stakeholders Interviewed

Stakeholder Type	Expertise	Country
`Primary Producer 1	Non-fed aquaculture	Italy
Expert 1	Pond system	Hungary
Primary Producer 2	RAS	Slovenia
Primary Producer 3	Intertidal and suspended	The Netherlands
Primary Producer 4	Intertidal and suspended	Ireland
Producers' organisation 1	All 5 production systems	Italy
Expert 2	All 5 production systems	Ireland
Technology provider	AI-based tools for aquaculture	Spain
Feed producer	All fed-aquaculture	EU

Description of method for cost analysis

A financial accounting approach, commonly applied in marginal abatement cost (MAC) studies for GHG emission reduction policies, was used. This approach is supported by the systematic literature review study of Huang et al (2016). The quantification of specific abatement costs of GHG emissions for each scenario and at EU MS level or most relevant geography involves the following steps:

Step 1: Gather upfront capital expenditure (CAPEX) and annual operational expenditure (OPEX) for proposed tools:

CAPEX and OPEX information for each proposed tool was collected alongside task 2. The data was sourced through a literature review and validated through stakeholder interviews to address any gaps or missing information. For the scenario cost analysis, the proposed tool is described at the category level. For example, the feed materials category may include items such as black soldier fly larvae meal, *Tenebrio molitor* meal, microalgae (*Nannochloropsis oceanica* dried biomass), poultry by-products meal, and single-cell protein (SCP). As such, the average cost will be calculated.

Step 2: Adjust CAPEX and OPEX to the base year 2025:

Since literature review includes data from different years, the CAPEX and OPEX are adjusted to the base year 2025 as follows:

$$\boldsymbol{Adjusted\ cost = Original\ cost\ x\ (1 + inflation\ rate\ in\ EU)^{(2025 - original\ year)}} \quad (\mathbf{1})$$

Where:

- Inflation rate in EU = 2% ([24]) ([25])

Step 3: Identify cost savings for each tool:

Each tool may generate cost savings through improved Feed Conversion Ratio (FCR), reduced energy consumption, or both. Cost savings are calculated as follows:

([24]) https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Inflation_in_the_euro_area

([25]) https://www.ecb.europa.eu/ecb/orga/tasks/monpol/html/index.en.html

$$\begin{aligned} &\textit{Cost savings} \\ &= (\textit{Production volume x feed price x feed use x improved FCR}\ \%) \\ &+ (\textit{electricity consumption x electricity price x energy reduction}\ \%) \quad (2) \end{aligned}$$

Table 50 – Expected savings with adopted tools

Cost savings	Description	Reference
Reduced FCR 12%	Breeding program is expected to reduce the FCR by 12%.	(Janssen et al 2018); personal communication with fish farmers during 2025 European Aquaculture Society (EAS) conference
Reduced FCR 3%	AI-based tool is expected to reduce the FCR by 3%.	Personal communication with fish farmers, company providing AI tools at EAS; (Fernández Sánchez et al 2023)
Reduced energy consumption 5%	Improvement of energy efficiency equipment is expected to reduce 5% of energy consumption.	(STECF et al 2025); personal communication with fish farmers at EAS
Lower electricity cost	Cost saving is expected via the difference between renewable energy and national electricity price	

Step 4: Calculate Net Present Value (NPV) for each tool:

The NPV for each tool is calculated as:

$$NPV = -CAPEX + \sum_{t=1}^{T} \frac{(\textit{annual cost savings} - \textit{annual OPEX})_t}{(1 + \textit{discount rate})^t} \quad (3)$$

Where:

- CAPEX = Upfront capital expenditure (Euro), incurred in the base year 2025.
- Annual cost savings (Euro) stem from either improved FCR, energy reduction, or a combination of both benefits.
- Annual OPEX = Annual operational expenditure (Euro).
- Discount Rate = Rate to discount future costs (e.g., 4%, adopted from Techno-Economic Study).
- T = Time horizon for the analysis (5 years for 2026-2030, 15 years for 2016-2040, and 25 years for 2026-2050).
- The salvage value of each tool is assumed to be zero at the end of time horizon.

Step 5: Calculate CO_2eq emission reduction for each scenario:

The CO_2eq emissions before and after adopting the tools for each scenario are calculated by multiplying the CO_2eq emissions before adoption with the adoption rate. The CO_2eq emissions before adoption are determined based on the 2024 conversion ratio described in Database task 1. This ratio represents the average tonnes CO_2eq/t LW conversion rate across species. These emissions are estimated for each production system. The correspondence between emission abatement achieved through tool implementation is presented in the table below.

Table 51 – Correspondence between emission abatement and tool implementation

Emission related to	Emerging feed materials and breeding programs	AI-based tools	Renewable energy	IMTA	Improvement of energy use efficiency
Feed and transportation	yes	yes	no	yes	yes
Electricity	no	yes	yes	yes	yes
Growth-out without electricity	no	yes	yes	yes	yes
Fuel	no	no	yes	no	yes
Others	no	yes	no	yes	yes
Hatchery	no	no	no	no	no

Step 6: Calculate cost of CO_2eq emission reduction for each scenario:

The marginal abatement cost (MAC) for a scenario is calculated as:

$$MAC = \frac{Total\ NPV\ for\ solutions}{Emission\ reduction\ target} \qquad (4)$$

Step 7: Rank the cost-effectiveness scenarios

Following quantification of marginal abatement costs, marginal abatement cost curves (MACCs) will be developed to identify, rank, and prioritise the emission abatement scenarios. These scenarios will be ranked based on their cost-effectiveness, starting from the lowest (most desirable) to the highest cost per tonnes CO_2eq reduced. The assessment will focus on three key timeframes: 2030, 2040, and 2050.

Step 8: Conduct sensitivity analysis

Next, a sensitivity analysis will be conducted to assess the impact of key parameters on the marginal abatement cost across the different emission reduction scenarios.

Step 9: Conduct granularity analysis

To detect heterogeneity in results across EU Member States, MAC values that fall outside the range of the median plus or minus 2.5 times the median absolute deviation will be identified as significant outliers, following the recommendation for outlier detection by Leys et al. (2013). For Member States with MAC values identified as outliers, further analysis will be performed, taking into account key factors influencing on these outliers.

Data description

Data required for the scenario cost analysis was gathered through findings of task 1, task 2, literature review and interviews with targeted stakeholders. Key variables are summarised in Table 52.

Table 52 – Key variables used for scenario cost analysis

Variable	Description	Data source
Production volumes (t LW)	Baseline and production projection	Task 1 and 2
CO_2eq emission target and adoption rate	ESR emission target (S2) and adoption rate of tools	Task 2, scenarios description
Emission conversion ratio	Emission related to feed and feed transportation, electricity, grow-out stage, fuel, others, and hatchery	Task 1
Electricity use (kWh)	Electricity use per t LW	Task 1
Fuel consumption (Liter)	Fuel use per t LW	Task 1
Feed consumption (tonne)	Feed use per t LW	Task 1
CAPEX (€)	Upfront capital expenditure of tools	Task 2, literature review, interviews
OPEX (€)	Annual operational expenditure of tools	Task 2, literature review, interviews
Improved FCR (%)	Reduced FCR with adopting tools	Literature review
Energy reduction (%)	Energy reduction with adopting tools	Literature review
Feed price (€)	Feed price in EU	Literature review
Electricity price (€)	Electricity price at MS level for non-household mid-sized consumers in 2024	Eurostat([26])
Fuel price (€)	Fuel price at MS level	Blue economy observatory([27])

([26]) EUROSTAT [ten00117] *Electricity prices by type of user* (2025) https://ec.europa.eu/eurostat/databrowser/product/page/ten00117

([27]) Topics - EU Blue Economy Observatory - European Commission

Cost input for scenario cost analysis

The costs associated with the proposed tools outlined in Scenarios 2, 3, 3b, 4, 5, and 5b are summarised in the tables below.

Regarding the cost of emerging feed materials, the cost price (€/kg) is calculated based on the replacement percentage of each ingredient with fishmeal. The price of fishmeal is 1.47 €/kg (EUMOFA 2023).

Table 53 – Costs associated with emerging feed materials

Material	Market price (€/kg)		Blended fishmeal price (€/kg)		Reference
Black Soldier Fly larvae meal (40% replacement)	1.66-1.78		1.57		(Abdel-Tawwab et al 2020; Nunes et al 2023; Vodounnou et al 2025)
Tenebrio molinal meal **(40% replacement)**	3.10-4.28		2.42		(Niyonsaba et al 2023)
Microalgae Nannochloropsis Oceania dried biomass **(21.4% replacement)**	1.38		1.46		(Vázquez-Romero et al 2024)
Poultry by-products meal (30% replacement)	0.694		1.24		(Serra et al 2024); Aquafeed project
Single Cell Protein **(30% replacement)**	1.77		1.80		(Jean & Brown 2024; Serra et al 2024)

Table 54 – Costs associated with breeding programs

	Description	Cost (€/t LW)	Reference
Annual CAPEX	Buildings and tanks	1.52	(Janssen et al 2018); Personal communication with fish farmers at EAS 2025
OPEX	Energy, oxygen, fuel, husbandry of nucleus, rearing selection, trait recording, external services	30	

Table 55 – Costs associated with AI-based tools

	Description	Cost (€/t LW)	Reference
Annual CAPEX	Infrastructure (sensors, camera, license for AI platform, IT server, automated feeder)	55	Personal communication with fish farmers, company providing AI tools at the European Aquaculture Society 2025; (Fernández Sánchez et al 2023)
OPEX	Annual licence, maintenance, energy	23	

Regarding renewable energy, the Levelized Cost of Energy (LCOE) is used as the operational cost. The renewable energy sources considered include solar

(Oliveira-Pinto & Stokkermans 2020), wind (EMBER 2025), wave (Joensen & Bingham 2024), biomass, biofuel, hydropower, and geothermal energy (European Commission 2020a). This cost is estimated based on an LCOE range of 0.068–0.141 €/kWh.

Table 56 – Costs associated with renewable energy

	Description	Cost	Reference
CAPEX	Electrification boat for cage and suspended production system, lifetime 20 years	1,241,000 €/electric boat; Electricity demand 566,333 kWh/boat	(Koričan et al 2023); Techno-economic study
OPEX	LCOE	0.091 €/kWh	

Regarding IMTA, data was collected at the farm level for multiple species, including mussels, oysters, macroalgae, and existing IMTA systems such as mussels, scallops, seaweed, and abalone combined with seaweed.

Table 57 – Costs associated with IMTA and effluent management

	Description	Cost (€/t LW)	Reference
Annual CAPEX	Farm infrastructure, installation, equipment	408	(da Silva et al 2022; García et al 2008; Navarro Forner 2021; Theodoridis et al 2017); interview with stakeholders
OPEX	Maintenance, labour, seedlings, utilities, consumable costs	741	

Improving energy use efficiency can potentially be achieved through regular equipment maintenance. According to STECF data, maintenance costs for equipment often account for 10% of the total operational costs but vary depending on the species, ranging from 115 to 316 €/t LW.

Table 58 – Costs associated with improvement of energy use efficiency

	Description	Cost (€/t LW)	Reference
Annual CAPEX	No need for a major change	0	(STECF et al 2025)
OPEX	Regular maintenance	144	

Table 59 – Costs associated with tools for hard-to-abate emissions

Description	Cost (€/t CO_2eq)	Reference
Voluntary carbon credit	56	(Collins et al 2022; Gold Standard 2025)
Ecosystem conservation and restoration support	23.3	(Carnell et al 2025; Eiselin et al 2024)

Limitations and Assumptions

Several limitations affect the interpretation of our findings, including data availability and data availability across production systems. As a result, certain assumptions were necessary.

- Limited data availability: Both the literature review and interviews provided limited cost data for certain tools such as emerging feed materials, breeding programs, renewable energy, AI tools, and IMTA, reflecting the early stage of these tools in Europe.
- Data specificity: Cost data were not available across five production systems and fish species.
- It is assumed that tools investments can generally be applied across production systems, except tools related to feed in the case of non-fed aquaculture, where feed is not required.
- Additional potential cost savings, apart from major expenses like feed and electricity, could not be assessed due to data limitations.

Validation of cost analysis

To ensure robustness and relevance, the findings are validated not only by cross-checking with similar studies in literature, the techno-economic study ([28]) (particularly for the electric boat) but also by utilising reliable data inputs from peer reviewed journals and Eurostat to generate dependable outputs. Additionally, validation is also conducted via personal communications with stakeholders during the European Aquaculture Society conference, interviews with stakeholders from tasks 2 and 4, and consultations with members of the ETP workshop.

Description of method for multi-criteria analysis and assessment of limitations

Task 4 used a qualitative Multi-Criteria Analysis (MCA) to evaluate the scenarios developed in task 2. The task brought together findings from tasks 1-3 in order to qualitatively evaluate the economic, environmental and social impacts of the scenarios developed in task 2. This qualitative multi-criteria analysis was done in an iterative process of desk-study, expert judgement and online expert focus groups. Under sub-task 4.2, limitations to the realisation of

([28]) Techno-economic analysis for the energy transition of the EU fisheries and aquaculture sector the scenarios were identified, following a PESTEL analysis of the EU aquaculture sector, outputs from the focus group and further expert interviews. The activities are described in more detail below.

Qualitative multi-criteria analysis

Multi-criteria analysis (MCA) is a useful decision-making tool which is best used to evaluate and compare different 'options' by assessing how various criteria perform against these options. It is then an essential step in the methodology to determine what these options are and how are they defined. The next step is to choose what criteria will be selected for the MCA, and these criteria aim to cover the potential complexation and breadth of the impacts of the different options. These criteria need to encompass not only the economic impact of a certain option for example, such as how much the option would cost, but it also needs to factor in other qualitative and quantitative factors such as the environmental and social impacts.

Once the criteria have been determined, the final step in setting up the MCA is to determine what available data can be used to 'score' how well a certain criterion performs under a specific option. This data can be both qualitative and quantitative, as the MCA methodology allows a mixture of different datasets.

Table 60 presents the main structure and decisions made for the MCA. Five different MCA's were carried out, one for each production system. The analysis was be done at the EU level (as this is the level at which the scenarios have been defined).

Table 60 – The main structure of the multi-criteria analysis

Component	Defined in this MCA
Objective	The overall objective of the MCA is to evaluate the social, environmental and economic impact of the five different scenarios developed under task 2.
Options	These have been defined as the five different scenarios developed under task 2. Including (1) Business as Usual, (2) Achievement ESR/EU targets, (3) Prioritise low investment, (4) Resilience to Climate Change and (5) Maximising Emission Reduction (5). The hard to abate tools such as purchasing carbon credits and investment in ecosystem conservation and restoration support will be used to develop two of the previously defined scenarios a bit further e.g. Low investment + added tool (3b) or Maximising Emissions Reduction + added tool (5b).
Criteria	These is a shortlist of criteria that encompass environmental, economic and social impacts. The methodology calls from between 9-12 criteria to be shortlisted, with an even split between the environmental, economic and social. The criteria selected were based on the needs of the Terms of Reference, the Policy relevance and the data availability. The full list of criteria discussed can be found in Annex 6, and the short list selected is presented in Table 31.
Scoring	The scoring is carried out using a series of indicators, which is data that helps to reflect the relationship between a certain criterion, and how it performs against a certain tool. This is an evaluative tool, and the assessments can be made with quantitative data where available, or qualitative. Interviews with tasks 1-3 were performed in order to determine what data for each scenario would be available for task 4. Where there is no quantitative data available for a criterion, a qualitative assessment will be carried out. A

Component	Defined in this MCA
	survey will be used to ask industry experts to qualitatively assess how a criterion performs against a certain tool (this was deemed easier than against the scenario), and then this assessment would be aggregated and scaled to the tool level.
Weights	This requires weighing the relative importance of each criterion. Initially an equal weighting will be performed and presented to the stakeholders and ETP. A weighting exercise will then take place with the industry experts during the focus groups.

Data collection

The development of the criteria longlist started with a review of the Terms of Reference to determine what was specifically requested, in addition to discussions with task 1-3 to determine what potential data would be available. Discussions internally amongst the task 4 researchers also took place to identify what criteria could be interesting to assess the impact of the different scenarios. Discussions were then carried out amongst the team in order to shortlist the criteria to a final list of 12 criteria (divided equally between environmental, economic and social).

A survey was developed and circulated with industry experts in early August to aid with the scoring of the criteria where quantitative data was not available. This survey introduced the project and the different tools that have been used to develop the scenarios. It was deemed easier for the experts to score the tools against the criteria rather than explaining the scenarios in detail at this stage. The task 4 researchers then aggregated the scoring for each tool to the scenario level. The survey was built using the platform LimeSurvey ([29]) and was circulated to various experts. 28 experts from different fields completed the survey.

Experts were asked early in the survey to define which production system they most identified with, as this helped researchers to assign their scoring to the relevant MCA. Experts were invited to answer the survey multiple times if they were familiar with more than one production system.

The survey presented the industry experts with a table with the combinations of criteria/tool, and asked them to score how they perceive a tool to impact a specific criterion with the following Likert scale:

- -2: the tool will have a strong negative impact on the criterion
- -1: the tool will have a slight negative impact on the criterion
- 0: the tool will have no noticeable impact on the criterion
- 1: the tool will have a slight positive impact on the criterion

([29]) LimeSurvey GmbH, Hamburg, Germany. URL http://www.limesurvey.org

- 2: the tool will have a strong positive impact on the criterion

A follow-up question was asked for some criteria that are less impact driven, and more the focus is on how easy the tool is to implement across the production system for that specific criterion. For this question, the following scoring was suggested:

- -2: the tool will be very difficult to implement due to the criteria
- -1: the tool will be difficult to implement due to the criteria
- 0: the tool will be neither difficult nor easy to implement due to the criteria
- 1: the tool will be easy to implement due to the criteria
- 2: the tool will be very easy to implement due to the criteria

For the full survey circulated, please see Annex 7. There were a few exceptions in the survey, because some tools or criteria were not deemed relevant for certain production systems (e.g. emerging feed materials are not relevant for non-fed aquaculture, or GHG emissions from production for the tool of carbon credits). Annex 7 includes a full overview of these exceptions.

A total of 28 surveys were completed by experts across the five production systems (Figure 35). Most experts who filled in the survey were cage (32%) and RAS (25%) experts. The respondents included stakeholders who were farmers, fish producers and processors, individuals from NGOs, trade associations and advocacy groups in addition to scientific and research individuals and those in the commercial feed industry (Figure 36).

Figure 35 – Percentage of survey responses from experts of each production system (total = 28)

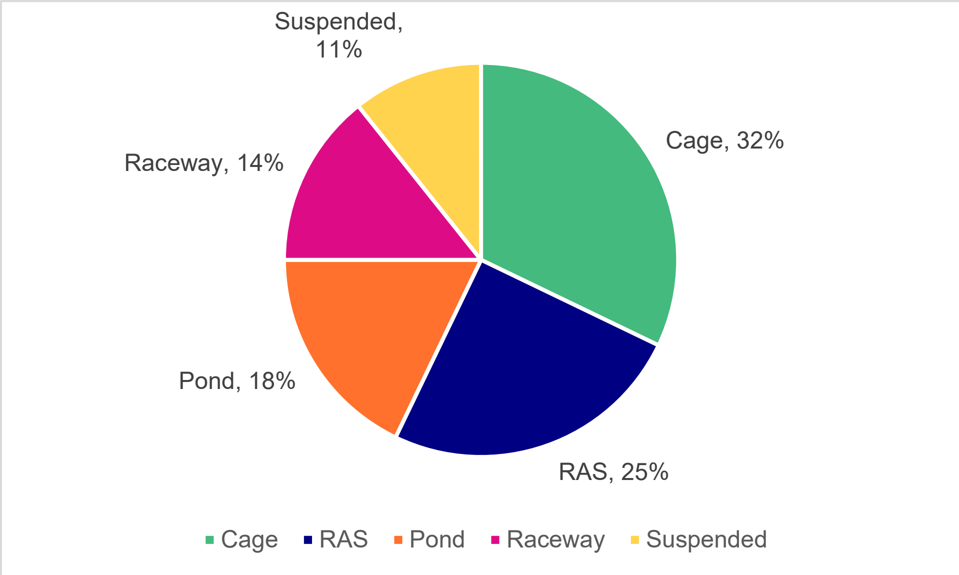
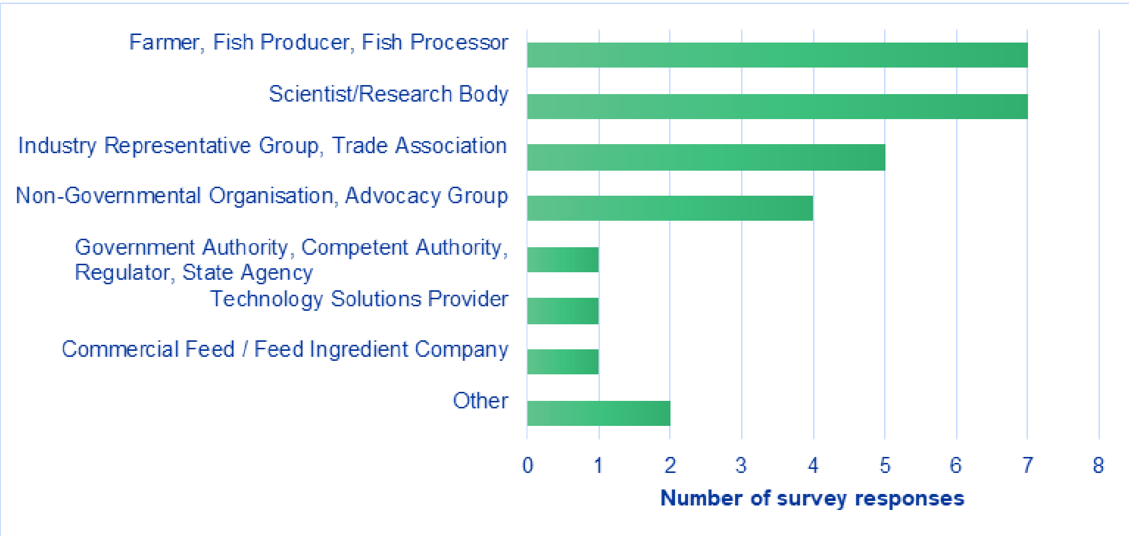


Figure 36 – Division of stakeholder categories that responded to the survey (total = 28)



7.1.1.1 Limitations and Assumptions

There was an assumption made that stakeholders would find it difficult to qualitatively assess how a certain criterion will perform against a scenario, as the scenario definitions are quite large and broad. Therefore, the decision was made that for each criterion, the scoring would be carried out at the tool level instead, with the assumption that these tools can then be scaled up to the scenario level. Table 7 (section 4.4.3) previously outlined which tools are included in which scenario. An equal distribution of the relevant tools for each scenario was assumed (for example in Scenario 3: emerging feed materials, IMTA and improved energy use efficiency have equal weight in the scoring of the scenario).

Some limitations that have emerged during the data collection phase for the MCA were based on the data availability from tasks 1-3. The data available from these tasks were GHG emissions from production and cost data (CAPEX and OPEX), meaning all of the social criteria and the remaining environmental and economic criteria (such as industry readiness) had to be assessed with a qualitative methodology. However, to end up with a uniform MCA table, GHG emission data and cost data also had to be transposed to a qualitative assessment by the study team. It was not possible to compare the data because of the different units in which the GHG and cost data were calculated (e.g. euros per tonne of LW, euros per kWh and euros per tonne CO_2eq). The data in the MCA tables for GHG emissions from production, CAPEX, and OPEX were thus normalised to the same Likert scale (-2 to 2) to be able to compare between the qualitative and quantitative data. This was done based on ranking the tools from least to most costly and least to most GHG emissions reduced.

Since the CAPEX and OPEX data both consider costs (for each tool to be implemented, an increase in costs is required), only negative numbers were assigned (ranging between -2 and 0) by the study team. Normalisation of the quantitative data was done assuming equal steps, using a ranking from the cheapest tool (0) to the most expensive (-2). To prevent the costs of a tool to count twice in the MCA, stakeholder responses to the criterion ‘operational cost reductions’ were adjusted to only be positive, ranging between 0 and 2 (negative scores were set to 0). At the time the survey was circulated, stakeholders could give negative scores for this criterion, however, the team adjusted this afterwards because it would mean an overlap with the cost data included already in the CAPEX and OPEX.

By normalising the indicators onto one common scale, a meaningful comparison across the criteria was possible, an essential step when conducting an MCA.

Validation of MCA

The survey responses helped the researchers to populate the five MCA’s with the final scores for each technological tool against each criterion. The validation of the aggregated scores took place across three validation workshops held in September and October 2025. Participants from all five production systems were invited to participate, with representative bodies such as the Aquaculture Advisory Council, European Aquaculture Technology and Innovation Platform, and Eurofish were all reached out to in an effort to garner more responses through their networks of contacts. Table 61 shows the stakeholders that participated in the MCA validation workshops and the production systems that were covered.

Table 61 – MCA Validation Workshops

Date	Number of Participants	Production System Covered
03/09/2025	5	Cage, Pond
05/09/2025	5	Pond, RAS
14/10/2025	6	Non-fed, Cage, RAS, Raceway

The primary focus of the validation workshops was on presenting the initial findings of the survey and MCA and to receive feedback on the aggregated scores for each criterion and tool. An interactive session was conducted at the end of the workshop in order to gain stakeholder weighting for each of the 12 criteria, as this is an essential step in the MCA methodology. These criteria rankings were then averaged for each production system and applied to the five different MCA's to get a final stakeholder weighted MCA. The workshop was further used to discuss what parameters could be used in the sensitivity analysis (see 6.3.3 for more detail).

Limitations

A PESTEL analysis was conducted to shed light on the current state and developments in the European aquaculture sector, looking at Political, Economic, Social, Technological, Environmental and Legal dimensions. The PESTEL analysis is informed by recent EU publications on aquaculture, supplemented with scientific literature.

Next, the study team prepared the SWOT analysis based on the following sources of information:

- Results of the analyses conducted in tasks 1-3.
- The expert focus groups
- Validation interviews with experts to validate the findings of the gaps and limitations.

A SWOT analysis was chosen due to its wide application in strategic planning technique that enables the systematic evaluation of internal and external factors influencing an organisation or project (or scenario in this case). It categorises strengths and weaknesses as internal dimensions, while opportunities and threats represent external conditions, thus offering a structured framework for developing strategic options. By matching strengths with opportunities and addressing weaknesses and threats, SWOT facilitates informed decision-making and strategic alignment (Gurel & Tat, 2017).

In total 15 validation interviews were conducted in the period Oct-Nov, the characteristics of these are provided below in Table 62.

Table 62 - List of stakeholders interviewed.

Stakeholder type	Expertise	Member State
Primary Producer 1	Cage aquaculture	Spain
Sector representative 1	Cage aquaculture	Norway
Primary producer 2	Pond aquaculture	Poland
Sector representative 2	All 5 production systems	EU
Expert 1	IMTA	Spain
Expert 2	Ponds and raceway aquaculture	Hungary
Expert 3	All 5 production systems	Denmark
Expert 4	All 5 production systems	Spain
Feed producer	All fed-aquaculture	EU
Expert 5	All 5 production systems	Italy
Primary producer 3	RAS	Portugal
Expert 6	Cages	Ireland
Expert 7	Emerging feed materials	Italy
Sector representative 3	All 5 production systems	EU
Expert 8	Cage aquaculture	Greece

Identification of key parameters for sensitivity analysis

The final subtask included the identification of parameters for the sensitivity analysis, to assess how the outcomes of the scenario analysis in task 3 and task 4 change under different inputs on key parameters. A longlist of possible parameters was prepared for the analysis. During the expert focus groups, additional parameters were discussed.

Description of method for reduction pathways and recommendations

Propose reduction pathways

Under sub-task 5.1, we propose reduction pathways including CO_2eq emission reduction both in absolute and relative terms (range) for each of the aquaculture production systems. The proposed reduction pathways are based on the results of the scenario analysis in task 3 and 4 and the consultation of stakeholders throughout the project.

The proposed reduction pathways describe which tools are available for the production system concerns, and their adaption rate between 2026-2050. The projected CO_2eq emission reduction is calculated using the calculations tools developed under task 3.

The costs for carbon neutrality by 2050

The costs for achieving carbon neutrality per proposed reduction pathway are calculated using the calculations tools developed under task 3.

Recommendations for policy measures

Recommendations for policy makers are formulated based on the focus groups (task 2), interviews and PESTEL analysis conducted under task 4.

Guidance in the interpretation and shortcomings of scenarios and pathways

The last sub-task provides guidance to the interpretation of the scenarios and pathways and is written based on the study teams' expert knowledge and experiences gained in drafting scenarios and pathways.

Annex 2: Database 1 – Screenshot illustrating the structure of the database including calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1								From literature	consider specific sources of energy used in different	grow out stage, comes from	For calculation purpose only	considering specific	Refers to grow out stage	For calculation purpose	
2	Species	Environment	Year	Production System (PS)	% PS Used	Production per sytems (tonnes)	Total production (Tonnes)	CO2eq emissions per ton of fish (t CO2eq/t LW)	Total CO2eq emissions per system (t CO2 eq),	Electricity use (kwh/ tLW)	from all processes except electricity	y use per ton of fish (t CO2 eq/ t LW)	emissions from electricity use (t	emissions excluding hatchery	emissions for feed production + transportation
3		Freshwater	2005	Ponds	85.9	729.291	849	1.70	1239.79	160.00	1078.62	0.13	97.72	1176.35	717.57
4		Freshwater		Raceways	14.1	119.709		1.80	215.48	7509.00	122.82	6.30	754.17	876.99	263.10
5		Freshwater	2006	Ponds	85.9	773.959	901	1.70	1315.73	160.00	1144.69	0.13	103.71	1248.40	761.52
6		Freshwater		Raceways	14.1	127.041		1.80	228.67	7509.00	130.34	6.30	800.36	930.70	279.21
7		Freshwater	2007	Ponds	85.9	704.38	820	1.70	1197.45	160.00	1041.78	0.13	94.39	1136.16	693.06
8		Freshwater		Raceways	14.1	115.62		1.80	208.12	7509.00	118.63	6.30	728.41	847.03	254.11
9		Freshwater	2008	Ponds	85.9	740.458	862	1.70	1258.78	160.00	1095.14	0.13	99.22	1194.36	728.56
10		Freshwater		Raceways	14.1	121.542		1.80	218.78	7509.00	124.70	6.30	765.71	890.42	267.13
11		Freshwater	2009	Ponds	85.9	594.428	692	1.70	1010.53	160.00	879.16	0.13	79.65	958.81	584.88
12		Freshwater		Raceways	14.1	97.572		1.80	175.63	7509.00	100.11	6.30	614.70	714.81	214.44
13		Freshwater	2010	Ponds	85.9	414.038	482	1.70	703.86	160.00	612.36	0.13	55.48	667.84	407.38
14		Freshwater		Raceways	14.1	67.962		1.80	122.33	7509.00	69.73	6.30	428.16	497.89	149.37
15		Freshwater	2011	Ponds	85.9	524.9349	611.1	1.70	892.39	160.00	776.38	0.13	70.34	846.72	516.50
16		Freshwater		Raceways	14.1	86.1651		1.80	155.10	7509.00	88.41	6.30	542.84	631.25	189.37
17		Freshwater	2012	Ponds	85.9	478.2912	556.8	1.70	813.10	160.00	707.39	0.13	64.09	771.48	470.61
18		Freshwater		Raceways	14.1	78.5088		1.80	141.32	7509.00	80.55	6.30	494.61	575.16	172.55
19		Freshwater	2013	Ponds	85.9	499.938	582	1.70	849.89	160.00	739.41	0.13	66.99	806.40	491.90
20		Freshwater		Raceways	14.1	82.062		1.80	147.71	7509.00	84.20	6.30	516.99	601.19	180.36
21		Freshwater	2014	Ponds	85.9	644.4218	750.2	1.70	1095.52	160.00	953.10	0.13	86.35	1039.45	634.07
22	Salmonoids	Freshwater		Raceways	14.1	105.7782		1.80	190.40	7509.00	108.53	6.30	666.40	774.93	232.48
23		Freshwater	2015	Ponds	85.9	563.504	656	1.70	957.96	160.00	833.42	0.13	75.51	908.93	554.45
24		Freshwater		Raceways	14.1	92.496		1.80	166.49	7509.00	94.90	6.30	582.72	677.63	203.29
25		Freshwater	2016	Ponds	85.9	715.8906	833.4	1.70	1217.01	160.00	1058.80	0.13	95.93	1154.73	704.39
26		Freshwater		Raceways	14.1	117.5094		1.80	211.52	7509.00	120.56	6.30	740.31	860.87	258.26
27		Freshwater	2017	Ponds	85.9	633.3407	737.3	1.70	1076.68	160.00	936.71	0.13	84.87	1021.58	623.16
28		Freshwater		Raceways	14.1	103.9593		1.80	187.13	7509.00	106.66	6.30	654.94	761.61	228.48
29		Freshwater	2018	Ponds	85.9	828.4196	964.4	1.70	1408.31	160.00	1225.23	0.13	111.01	1336.24	815.11
30		Freshwater		Raceways	14.1	135.9804		1.80	244.76	7509.00	139.52	6.30	856.68	996.19	298.86
31		Freshwater	2019	Ponds	85.9	804.9689	937.1	1.70	1368.45	160.00	1190.55	0.13	107.87	1298.41	792.03
32		Freshwater		Raceways	14.1	132.1311		1.80	237.84	7509.00	135.57	6.30	832.43	967.99	290.40
33		Freshwater	2020	Ponds	85.9	741.6606	863.4	1.70	1260.82	160.00	1096.92	0.13	99.38	1196.30	729.74
34		Freshwater		Raceways	14.1	121.7394		1.80	219.13	7509.00	124.90	6.30	766.96	891.86	267.56
35		Freshwater	2021	Ponds	85.9	799.9008	931.2	1.70	1359.83	160.00	1183.05	0.13	107.19	1290.24	787.05
36		Freshwater		Raceways	14.1	131.2992		1.80	236.34	7509.00	134.71	6.30	827.18	961.90	288.57

Annex 3: Screenshot of Database 2 – Simplified, ready-to-use version illustrated by Salmonoids data in Austria

Country	Species	Environment	Year	Production System (PS)	% PS Used	Production per sytems (tonnes)	Total CO2eq emissions from electricity use (t CO2eq)	Total CO2eq emissions for feed production + transportation (tCO2 eq)	CO2eq emissions from grow-out stage (electricity + materials) (tCO2 eq)	Total emissions from feed transportation	Total CO2eq emissions from other processes (tCO2 eq)	Total CO2eq emissions from hatchery stage (tCO2 eq)	Total CO2eq emissions from boat fuel consumption (tCO2 eq)	Total CO2eq emissions (t CO2 eq)
Austria	Salmonoids	Freshwater	2005	Pond	38	782.8	267.7176	863.8233383	477.7162248	47.24757143	63.50815694	140.5	0	1545.55249
Austria	Salmonoids	Freshwater	2005	Raceways	52	1071.2	244.2336	1501.39392	514.176	64.65457143	41.13408	205.7	0	2262.3744
Austria	Salmonoids	Freshwater	2005	RAS	10	206	2204.2	1140.3336	2470.7228	12.43357143	190.0556	380.1	0	4181.2232
Austria	Salmonoids	Freshwater	2006	Pond	38	766.84	262.25928	846.2114061	467.9763794	46.28427143	62.21333044	137.6	0	1514.04123
Austria	Salmonoids	Freshwater	2006	Raceways	52	1049.36	239.25408	1470.782976	503.6928	63.33637143	40.295424	201.5	0	2216.24832
Austria	Salmonoids	Freshwater	2006	RAS	10	201.8	2159.26	1117.08408	2420.34884	12.18007143	186.18068	372.4	0	4095.97496
Austria	Salmonoids	Freshwater	2007	Pond	38	754.68	258.10056	832.7927912	460.5555449	45.55032857	61.22679597	135.5	0	1490.03265
Austria	Salmonoids	Freshwater	2007	Raceways	52	1032.72	235.46016	1447.460352	495.7056	62.33202857	39.656448	198.3	0	2181.10464
Austria	Salmonoids	Freshwater	2007	RAS	10	198.6	2125.02	1099.37016	2381.96868	11.98692857	183.22836	366.5	0	4031.02392
Austria	Salmonoids	Freshwater	2008	Pond	38	589	201.438	649.9641623	359.446674	35.55035714	47.78526372	105.7	0	1162.91571
Austria	Salmonoids	Freshwater	2008	Raceways	52	806	183.768	1129.6896	386.88	48.64785714	30.9504	154.8	0	1702.272
Austria	Salmonoids	Freshwater	2008	RAS	10	155	1658.5	858.018	1859.039	9.355357143	143.003	286	0	3146.066
Austria	Salmonoids	Freshwater	2009	Pond	38	614.84	210.27528	678.4787191	375.2159474	37.10998571	49.88164948	110.4	0	1213.93395
Austria	Salmonoids	Freshwater	2009	Raceways	52	841.36	191.83008	1179.250176	403.8528	50.78208571	32.308224	161.5	0	1776.95232
Austria	Salmonoids	Freshwater	2009	RAS	10	161.8	1731.26	895.66008	1940.59684	9.765785714	149.27668	298.6	0	3284.08696
Austria	Salmonoids	Freshwater	2010	Pond	38	608.76	208.19592	671.7694116	371.5055302	36.74301429	49.38838224	109.3	0	1201.92966
Austria	Salmonoids	Freshwater	2010	Raceways	52	833.04	189.93312	1167.588864	399.8592	50.27991429	31.988736	159.9	0	1759.38048
Austria	Salmonoids	Freshwater	2010	RAS	10	160.2	1714.14	886.80312	1921.40676	9.669214286	147.80052	295.6	0	3251.61144
Austria	Salmonoids	Freshwater	2011	Pond	38	780.9	267.0678	861.7266797	476.5567194	47.13289286	63.35401093	140.2	0	1541.80115
Austria	Salmonoids	Freshwater	2011	Raceways	52	1068.6	243.6408	1497.74976	512.928	64.49764286	41.03424	205.2	0	2256.8832
Austria	Salmonoids	Freshwater	2011	RAS	10	205.5	2198.85	1137.5658	2464.7259	12.40339286	189.5943	379.2	0	4171.0746
Austria	Salmonoids	Freshwater	2012	Pond	38	821.18	280.84356	906.1758417	501.1382339	49.56407857	66.62190639	147.4	0	1621.32958
Austria	Salmonoids	Freshwater	2012	Raceways	52	1123.72	256.20816	1575.005952	539.3856	67.82452857	43.150848	215.8	0	2373.29664
Austria	Salmonoids	Freshwater	2012	RAS	10	216.1	2312.27	1196.24316	2591.86018	13.04317857	199.37386	398.7	0	4386.22492

Annex 4: Feedback from interviewed stakeholders

Emerging feed materials

The experts expressed mixed views on feed materials as a tool for reducing emissions. Expert 1 was sceptical about the potential of emerging feed materials, stating: "*These ingredients are still in a very, very limited use in the aquaculture industry. I think it's only 0.2% of the total feed ingredient use comes from these new ingredients*." This expert questioned the energy efficiency of alternative proteins, noting that "*The insect production for example is quite energy intensive technologies, so I'm not sure and they don't have a comprehensive LCA or energy audit on these production technologies yet.*" However, this expert saw significant potential in poultry by-products and emphasised a critical regulatory gap: "*What I miss here is the utilisation of the waste from the slaughterhouse from the aquaculture. We have quite complicated in Europe legislation about using waste from the processing to putting back to the fish feed*."

Expert 3 provided context about the complexity of emissions accounting in feed production, explaining that "if it's about direct emissions, I will always assume that it's mostly about the energy transition. The farms specifically themselves." He highlighted that feed materials often come from other countries, making their emissions difficult to capture in national reduction efforts. Expert 4 reinforced the economic challenges, stating: "The issue is that they cost more than soy, and so there's a great reluctance upon, I would say, feed companies to adopt new protein sources."

Breeding programs and genetic improvement

There was strong consensus among experts that breeding programs offer significant potential for emissions reduction. Expert 1 emphasised: "*I think breeding programme would be the most urgent because it takes time to have the appropriate genetic material... In Hungary, the biggest issue now is the impact of the climate change. We have much warmer summers and much less water than we have before*." Producer 4 compared aquaculture unfavourably to other sectors, noting: "*If we compare aquaculture with the poultry industry, we are far, far behind... Disease outbreaks, the major problem in European aquaculture in the recent years because of the climate change, changing the fish diets and also lack of the suitable breeding program*."

Expert 4 highlighted that breeding programs would likely continue to focus on traditional metrics rather than emissions reduction: "*I would think most breeding programs to date have focused on growth rate and survival... I still think those two metrics are the main drivers from most breeding programs*." This expert predicted that climate adaptation would be the priority, particularly for "*places* *that traditionally grew shellfish or fish in certain areas are finding that challenging, so I think breeding programs would probably tend to focus more on that than selecting breeds that optimise the efficiency of novel ingredients*."

Artificial Intelligence and digitalisation

AI-based tools received strong support across all interviewees, though experts emphasised the need for broader digitalization beyond just AI. Expert 1 suggested: "*I would say digitalisation in aquaculture, so probably AI, I would say a more broad term here as digitalization, we know that there is a lot of uneaten feed still in the aquaculture industry in both in the marine and freshwater*." Producer 4 was particularly enthusiastic about the potential of AI, noting: "*I think it's very big potential because the technology is more and more affordable like this industry cameras cost 10 years ago like fortune. Today it's really small money... It's important to improve FCR because feeding by hand or feeding by automatic system which measure only the water quality parameters, it's not suitable if we could observe the fish behaviour*."

Expert 4 provided a comprehensive view of AI's potential impact: "I think the big area we'll see AI being used is to make decisions on all the data that's been generated in agriculture. There are enormous amounts of data... every farm in the world has water quality data, feed efficiency data, FCR, but they're very complex interactions happening within marine environments and freshwater environments and we will use AI to get more insights from the data that's been generated."

Species diversification

Species diversification emerged as one of the most controversial tools. Expert 1 criticised the promotion of pike perch as an alternative species: "*Pike perch, the future of the freshwater aquaculture for nearly 40 years now. But I think it's a dead end because pike perch doesn't have the market potential to be a mass produced species in Europe... there's a massive import of frozen pike perch from Kazakhstan*." Instead, this expert advocated for African catfish: "*If I would suggest an alternative species which is underdeveloped at the moment, but it's growing very fast, it is the African catfish production in Europe.*"

Expert 4 was even more sceptical about diversification's potential: "I'm a bit conflicted on this, we're not going to see big volumes of any of the species that you've listed there. They're species that are expensive to produce, take a long time to produce, they're niche markets. Turbot is not going to feed the world or pike perch or halibut." Producer 4 agreed that warm-water species would be the future but cautioned: "I doubt that pike perch will be the future or any fishes which have a very big added value."

Integrated Multi-Trophic Aquaculture (IMTA)

IMTA received mixed reviews, with practical challenges frequently cited. Expert 4 was critical: “IMTA sounds nice, looks nice, but is it economically viable? I’m not convinced. And your average salmon farmer or sea bass farmer does not want to grow seaweed as well and shellfish.” However, Producer 7 provided a successful case study of IMTA implementation: “I would say IMTA because we’re using the abalone effluent to feed those different like the sea lettuce and where palmaria can grow in our system... The more abalone you grow, the more of good nutrient. It’s not like you’re having to add another fertilizer. It’s just something that’s natural in the seawater anyway."

Producer 4 expressed cautious optimism but noted the challenge of commercialisation: “IMTA has potential. Because we are starting a project together about developing an IMTA in farm... only thing is to move it from experimental phase to the commercial sustainable tool.”

Renewable energy and equipment efficiency

Renewable energy emerged as one of the most promising and actionable tools, though significant regulatory barriers were identified. Expert 1 highlighted the administrative challenges: “*Farmers see a great potential in the energy transition to use renewable energy, and it’s an ongoing process... The problem here that a large area of fish ponds, especially in Hungary, were 50%, nearly 50% of the fish ponds is Natura 2000 area, and usually the environmental authorities does not allow for the farmers to put wind turbines or even just floating solar panels*.”

Producer 7 revealed regulatory constraints in Ireland: “If we wanted to run the whole system, we need 400 panels. But again, the electricity companies will not allow you to get 400 panels because they need to make money too... you are only allowed a third of what you need.” This producer had successfully reduced energy costs through renewable energy adoption: “We were spending at the very beginning about 5000 euros on electricity per six weeks and once we got in the recirculation and the turbine, it actually cut that in half.”

Expert 4 strongly emphasised the potential of energy efficiency improvements: “I would think that combined energy transition and improved efficiency of equipment offer the most potential... I don’t know what the figures are for oxygen generation for aquaculture, but they must be enormous... if you could just improve by 1% or 2% the energy efficiency of those paddle wheel aerators, then you have a real scale effect.”

Scenario assessment and Implementation priorities

Regarding the proposed scenarios for emission reduction, experts generally supported focusing on energy and efficiency measures but questioned some allocations. Expert 4 critiqued the scenario percentages: "*I would focus on* *energy transition and improved efficiency of equipment. I think they'll have the two biggest cumulative effects... I just can't see IMTA having a big impact*." Expert 1 suggested adjustments for landlocked countries: "*The landlocked countries where pond aquaculture is the most developed, they should have a same rate, same share for the energy transition possibilities because I would calculate here with the possibility to have on-farm renewable energy*."

Producer 4 expressed pessimism about the future of European aquaculture itself: "I think that we will have a very good reduction of emission because people doesn't want to do fish farming anymore... There will be no more fish farms in Slovenia, the older people." This producer argued that emission reduction targets might be achieved through production decline rather than technological improvement: "Reduction of emission means that we will reduce the production. If we want to keep the production, we have to spend more and more energy and oxygen and everything."

Cost information

The cost data revealed significant challenges in implementing sustainable tools. Producer 7 provided detailed cost breakdowns for their IMTA system: "*When we first set up the whole system it cost 300,000, it was 200,000 to set up the system, but then it was another 80,000 for the hatchery*." Expert 4 criticised the cost data presented in the study: "*Smart feeding system... I think the OPEX cost, the euro per tonne cost are very high and I did not understand why. It's 4590... I think it's not realistic, those very high numbers*."

Expert 3 highlighted the challenge of obtaining accurate cost data: "I'm with an industry association, so we work on a pretty competitive basis. It's typically information that doesn't reach us."

Key implementation challenges

Several overarching challenges emerged from the interviews. Market dynamics and consumer behaviour were frequently cited as barriers. Expert 4 explained: "*Unless the consumer is willing to pay more for alternative protein sources, it's not going to happen... whilst there's a social and moral obligation to reduce emissions, it still comes down to cost. What is cost sustainable?"* Producer 7 highlighted systemic inequities in support: "*Aquaculture needs to be up there with agriculture. It shouldn't be under fisheries because fisheries is getting everything... Aquaculture is at the bottom and there's nothing left*."

The complexity of emissions accounting across international supply chains was another significant challenge. Expert 3 noted: "If it's about direct emissions, I will always assume that it's mostly about the energy transition... The feed comes often imported and has like the main emissions related to that or land use and things like possible deforestation."

Annex 5: Longlist of criteria discussed for MCA

This table shows the initial longlist of criteria that was identified. To get to the final shortlist of criteria, the data quality and relevance were weighted between 1 and 3. For the weighting of the data quality, 3 means it can be calculated in the project, 2 can be retrieved through industry experts, and 1 relies on literature review and assessments by the project team. For the weighting of relevance, 3 is very relevant (e.g. mentioned in the TOR, or in line with important EU Aquaculture policy documents), 2 is fairly relevant, and 1 is not relevant at all (in some instances, they might not be deemed relevant as the criteria overlaps with another, or is included in the definition of the scenario). We also determined whether the assessment of would have to be done at the scenario or tool level. Darker green scored 6 (the maximum) and the lighter green scored 5. This helped us to finalise our shortlist of criteria.

Criteria	Criteria Type	Definition	Data available at which level: Scenario or tool?	Relevant tasks	Weighting data (1-3)	Weighting relevance (1-3)
Space requirements of new systems	Economic	How much space is required for new systems (cross over between land-use for food and also infrastructure)	Tool	Ask industry experts	1	2
CAPEX	Economic	Capital costs to implement scenarios	Scenario	T3 (per scenario, per country for scenario 2)	3	3
OPEX	Economic	Operational costs to implement scenarios	Scenario	T3	3	3
Marginal Abatement Cost	Economic	Cost of reducing emissions by one unit	Scenario	T3	3	3
Operational cost reductions	Economic	Operational costs relating to fuel and energy use	Tool	Ask industry experts	2	3
Reduced Cost volatility	Economic	Vulnerability to fluctuations in energy prices	Tool	Ask industry experts	1	2
AI energy consumption	Economic	Associated with data storage - how much energy is needed to store the data (changes across	Scenario	T2	1	1

Criteria	Criteria Type	Definition	Data available at which level: Scenario or tool?	Relevant tasks	Weighting data (1-3)	Weighting relevance (1-3)
		countries too due to climate) - for AI tool				
Energy mixes	Economic		Scenario	T1	1	2
Value of feed (per country)	Economic	Price industry would have to pay per year on feed	Tool	STECF, Ask industry experts	1	2
Infrastructure requirements	Economic	Level of change to infrastructure required to implement tools	Tool	Ask industry experts	2	2
Industry Readiness	Economic	How difficult the industry will find implementing the required technological tools	Tool	Ask industry experts	2	3
Circularity	Environmental	level to which the proposed scenario changes the degree of circularity (reusing and regenerating materials and resources like water and energy) within the industry	Scenario	Ask industry experts	2	1
Resilience to climate change	Environmental	Adaptability of species to warmer climates, how well species will cope with e.g. rising seawater temperatures	Scenario	Ask industry experts	1	1
Sustainability Improvements	Environmental	Improvements in sustainable energy use (less use of 'grey' energy), e.g. due to fuel efficiency measures and the switch to renewable, low-carbon power sources	Tool	Ask industry experts	1	2
GHG emissions needed for production	Environmental	GHG emissions (per t and/or total for industry)	Scenario	T1-3	3	3

Criteria	Criteria Type	Definition	Data available at which level: Scenario or tool?	Relevant tasks	Weighting data (1-3)	Weighting relevance (1-3)
Animal welfare	Environmental	Impact on animal welfare of farmed species (finfish, cephalopods, crustaceans)	Tool	Ask industry experts	1	1
Disease transmission	Environmental	The risk of spreading pathogens, pests and parasites due to the aquaculture farm. Also includes the risk of antibiotic resistance.	Tool	Ask industry experts	1	1
Impact on wild populations and ecosystems	Environmental	Impacts like introduction of invasive species, depletion of wild stocks due to overfishing for fish oil and fish meal, escaped fish from farms, bycatch (from fishing for feed).	Scenario/Tool	Ask industry experts	2	3
Land-use change Land usage	Environmental	Change in amount and type of space required for new aquaculture production systems, also related to the destruction of habitat (e.g. wetland conversion for ponds)	Tool	Ask industry experts	2	3
Water usage	Environmental	Amount of (fresh) water needed for cultivation.	Tool	Ask industry experts	2	3
Amount of land needed for (feed) production	Environmental	Space required for production of aquaculture feed and aquaculture products, related to the destruction of habitat (e.g. wetland conversion for ponds)	Tool	Ask industry experts	2	2
Water pollution	Environmental	Change in nutrient level and chemical use. Can be negative due to nutrient release into open water or positive due to nutrient removal by aquaculture species.	Tool	Ask industry experts	2	2

Criteria	Criteria Type	Definition	Data available at which level: Scenario or tool?	Relevant tasks	Weighting data (1-3)	Weighting relevance (1-3)
Biodiversity	Environmental	Impact on biodiversity both local and impacted by feed production. This can for example be reduced pressure on wild stocks and enhanced natural production, but also introduction of invasive species, disease transmission and habitat destruction.	Tool	Ask industry experts	2	2
Number of employees in the sector	Social	Number of employees within the aquaculture sector engaged in the renewable energy, demographics may also be considered	Tool	Ask industry experts	2	3
Potential safety implications	Social	Implications for safety (worker, consumer), working conditions	Tool	Ask industry experts	2	3
Match with current regulatory landscape	Social	How well scenario is covered by existing regulations	Tool	Ask industry experts	2	3
Impact on skills required	Social	Possible impacts of tool to the skills needed across the sector	Tool	Ask industry experts	2	3
Social acceptance	Social	Consumers or companies accept these innovations	Tool	Ask industry experts	1	1
Opportunities for involvement local expertise	Social	Tool which requires local companies or expertise (indirectly stimulating local economy) and reduced dependency on national help	Tool	Ask industry experts	1	1

Annex 6: Survey circulated to industry experts for the MCA

There were a few exceptions of tools or criteria that were not deemed relevant to ask about in the survey for certain production systems. These were:

- Low trophic aquaculture was added to the survey to raceway, RAS and non-fed systems. This question focused on non-finfish species which was thought not to be relevant for cages or freshwater pond aquaculture.
- The criterion 'GHG emissions from production' was not included in the survey for carbon credits, low trophic aquaculture and ecosystem conservation and restoration support. This is because these tools by themselves already offset emissions and do not produce GHG emissions.
- No Improvement of energy use efficiency surveyed for pond systems. Energy use on ponds in the EU was considered to be low and the systems are not well adapted to change this factor.
- No emerging feed materials, AI-based tools and improvement of energy use efficiency surveyed for non-fed systems. These systems are not fed and the use of AI-based tools focused on reductions in FCR, energy use was considered to be low and mainly included boats which were covered under renewable energy.
- No costs included for low trophic aquaculture, since this was not an tool for which calculations were done in task 3.
- Diversification of species and investment in ocean alkalinity enhancement were surveyed at first but taken out of the results since these tools were omitted from the final report.

Greenhouse Gas Emission in Aquaculture

This survey is conducted as part of the European Maritime, Fisheries, and Aquaculture Fund (EMFAF) study "EU Aquaculture: GHG Reduction Costs and Pathways to Net Zero by 2050".

The EU is committed to reach net zero greenhouse gas emissions by 2050; to achieve this target wide-spread changes are required across almost every industry and the aquaculture industry is no exception. Under this study work is being carried out to identify various solutions to reduce greenhouse gas emissions associated with European Aquaculture production and to assess their viability, cost efficiency, and emissions reduction scale under a range of scenarios.

We need input from industry experts to properly validate these solutions and to provide robust and realistic recommendations moving forward. As such we ask that you provide a qualitative assessment of the impact of a range of solutions to certain key social, economic, and environmental criteria. A summary of the proposed solutions can be found below.

Survey responses will form part of a wider multi-criteria analysis where criteria are ranked and the most opportune solutions are identified.

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Introductory Questions

Your name:

Your email:

*
What category of stakeholder best describes you?

Choose one of the following answers

- ○ Farmer, Fish Producer, Fish Processor
- ○ Government Authority, Competent Authority, Regulator, State Agency
- ○ Industry Representative Group, Trade Association
- ○ Non-Governmental Organisation, Advocacy Group
- ○ Technology Solutions Provider
- ○ Commercial Feed / Feed Ingredient Company
- ○ Scientist/Research Body
- ○ 3rd Party Certification & Standards Organisation
- ○ Other:

Next

Production systems

The Multi-Criteria Analysis will focus on the best solutions for five different production systems. Four systems relate to the culture of finfish and, where applicable, crustaceans: cage culture in fresh and marine environments, pond culture, raceway culture, and RAS both marine and freshwater. The final system is the culture of molluscs and macroalgae in suspended culture including bouchot. Please select the culture system that you are most knowledgeable about and assess the solutions and criteria in the context of that system.

Please select the production system you are most familiar with

Choose one of the following answers

Please choose...

Please choose...
Cage
Pond
Raceway
RAS
Suspended

Next

Cage Aquaculture Solutions Evaluation

Please familiarise yourself with the list of solutions below so that you can assess the most optimal solution for each criteria in the tables at the bottom.

Novel Feed Ingredients: Feed production is a major contributor to greenhouse gas emissions in aquaculture production. The widespread adoption of alternative feed ingredients may reduce reliance of wild forage fish, allow for reuse of waste materials, and improve FCR and fish health. Alternatives include insect meal, algae oils and meals, poultry by-products, and single cell proteins. Inclusion rates differ between species.

Breeding programs: Whilst a growing number of aquaculture species produced in Europe come from selective breeding programs there is still unmet potential both in the number of species and the level at which this solution can result in improving performance of key characteristics. Advances in genomic selection, marker-assisted selection, phenotyping, genome editing, functional genomics, and tools such as induced sterility have been shown to improve growth rates, FCR, resistance to disease, tolerance of suboptimal environmental conditions, and many more commercially important traits. Reducing mortalities and reducing feed use requirements will lower the greenhouse gas emissions from the sector.

AI tools: Artificial intelligence and automation are rapidly being used to tackle a wide range of issues in aquaculture and beyond. Uses for AI tools in the aquaculture industry include environmental and water quality monitoring, automatic feeding linked to factors such as fish behavior and the environment, early detection of disease, and smart control of land-based RAS facilities. Whilst these systems require the use of natural resources for their construction and energy for their operation studies have shown they can effectively reduce FCRs and mortality rates and improve growth rates and operational efficiency.

Diversification of species: European aquaculture is based around a small number of core species; these species account for a small fraction of the number cultivated worldwide and the number of native species possible to cultivate in the EU. As climate change continues to influence temperatures, salinity, and seasonal weather patterns around Europe there is growing interest in farming an increasingly diverse range of species to enhance the industries robustness to climate change. Species better adapted to local environmental conditions will have improved FCRs, enhanced growth, and reduced mortality compared to less well adapted species.

IMTA: Integrated multi-trophic aquaculture (IMTA) can help reduce greenhouse gas emissions through nutrient recycling and waste management, reducing damage to fragile and important ecosystems, and possibly carbon sequestration. IMTA can be used in freshwater, brackish, and saline environments and incorporate a range of different species.

Renewable energy: Converting energy sources from more traditional oil, coal, and gas to renewable sources can play a significant role in reducing an industry's GHG outputs. Adoption at grid level is required for many users to access these renewable energy sources but on-site adoption of small-scale renewable energy generation can reduce inputs at farm or processer level, when scaled up these savings can result in significant reductions to GHG emissions. Emissions can also be reduced by switching from fossil fuel reliant vehicles such as boats to electric vehicles.

Energy reduction efforts: Energy reduction efforts help to address unnecessary and inefficient energy use at site level. Measures such as upgrading to more energy efficient equipment, regular maintenance, optimization of transport and operation practices, and energy audits improve the energy efficiency of operations and therefore reduce associated greenhouse gas emissions.

Low Trophic Aquaculture: The adoption of aquaculture of low trophic species can reduce emissions from feed production and culture itself. Species such as algae, molluscs or other plants (duckweed) can remove excess nutrients from the environment and there is evidence that they may sequester carbon. These species don't require inputs of feed and energy use requirements are also lower for their culture. Lower trophic fish species require less inputs of fish oil and fish meal and at more extensive levels can feed on natural production in the pond or system in which they are grown.

Buying Carbon Credits: Some greenhouse gas emissions may be hard to abate even with significant investment in a diverse range of solutions. To offset these emissions tools like carbon credits may be used. Purchasing carbon credits as part of the voluntary carbon market can reduce the net greenhouse gas emissions of the European aquaculture sector.

Investment in Ecosystem Restoration: Restoring degraded ecosystems such as wetlands and seagrass meadows can provide environmental benefits such as water purification, biomass improvements and species conservation, pollution mitigation, protection against climate change, and reduction of atmospheric greenhouse gases through carbon sequestration.

Investment in Ocean Alkalinity Enhancement: Ocean alkalinity enhancement is an approach to carbon removal that involves adding alkaline substances to seawater to accelerate the ocean's natural carbon sink. Adding alkalinity to the ocean converts dissolved inorganic CO2 in seawater into bicarbonates and carbonates, which are stable forms of carbon with a lifetime of approximately 10,000 years. The resulting CO2 deficit in surface waters is quickly rebalanced via a net movement of atmospheric CO2 into the ocean, to reestablish equilibrium.

Question 1: Please provide a score for how you perceive each solution to impact each criterion, using the following Likert scale:

- **-2: the solution will have a strong negative impact on the criteria**
- **-1: the solution will have a slight negative impact on the criteria**
- **0: the solution will have no noticeable impact on the criteria**
- **1: the solution will have a slight positive impact on the criteria**
- **2: the solution will have a strong positive impact on the criteria**

	Novel Feed Ingredients	Breeding programs	AI tools	Diversification of species	IMTA	Energy Conversion	Energy Reduction	Low Trophic Aquaculture	Carbon Credits	Investment in Ecosystem Restoration	Enhancing Ocean Alkalinity
Operational costs for aquaculture producers	...	...	...	...	...	...	...	...	...	...	...
Implications for safety - worker, consumer, working conditions etc	... -2	...	...	...	...	...	...	...	...	...	...
Increase in the number of employees engaged within the aquaculture sector	-1	...	...	...	...	...	...	...	...	...	...
Impacts like introduction of invasive species, depletion of wild stocks due to overfishing for fish oil and fish meal, escapes fish from farms, water pollution	0 1 2	...	...	...	...	...	...	...	...	...	...
Amount of fresh water required for the same volume of production	...	...	...	...	...	...	...	...	...	...	...
Amount of space required for new aquaculture production systems, also related to the destruction of habitat (e.g. wetland conversion for ponds)	...	...	...	...	...	...	...	...	...	...	...

Question 2: Please provide a score for how easily each solution will be implement across the production sector due to each criterion, using the following Likert scale:

- **-2: the solution will be very difficult to implement due to the criteria**
- **-1: the solution will be difficult to implement due to the criteria**
- **0: the solution will be neither difficult or easy to implement due to the criteria**
- **1: the solution will be easy to implement due to the criteria**
- **2: the solution will be very easy to implement due to the criteria**

	Novel Feed Ingredients	Breeding programs	AI tools	Diversification of species	IMTA	Energy Conversion	Energy Reduction	Low Trophic Aquaculture	Carbon Credits	Investment in Ecosystem Restoration	Enhancing Ocean Alkalinity
How well is the solution covered by existing regulations	...	...	...	...	...	...	...	...	...	...	...
How well is the solution covered by existing skills across the sector	...	...	...	...	...	...	...	...	...	...	...
How ready is the industry to implement the solution	...	...	...	...	...	...	...	...	...	...	...

Next

Annex 7: Summary of Stakeholder consultation through the ETP

On September 15th, the study team organised a validation workshop with ETP and other invited to present and discuss assumptions and preliminary results. The summary of that discussion and the resulting actions is presented below.

Feedback on Baseline GHG emission

The initial baseline was generally well received and there was general agreement of the findings, assumptions, and with the presentation of the results. Across the group there was enthusiasm for the work and how proper identification of the most energy dependent elements of the EU aquaculture industry can help focuses emissions reduction efforts. There were, however, several points that were mentioned on how the accuracy of the calculations could be improved.

Emissions assigned to feed transport were considered to be too high and the distance chosen for feed transport was questioned. This resulted in refinement of the formula used to calculate transport emissions, however after discussion with the commission the distance was kept the same.

Hatcheries were not originally considered within the system boundaries, however following the ETP workshop these were added on the advice of the stakeholders.

RAS energy consumption was thought to be high in the original calculations, and this was checked and adjusted accordingly.

There was no separation of the emissions from fuel consumption of vessels on farms from other elements of production, stakeholder advice was to separate this out and this was done.

Production system proportions were considered to be too presumptive. These were rechecked and clear errors were improved but due to limitations in the available data assumptions of historic production by system had to be made.

It was also mentioned that given the complexity of the calculations all assumptions should be made clear, and this has been done in the report.

Feedback on Tools and Scenarios

Overall, the tools proposed were thought to be appropriate and fitting the context to EU aquaculture. Comments during the workshop included the need to consider appropriate adoption rates for things like renewable energies and scale back suggested rates of adoption for things like emerging feed materials (particularly microalgae) considering both technology readiness, cost, and nutritional compatibility.

AI adoption was considered important but as were methods of react once problems like disease should occur. This resulted in a scaling back of its impact in the non-fed aquaculture predictions. Values of its reduction potential were also revised following feedback.

IMTA was one of the most divisive tools and there were questions over its ability to decrease carbon as a carbon sink. This feedback along with later interviews resulted in a revision of the potential emissions reduction impact of IMTA from earlier models.

Breeding programs and AI focused on improving FCR and reducing fish loss as their primary targets and these were agreed as the most effective pathways to reduce energy use.

A topic of much debate during the workshop was an appropriate level of predicted growth for the industry. In the end it was decided that the FAO’s figure of 1.6% was the most appropriate. Some members of the workshop doubted this was possible whilst others were optimistic of higher rates given the correct support from the EU.

Some alternative technologies mentioned were biofloc and pond-in-pond technology but these were considered too niche for adoption into the model.

Feedback on Scenario cost analysis

Capital expenditure (CAPEX) was seen as the biggest barrier for adoption of technologies, in particular renewable energy on farms. Following comments on CAPEX levels in general these were reevaluated.

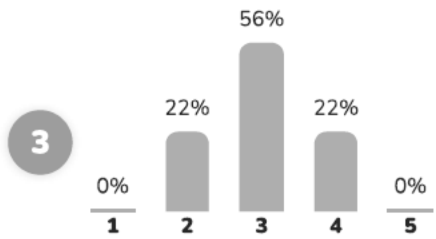
Feedback on Impact, limitations, gaps, and sensitivity analysis of scenarios (task 4)

The second half of the workshop asked that alongside providing comments, the participants vote on the feasibility of the scenarios.

Scenario 2 (Effort sharing regulation) - specific feedback

Feasibility score: Average 3.0 (9 responses)

Figure 37 – Feasibility score Scenario 2



Main barriers to implementing Scenario 2

Time was a key consideration with feedback that the generation time required to see gains in breeding programs can be impede potential gains of this tool. On the other hand, AI was the tool thought to be moving the fastest but due to this there was a high level of confusion and uncertainty of the correct technology to invest in.

Infrastructure was seen as a key barrier for renewable energy with marine aquaculture thought to be more difficult than other systems. Support on cost as well as tools to help implementation were thought to be needed to help the adoption of AI tools which gains in sustainable feeds were highly reliant on other sectors as well as imports to the EU. The availability and scale of new ingredient production were also barriers and given the large percentage of emissions from feed, these were seen as important barriers to overall emission reduction.

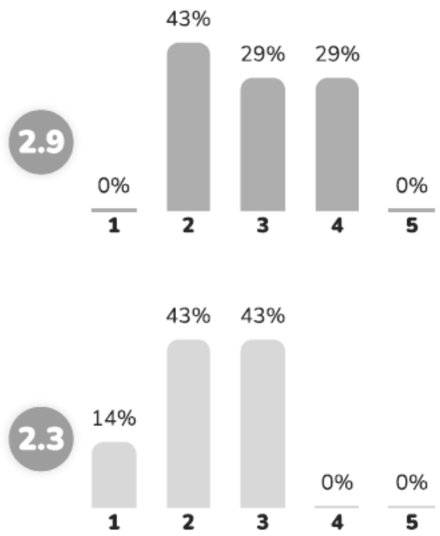
Finally supporting regulations were seen as important but considered to be a somewhat “chicken and egg” situation were regulations are required to support the adoption of technological tools but without some level of uptake of tools regulations would not be implemented.

Scenario 3&3B (Low investment) - specific feedback

Feasibility score 3: Average 2.9 (6 responses).

Feasibility score 3B: Average 2.3 (6 responses).

Figure 38 – Feasibility scores Scenarios 3 and 3b



Barriers of implementing Scenario 3 and 3B

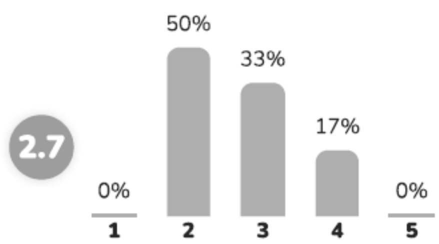
For Scenarios 3 and 3b, which rely on low investment within the industry, the level of inclusion of emerging feed materials was thought to be too high and a barrier to success. The suggested use of carbon credits was not well received and feedback led to a reworking on how this potential tool is presented with clear distinctions between the responsibilities of individual farmers and the use of credits as a mitigation tool used on a wider level.

Costs both CAPEX and OPEX were seen as barriers despite the emphasis on low investment.

Scenario 4 (Resilience to climate change) - specific feedback

Feasibility score: Average 2.7 (6 responses).

Figure 39 – Feasibility score Scenario 4



Barriers to implementing Scenario 4

For Scenario 4 the key barriers to implementation were thought to be the assumed level of uptake of emerging feed materials.

AI was thought to be useful, but a barrier would present itself if other efforts such as vaccines and more research and development to solve challenges were not invested in.

Scenario 5&5B (Maximize GHG reduction) - specific feedback

Figure 40 – Feasibility score Scenarios 5 and 5b

Feasibility score for Scenario 5 and 5B, respectively: Average 2.0 (6 responses).

Barriers to implementing Scenario 5 and 5b

Scenarios 5 and 5b were thought to be the most unrealistic. Some of this stems from the key scenario assumption that maximises GHG reduction with a disregard for cost, something that most stakeholders considered to be unrealistic within the aquaculture industry. As such economic realities were considered a key barrier to these scenarios.

Other barriers include the adoption rates of emerging feed materials and to a lesser extent AI.

Assumptions on renewable energy were thought to be realistic and the scenarios to be technically feasible.

Key take-aways from the ETP consultation

Assumptions

- ✓ The feed transport-to-production emissions ratio may be inaccurate; direct contact could be an option.
- ✓ Production ratios for different systems need refinement, as assuming uniformity is problematic.
- ✓ Hatchery production was estimated on the basis of on only two articles and its contribution to overall emissions might not be accurate.

Tools

- ✓ Carbon sequestration and IMTA are worth exploring further.
- ✓ Energy use calculations need clarification or refinement.
- ✓ AI benefits are promising but scenarios without AI and IMTA should also be considered due to feasibility concerns.
- ✓ Non-electricity energy use is unclear, especially when discussing capex for renewable energy; this needs further investigation.
- ✓ Increase in production
- ✓ A sensitivity analysis on sector growth rate for the next 25 years is recommended.

Scenarios

- ✓ Scenario 2: Capex costs, particularly for renewable energy, will be revised.
- ✓ Scenario 3/3b: High adoption of emerging feed materials is assumed, but challenges related to availability and effective sustainability remain. Access to carbon credit markets also remains a challenge.
- ✓ Scenario 4: Overlaps with Scenario 3; distinctiveness needs improvement. Reassess emissions reductions from IMTA and consider losses from sea temperatures and disease.
- ✓ Scenario 5/5b: Short-term assumptions appear overly optimistic.
- ✓ Scenarios are generally relevant, but RAS developments could increase its prevalence as a production system in the future.

Annex 8: Description of production methods

Fish production methods

Cages

Fish cages are floating or submerged enclosures placed in natural water bodies such as lakes, reservoirs, or coastal marine areas. They allow water exchange between the cage and the surrounding environment, enabling natural water flow to remove waste and provide oxygen. They are typically used for species that adapt well to confined open-water environments, including salmon, sea bass, and trout. Cages usually have higher stocking densities than extensive systems, allowing a higher production, but often causing environmental concerns such as nutrient pollution, disease transmission to wild populations, and risks from weather or predators.

The main advantages of this production system include lower construction costs compared to land-based systems and utilization of natural water conditions.

Source: https://www.sciencing.com/about-5489412-fish-cage-production/

Tanks and Raceways

Tanks are land-based containers, often rectangular or circular, used in controlled environments for fish production, while raceways are long, narrow channels with a continuous flow of fresh water, designed to provide a controlled environment with flowing water to remove waste and supply oxygen.

Both systems provide high levels of control over water quality, temperature, and feeding. They support higher stocking densities compared to ponds due to controlled water flow and aeration.

These systems require continuous water supply, often from a river or spring, and proper waste management to prevent pollution.

Source: https://www.fao.org/fishery/photolibrary/photo/detail/en/c/117793/

Ponds

Ponds are shallow, enclosed bodies of water, either natural or man-made, used extensively in aquaculture. They have a relatively low engineering complexity but require suitable soil types, such as clay or clay-silt, to retain water without leakage. Stocking densities are generally lower than tanks or raceways, and ponds rely on natural productivity augmented by fertilization.

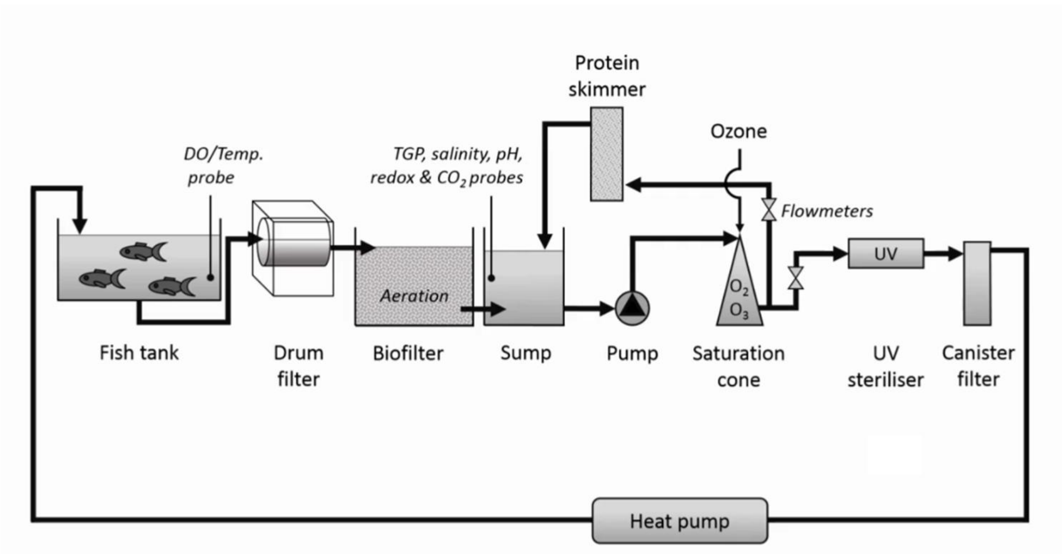
Water management in ponds varies; some are flow-through with water continuously supplied and drained, others are static or semi-static.

Species such as carp, tilapia, catfish, and shrimp are commonly farmed in ponds.

Source: https://www.nagodas.com/pond-traditional-culture.php

Recirculating Aquaculture Systems (RAS)

RAS are highly engineered, land-based systems that treat and recycle water within a closed-loop system. Water usually goes through a series of connected fish tanks and back to a biofilter where nitrifying bacteria turns the toxic ammonia into less toxic nitrate and can then be sent back to the fish tanks. A drum filter removes the solid waste from the water before being sent back to the fish tanks. Optimal water quality is also often maintained through oxygenation, and automated water monitoring.



RAS enable very high stocking densities and year-round production independent of external water sources. However, these systems have high capital and operational costs due to pumps, filters, sensors, and energy use.

Positive aspects of RAS production include biosecurity advantages by minimizing disease risks from external sources and reduction of water use and effluent discharge.

Non-fed aquaculture production methods

Figure 41 – Mussel culture methods

(a) seed fishery, (b) seed mussel collectors, (c) hatchery production (d) bottom culture, all in The Netherlands, (e) Bouchot culture in France (https://reporterre.net/Les-moules-du-Mont-Saint-Michel-etouffent-la-baie-magnifique), (f) raft culture in Spain and (g) longline culture in New Zealand. Source of pictures: Jacob Capelle (a and d), Aad Smaal (e) and Pauline Kamermans (b, c, f, and g)

Bottom culture

Mussel bottom culture is typically practised on shallow mudflats in areas where there are extensive naturally occurring mussel seed beds (Fig. X.3d). In the Netherlands, Germany, UK and Ireland, seed fished from natural beds is the main source for bottom culture. Mussel seed from wild beds are relayed on bottom plots (lease sites) where the mussels are maintained until harvest. Bottom culture is an extensive culture where the mussels are still, to a large extent, subjected to, and dependent on the environment. Mussel farmers in the Netherlands are in a transition process from fishing seed from natural beds to harvesting seed with collectors. A stepwise approach is taken: every 2 years a decision on reduction of seed fishing and expansion of the area reserved for seed collection is made based on the annual yield of the collectors. The shift from fishing to using collectors results in a higher mussel biomass in the system, because areas with natural beds are no longer fished and spat survival is enhanced on the collectors (Kamermans and Capelle, 2019).

For oyster, bottom cultures are known as oyster “beds” or “lays”. The oysters are not held in any form of containment device and are harvested either by dredge, by rake or by hand. This traditional technique is commonly used in the United Kingdom of Great Britain and Northern Ireland, the Kingdom of the Netherlands, Asia and the United States of America. In contrast to off-bottom cultivation, which is mainly performed in the intertidal areas, on-bottom cultivation can be performed in both the intertidal and subtidal zones

Bouchot

Bouchot culture (pole culture) is conducted exclusively in France, in areas with flat intertidal mudflats and a relatively large tidal range (Fig. X.3e). In bouchot culture, mussel seed is collected on ropes, that are placed in horizontal racks in the water column when larvae are present. The ropes are then wound around poles in the intertidal zone for grow-out. Bouchot culture dates back to the thirteenth century and the principles and methods remain largely unchanged. Technical developments are very much restricted to mechanical methods to increase harvest efficiency. Amphibious vehicles are used to harvest the bouchots by means of a cylinder that can be lowered over the poles and scrapes off the mussels (Prou and Goulletquer 2002). Processing, size grading and restocking is also mechanized. Spatial conflicts on bivalve culture with other users is limiting the expansion of bouchot culture in France and has stimulated the development of longline cultures (Prou and Goulletquer 2002) (See in Kamermans and Capelle, 2019).

Longline and raft (suspended)

In bays with deep waters and bays with rocky shores, rafts and longlines are more commonly used for the grow-out of mussels (Fig. X.3f, g). Originally developed in the Mediterranean, large-scale raft culture is conducted primarily in Spain, and in more recent times, extensively at the northwest coast of Spain, where local upwelling results in a high food availability (Figueiras et al. 2002). In raft culture, mussels are grown on ropes hanging from rafts. In rope or longline culture mussels are grown on ropes attached to floating buoys at the water surface or submerged buoys. Longline culture is globally the most used culture method for mussels. Countries where high biomasses of mussels are produced on longlines are New Zealand, China, Italy and Chile. Culture practices can be summarized as (1) obtaining seed, (2) stocking and growing on rope, (3) restocking after thinning out and outgrow to consumption size. Major issues in off-bottom culture is resource requirement, density dependent growth and losses and biofouling. Self-thinning occurs when biomass increased through growth and food or space becomes limited. Seed for off-bottom culture is obtained mainly with seed collectors. However, when natural settlement is scarce other methods are used. For example, scratching from the shore rocks in Galicia (Spain) (Kamermans and Capelle, 2029)

For oyster suspended production, oysters are attached to ropes which hung suspended from longlines or from ropes or lanterns suspended from tables. The culture in longline systems does not differ from mussel culture. Tables can be found in the Mediterranean part of France (i.e.,Thau Lagoon)

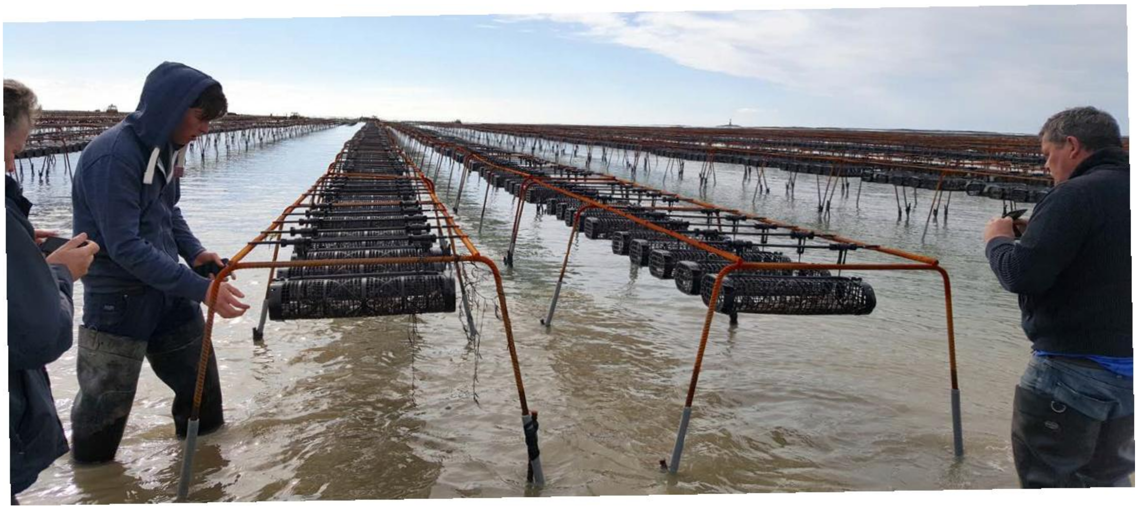
Source: Mercer et al (2024)

Off-bottom

Oyster

Off-bottom cultivation on trestles

The most common off-bottom technique is growing the oysters in bags laid on trestles installed in the intertidal zone. It is the traditional production technique that is widely used all along the European Atlantic coast of France, Ireland and the United Kingdom of Great Britain and Northern Ireland. In most of the above-mentioned countries, where exposure to the air due to the tidal movement helps to create a product with a strong shell and long shelf life, the oysters are traditionally sold and consumed as raw product and not processed in any way. With globalisation, these high-quality oysters are now exported all over the world in their natural state.



Source: Mercer et al (2024)

Off-bottom cultivation in baskets

Another technique, that has been developed more recently, consists of growing the oysters in baskets suspended off the bottom by various supports (Figures 4.17, 4.18, 4.19 and 4.20). Suspended basket cultivation is mainly performed in Australia and New Zealand and is progressively spreading to many other countries. Basket cultivation is also considered to be an “off-bottom” system rather than a “Suspended” system because in most cases the baskets are separated from the bottom by less than 1–1.5 m.

Source: Mercer et al (2024)

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