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Report

Carbon footprint of fisheries
- a review of standards, methods and tools

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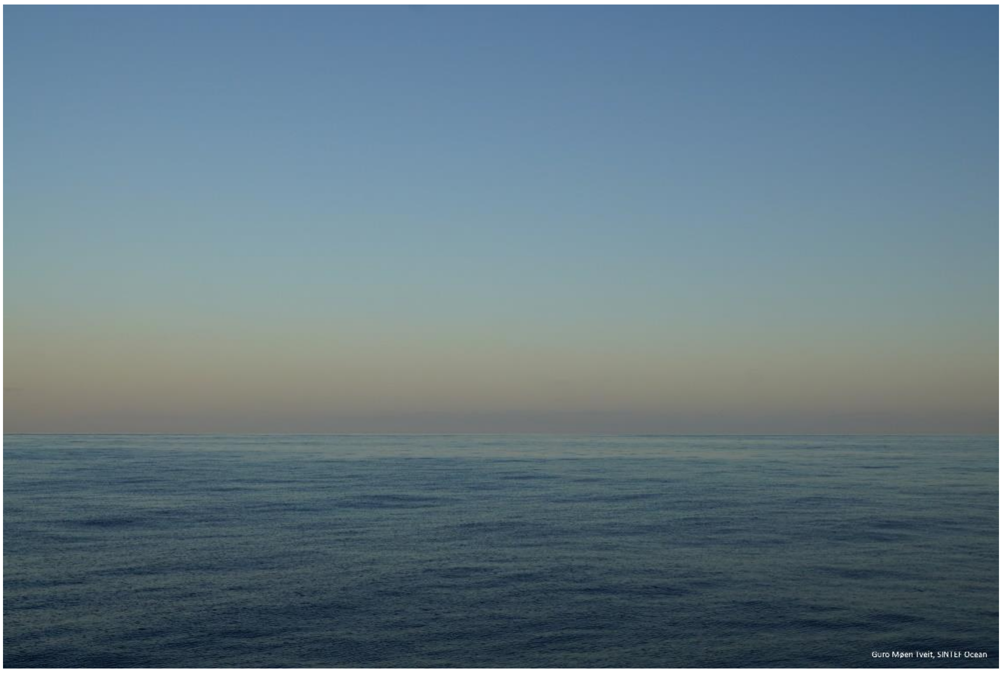
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ABSTRACT

This report provides an overview of standards, methods, certification schemes, tools, and previous studies related to the carbon footprint (CF) of seafood, both in general but especially related to fishing vessels and refrigeration systems. The aim is to give various perspectives on CF estimations for fisheries, as a basis for further work in CoolFish.

A few standards are specifically developed for seafood products; the British PAS2050:2 and the Norwegian NS-9418. Sustainability certifications typically evaluate harvesting pressure, fishing practices and fisheries management. Even if energy use and emissions are often built into the assessment criteria, the CF is rarely specifically addressed.

Online tools are available for CF estimations of seafood products, or parts of the product chain. Data for the fishery stage are based on conventional diesel propulsion, and the refrigeration system is only addressed by default values on refrigerant leakage.

Previous studies on CF assessment of captured sea-food shows that the fishing vessel's fuel consumption is generally the dominant contributor. Emissions of synthetic refrigerants can also play an important role, as can air transportation. More disaggregated data on fuel use are required to evaluate on-board measures for CF reduction.

Further work in CoolFish could contribute with estimations of fuel use for propulsion and refrigeration, for different fishing vessels and operational modes.

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1 Introduction

One objective of the CoolFish project is to evaluate and adapt existing methodologies for estimating the carbon footprint of a fishing vessel, with focus on its cooling and heating systems. This report provides a review of different methods, tools, standards, and certification schemes that are related to the carbon footprint (CF) of seafood, in general, and to fishing vessels and refrigeration systems specifically.

However well the seafood industry compares to other food industries, in terms of its greenhouse gas (GHG) emissions, there is room for improvement right across the supply chain. Even though estimating the carbon footprint of seafood products is fraught with many variables, there is much to be learned by looking at the key components contributing to the carbon footprint of wild-caught and farmed fish. For products originating in capture fisheries, the fishing stage itself is typically the dominant contributor, while for farmed fish it is primarily related to the feed. Transportation can in some cases generate significant emissions, depending on the distance and mode of transportation [1].

This report focuses on the carbon footprint of captured fish. The direct fuel intensity and resulting emissions of various capture fisheries may differ by orders of magnitude, depending on the fishing method employed, the abundance and health of the targeted stocks and the distance to fishing grounds, among others. In addition, many fishing vessels have a large fuel consumption related to refrigeration of the captured fish. For ships with refrigeration systems onboard, leakage of refrigerants (fluorinated gases) can be an important contributor to the total GHG emissions [2] [3].

The main objective with the review presented in this report is to give different perspectives on carbon footprint estimations for fisheries, as a basis for further work on this topic in CoolFish. For this purpose, two other complementary reports are prepared; one reviewing alternative fuels and propulsion systems, replacing conventional diesel engine propulsion onboard fishing vessels; the other reviewing refrigeration systems and refrigerants applied onboard fishing vessels.

2 Methodologies and standards for carbon footprint estimations

This chapter presents the most applied methodologies / standards for estimating the carbon footprint of a product, followed by those specifically developed for seafood products. The first section gives a brief introduction to Life Cycle Analysis and Carbon Footprint estimations since these are closely related.

2.1 Brief about Life Cycle Analysis and Carbon Footprint

2.1.1 Life Cycle Analysis (LCA)

LCA is a method to map and quantify the environmental impacts that a product causes through its life cycle. The "LCA book" keeps record of mass and energy flows and maps where environmental impacts are caused. LCA is standardized by ISO in their 14000 family on environmental management.

LCA is holistic by taking a complete life cycle, or a complete production system, into account and by including a complementary set of environmental impacts. Typical LCA impact categories include global warming, acidification, eutrophication, ozone layer depletion and aquatic/marine/terrestrial eco-toxicity [4]. The holistic approach avoids sub-optimization as it will help in discovering how environmental impacts might have changed location rather than been reduced or how one environmental impact has been traded off for another. Or even better, explaining and quantifying the net reduction of environmental impacts caused by a change in the system (e.g. reduction in GHG emissions by using alternative refrigeration systems) [5].

2.1.2 Carbon Footprint (CF) estimation

Estimation of the CF related to a product or service is a simplified form of LCA. It provides a single numerical index of environmental performance, which is easily understandable. However, the CF concept may be criticized as being one-dimensional, as it focuses solely on climate change effects while completely excluding all other environmental aspects.

Currently, there are two types of methodology approaches for the CF calculation: one is based on the organization and the other on the product. The CF of a product is the total GHG emissions generated during a defined system boundary (life cycle stages). GHGs are considered all gaseous substances for which the IPCC (Integrated Pollution Prevention and Control) has defined a global warming potential (GWP), expressed in mass-based CO_2 equivalents ($CO_{2,eq}$).

Results from a CF estimation will vary widely depending on the methodology applied differing in, for example, which life-stages and parameters that are included in the calculations. The life cycle stages are defined by the following system boundaries [6] [7]:

- **Cradle-to-grave / business-to-consumer** includes emissions and removals generated during the full life of cycle of the product
- **Cradle-to-gate / business-to-business** includes emissions and removals up to where the product leaves the organization
- **Gate-to-gate** includes emissions and removals in the supply chain.
- **Partial CF** includes emissions and removals related only to specific stages

2.2 Standards for CF estimations

Measuring the carbon footprint is considered by the UNs Framework Convention on Climate Change as a keyway of contributing to the achievement of international climate action goals. It allows organizations to more accurately see where the main impacts on their carbon footprint are generated and, thus, to take appropriate actions to reduce it.

There are three main Product Carbon Footprint (PCF) standards that are applied worldwide: PAS 2050, GHG Protocol and ISO 14067. All three provide requirements and guidelines on the decisions to be made when conducting a carbon footprint study. They all build on existing LCA methods established through ISO 14040 and ISO 14044. Decisions involve LCA issues, such as goal and scope definition, data collection strategies and reporting. Moreover, these standards provide requirements on specific issues relevant for the CF, including land-use change, carbon uptake, biogenic carbon emissions, soil carbon change, and green electricity [8].

Several comparisons on CF accounting methods have been conducted for various products. The use of different methods often leads to numerical differences in the CF value. Key aspects causing inconsistency are mostly related to system boundary, cut-off criteria, biogenic carbon treatment, and allocation [9]. For CF estimations related to seafood, PAS 2050 is widely used, probably since it includes specific guidelines for seafood products.

In addition to these internationally recognised standards, numerous other initiatives have been initiated by either public or private organisations at the regional and local level. Some of these initiatives focus solely on GHG emissions, while others include other environmental impacts as well.

2.2.1 ISO 14067

The international standardization organization (ISO) provides the most widely used standards for LCA in their ISO 14000 family for environmental management. This series of standards cover how LCAs can be used, performed, communicated and audited. The ISO 14000 standards have formed the basis for many sectors and/or impact specific standards [8].

The recently published ISO 14067 is part of the ISO 14060 family of standards for quantifying, monitoring, reporting and validating GHG emissions to support a low-carbon economy. ISO 14067:2018, *Carbon footprint of products*, provides globally agreed principles for quantification and communicating of GHG emissions. Unlike the PAS 2050 and the GHG protocol, the ISO 14067 allows the assessment of full or partial life cycle stages.

The ISO 14067 standard replaces the technical specification ISO/TS 14067:2013, which was upgraded to International Standard status after the market signalled a need for a more in-depth document. Key changes from the technical specification include greater focus on quantification (by moving other topics such as communication to other standards in the ISO 14000 environmental management family); greater clarity on a range of aspects, such as calculating the use of electricity; and the introduction of specific guidance for agricultural and forestry products [10].

ISO 14067 makes a valuable contribution to GHG quantification, allowing a transparent communication and comparison of CFs made among identical quantification and communication requirements. It is consistent with other environmental standards, for instance ISO 14025 (environmental labels and declarations), ISO 14044 (lifecycle assessment), and BSI PAS 2050 [11].

2.2.2 PAS 2050

The PAS 2050:2011 is a Publicly Available Specification (PAS), developed by the British Standards Institute (BSI), providing a generic method for assessing the life cycle GHG emissions / CF of products and services. The PAS 2050 is today one of the most applied standards for GHG assessment of products, globally. The life-cycles boundaries included are cradle-to-grave and cradle-to gate. In 2012, the PAS-2050-2 was published, with the purpose of providing supplementary requirements and additional guidance for the consistent application of PAS 2050:2011 to seafood and other aquatic food products (see section 2.4.1).

2.2.3 GHG Protocol Product Standard

The GHG Protocol Product Standard has been developed by the World Resources Institute (WRI) and Business Council for Sustainable Development (WBCSD). It was launched in October 2011, based on ISO standards and the first version of PAS 2050, with the aim to provide detailed guidelines on accounting and reporting. As for the PAS 2050, it allows for both cradle-to-grave and cradle-to-gate analyses [9].

2.3 Environmental product declarations and category rules

Environmental product declarations (EPDs) offer an international standard of communication to objectively compare and describe a product’s environmental impact throughout its entire life cycle, from cradle to grave. In recent years, the increasing demand for LCA-based product declarations, such as EPDs, has generated a need for rules enabling comparable declarations on products within the same category. These rules are defined as *Product Category Rules* (PCRs) in ISO 14025; *Product Rules* in the GHG Protocol Product Standard; and as *Supplementary Requirements* in PAS 2050.

2.3.1 Product Environmental Footprint (PEF) guide

The EUs standardised method for assessing the Product Environmental Footprint (PEF) is described by the PEF guide "*Annex to Commission Recommendation 2013/179/EU on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations*". The PEF method is based on LCA to quantify the relevant environmental impacts of products (goods or services). It builds on existing approaches and international standards, with the aim of setting the basis for better reproducibility and comparability of the results. However, comparability is only possible if the results are based on the same Product Environmental Footprint Category Rules (PEFCR) [12].

2.3.2 Product Environmental Footprint Category Rules (PEFCR)

PEFCRs provide specific guidance for calculating a product’s potential life cycle environmental impact and are developed according to the PEF Guide. The development of PEFCRs aims to focus the PEF studies on those aspects and parameters that are most relevant in determining the environmental performance of a given product. A PEFCR shall further specify requirements made in the general PEF Guide and shall add new requirements where the PEF Guide provides several choices or does not cover sufficiently the particularity of the life cycle for a specific product category [5] [13].

2.3.3 Carbon Footprint Performance (CFP) communication

Since CF estimations are becoming increasingly popular among companies to differentiate their products in a competitive market, the importance of communicating the product's carbon footprint is also increasing. This can be made in the form of CFP external communication reports, CFP performance tracking reports, CFP declarations, or CFP labels. It can also be complemented by an external communication report (ECR) and a carbon footprint performance report (CFPR). These two reports depend less on quantification, instead provide quick and traceable information to the final consumers. There are standardized ISO templates available (for purchase) [11].

2.4 Standards related to seafood products

Many previous studies state the lack of standardised, widely applicable fishery-specific impact categories related to technological, spatial and temporal variation in fishing operations [4]. Two standards that have been developed specifically for seafood products are presented below. Although these standards provide substantial support, a number of challenges remain in undertaking assessments of seafood products, as discussed in *Handbook of GHG assessment of Seafood products* [8].

2.4.1 PAS-2050-2:2012

This PAS was prepared at the request of, and with significant input from, representatives of the global seafood industry. It contains requirements for the assessment of life cycle GHG emissions that are specifically associated with seafood and other aquatic food products. The requirements are supplementary to those specified in PAS 2050:2011 for product carbon footprints. Figure 2-1 shows the scope of the PAS 2050:2 (blue dotted line) [14].

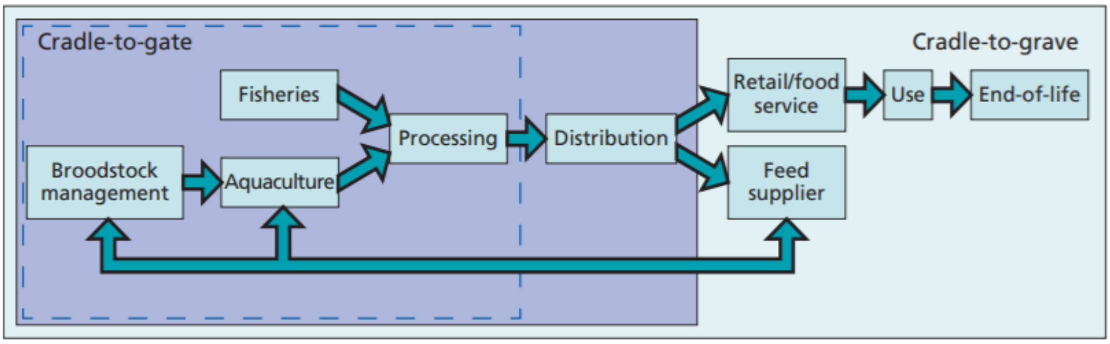


Figure 2-1: Scope of PAS 2050-2 in the context of PAS 2050:2011 [14].

The PAS 2050-2 provides a common approach to assess GHG emissions associated with both wild caught and farmed fish products. It enables organizations to review their activities at all stages of the seafood lifecycle - from brood-stock rearing to fish capturing, farming and slaughtering, landing and auctioning, fish processing, transport and preservation. Figure 2-2 shows the typical stages included in a cradle-to-gate assessment of seafood products [14].

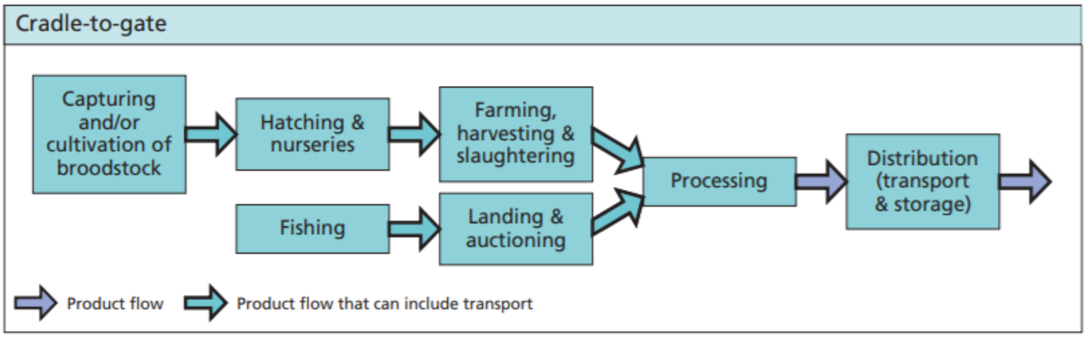


Figure 2-2: Typical system boundary for cradle-to-gate assessment of seafood products [14].

Beyond guiding industry CF assessments, the specification helps to clarify and gain consensus on key hotspot impact areas for GHG emissions related to seafood. Parameters categorised as "always significant impact" include *energy (diesel, gas, electricity*) and co-products where present. Among parameters with "potential for significant impact" are *materials used for cooling; ice and refrigerants*, materials used for processing, and transport.

2.4.2 NS 9418:2013

This Norwegian standard contains product category rules for calculating and communicating the carbon footprint of seafood products, as defined in ISO/TS 14067. The overarching aim of NS 9418:2013 is to provide a basis for reliable and accurate information about the climate impact of the product, and a basis for the development of tools and databases for calculating CF of seafood products. The standard is a living document meaning that if changes occur, which are relevant for the CF calculation in the LCA methodology or concerning new technologies employed, amendments shall be made and published.

In addition to providing credible and transparent information about the products' climate impact, it also provides incentives for further improvements and associated reductions in energy consumption and climate impact from all links in the seafood value chain. The standard is based on reports and studies by stakeholders, experiences from the sector and from the pilot project "*Mapping of initiatives/guidelines prepared in connection with carbon footprints of fish and fish products*", which forms a part of the Norwegian authorities' long-term efforts to make Norway a low-emissions country in terms of GHGs [15].

2.5 Standards related to refrigeration systems

Several indices have been developed to measure the impact on climate change from refrigeration and from heating, ventilation and air conditioning (HVAC) systems, including Life Cycle Climate Performance (LCCP) and Total Equivalent Warming Impact (TEWI).

2.5.1 Life Cycle Climate Performance (LCCP)

The LCCP analysis is a method for evaluating the potential global warming impact of HVAC and refrigeration systems, by calculating the sum of direct and indirect emissions [CO_2 equivalents] generated over the system's lifetime. Indirect emissions are related to energy consumption during the manufacturing process, operational lifetime, and disposal of the system. Direct emissions include release of refrigerant into the atmosphere, caused by annual leakage from the operating unit and leakage during the disposal of the unit. Average values of the end of life leakage (EOL) and annual leakage rate (ALR) are provided for different system types. Marine units have the highest ALR (20%) while the EOL (15%) is similar to other systems [16].

The International Institute of Refrigeration (IIR) has developed guidelines for performing LCCP analysis, to provide a harmonized method for all types of stationary air conditioning, refrigeration, heating, and heat pump systems. It aims to provide designers, facility operators and manufacturers a way to effectively evaluate and compare the environmental impact of different systems over the course of their lifetimes. However, as noted in the guidelines, since LCCP calculations are dependent on several assumptions, it should be used as a comparison tool for systems with similar performance and function. It is not intended to be used as a definitive estimate of lifetime emissions [16].

2.5.2 Total Equivalent Warming Impact (TEWI)

A calculation of the Total Equivalent Warming Impact (TEWI) is a simplified version of a LCCP analysis. TEWI is mostly used for assessing the global warming impact of an equipment at design stage based on the total GHG emissions [CO_2 equivalents] during the operation of the equipment, and the disposal of refrigerant at the end of life. It specifically excludes direct emissions during manufacturing of equipment and fluids, and the GHG emissions associated with embodied energy in materials. The justification for excluding these items is that they typically equate to around 1% of total life cycle emissions in refrigerating applications.

Typical values for the annual leakage rate are given for different equipment types and applications. For marine units, the leakage rate ranges between 20% and 40%. For further details on definitions, calculation methodology and parameters, refer to *AIRAH Best Practice Guideline: Methods of Calculating Total Equivalent Warming Impact* [17].

As for a LCCP analysis, it should be emphasised that the TEWI comparison, to be of real value, must relate to systems of equal duty and function. There is little practical purpose in comparing, for example, the TEWI values of a domestic refrigerator and of a supermarket display cabinet.

For fishing vessels, a TEWI analysis could assist fleet operators to compare the GHG emissions (or CF) of the different technical options available that meet their refrigerating requirements. One of the critical steps in performing a TEWI analysis is to understand the total energy consumption of the refrigeration systems. To increase the awareness of the primary sources for energy consumption onboard the vessel, and to determine what portion of fuel consumption is consumed to power the refrigeration system, an energy audit should be performed. For example, the daily energy consumption might vary depending on the type of catch due to different operation behaviours for different species [18].

3 Tools

This chapter presents some tools related to carbon footprint estimations of seafood products, fisheries, fishing vessels and refrigeration systems.

3.1 Need for tools

Consumer pressure and statutory requirements are expected to move the considerations of the seafood industry's carbon emissions towards fuel use, thus moving the focus from the periphery of fisheries management to the "centre stage". Fisheries science needs to prepare new assessment methods and models, data collection processes, targets, limits, and indicators to prepare for this change [19].

The development of such tools / assessment models is often hampered by poor data on fuel consumption. In Europe, fuel use is usually reported by fleet sector rather than by individual vessel, and even more seldom there is access to disaggregated fuel consumption between propulsion and other auxiliaries, such as cooling and heating systems. If emissions are to be reduced in the fishing industry, and if net zero emission statutory requirements are to be considered, better fuel-use data at greater resolution will be needed [20].

There are different ways marine science can provide the fishing industry with tools, helping them to reduce their GHG emissions, such as [21];

- Developing new data collection/archiving systems, which integrate detailed fuel use with other fisheries data (e.g. catch and effort), to be used in a tool for monitoring emissions.
- Provide independent published information/data sheets on GHG emissions in a fleet/fishery.

3.2 Frisbee tool – food cold chain

This tool was developed within the EU FP7 project FRISBEE (Food Refrigeration Innovation for Safety, consumer Benefit, Environmental impact and Energy optimisation).

3.2.1 Overview

The tool was developed for the purpose of assessing and optimising refrigeration technologies along European food cold chain, in terms of food quality, energy use and global warming impact. These three sustainability indicators (quality, energy use, GHG emissions) are coupled through temperature, leading to a potential trade-off. The tool can be used by various stakeholders in the food cold chain, e.g. consumers, food retailers, food logistics companies and manufacturers of refrigeration equipment [22]. It is available for free at http://frisbeetool.eu/FrisbeeTool/download.html.

Six main product categories have been considered, among them fish products (salmon fillets). For example, reference cold chains for chilled and super-chilled salmon are included. Functionalities of the tool include (among others) [23]:

- The user can select a reference cold chain for each product and build a tailor-made cold chain using representative cold chain blocks.
- New technologies are incorporated, such as super-chilling and super-cooling as well as phase change material (PCM) cover around products in chilled, frozen and super-chilled storage.
- Simulations of dynamic energy use and quantified CO_2 emissions through TEWI analysis
- Predictions of quality changes along the cold chain as a function of temperature and duration.

Figure 3-1 shows the model structure while Figure 3-2 shows a screen dump of a cold chain block for a distribution storage, including a cold room and the refrigeration system.

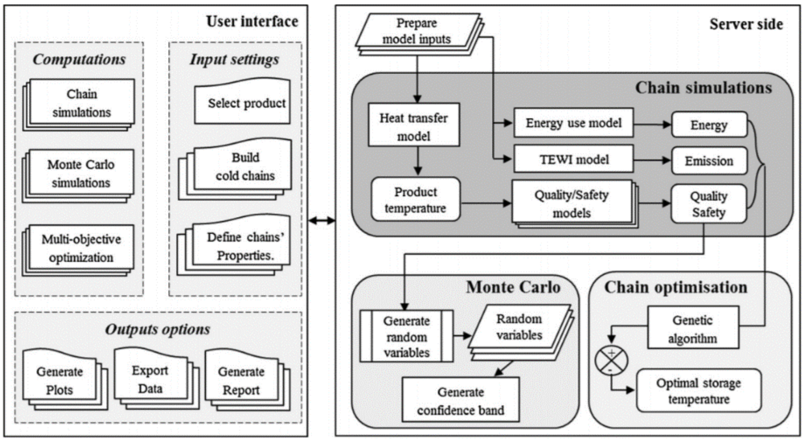
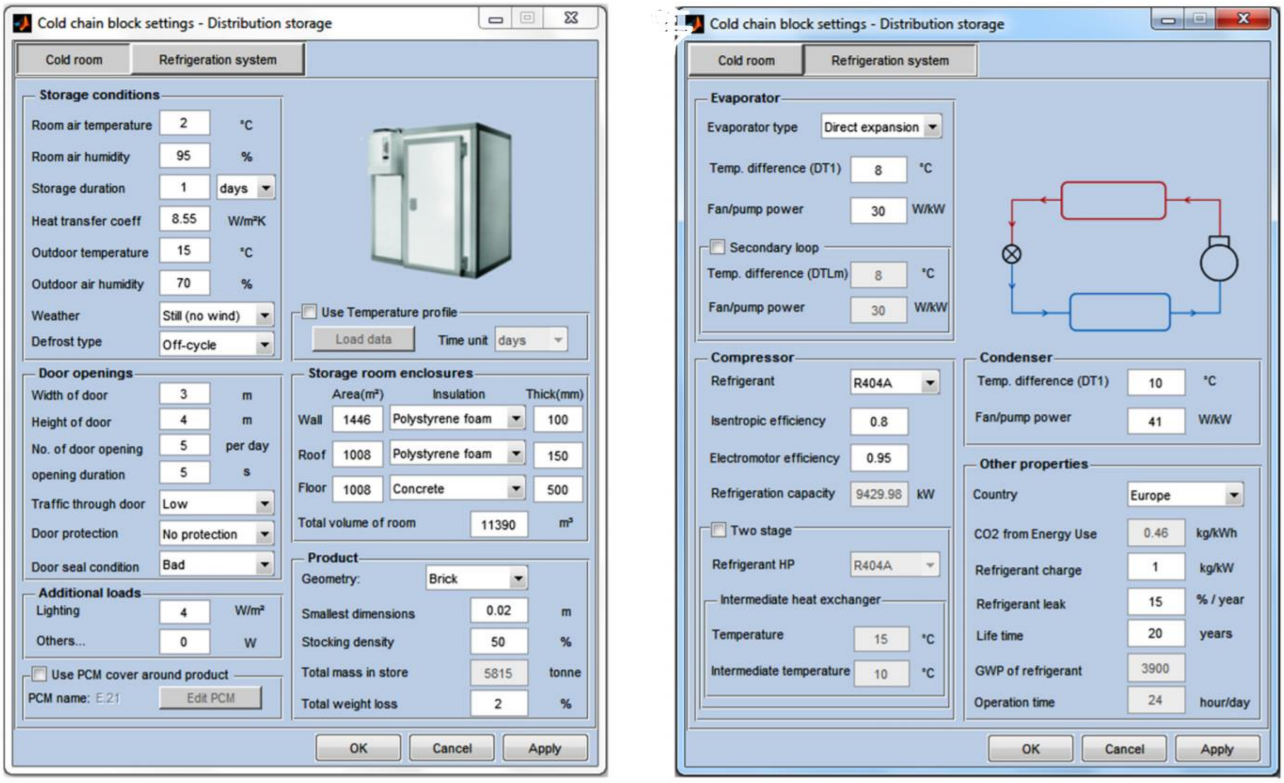


Figure 3-1: Frisbee tool – model structure [23]. Used with permission.



Cold chain block settings - Distribution storage

Storage conditions
Room air temperature 2 °C
Room air humidity 95 %
Storage duration 1 days
Heat transfer coeff 8.55 W/m²K
Outdoor temperature 15 °C
Outdoor air humidity 70 %
Weather Still (no wind)
Defrost type Off-cycle

☐ Use Temperature profile
Time unit days

Door openings
Width of door 3 m
Height of door 4 m
No. of door opening 5 per day
opening duration 5 s
Traffic through door Low
Door protection No protection
Door seal condition Bad

Storage room enclosures

	Area(m²)	Insulation	Thick(mm)
Wall	1446	Polystyrene foam	100
Roof	1008	Polystyrene foam	150
Floor	1008	Concrete	500

Total volume of room 11390 m³

Additional loads
Lighting 4 W/m²
Others... 0 W

☐ Use PCM cover around product
PCM name: E21

Product
Geometry: Brick
Smallest dimensions 0.02 m
Stocking density 50 %
Total mass in store 5815 tonne
Total weight loss 2 %

Cold chain block settings - Distribution storage

Evaporator
Evaporator type Direct expansion
Temp. difference (DT1) 8 °C
Fan/pump power 30 W/kW

☐ Secondary loop
Temp. difference (DTLm) 8 °C
Fan/pump power 30 W/kW

Compressor
Refrigerant R404A
Isentropic efficiency 0.8
Electromotor efficiency 0.95
Refrigeration capacity 9429.98 kW

☐ Two stage
Refrigerant HP R404A

Intermediate heat exchanger
Temperature 15 °C
Intermediate temperature 10 °C

Condenser
Temp. difference (DT1) 10 °C
Fan/pump power 41 W/kW

Other properties
Country Europe
CO2 from Energy Use 0.46 kg/kWh
Refrigerant charge 1 kg/kW
Refrigerant leak 15 % / year
Life time 20 years
GWP of refrigerant 3900
Operation time 24 hour/day

Figure 3-2: Frisbee tool – example of cold chain block settings [23]. Used with permission.

3.2.2 Energy use calculations

Estimations of energy use are based on heat balance models considering the refrigerant applied, the temperature sources, data quantifying efficiencies of the main components (heat exchangers, compressors, etc.) and the type of refrigeration cycle. The total heat load is the sum of the process' heat loads (energy needed to cool or freeze the product to the desired conservation temperature), transmission losses through walls, heat input from door openings, fans, fork-lifts, personnel, lighting, etc. The total energy consumption also includes additional power consumptions by fans, floor heating, defrosting and lighting.

3.2.3 Global warming impact assessment

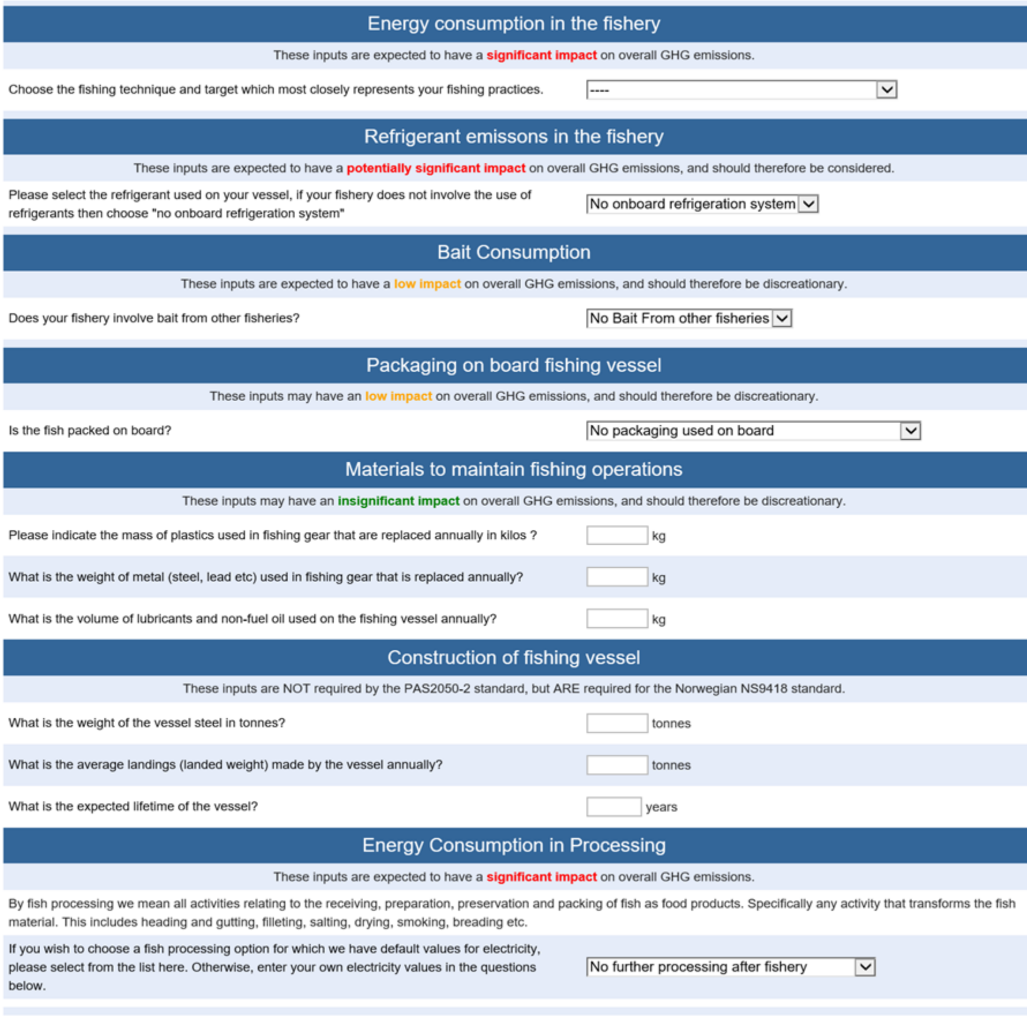
TEWI is applied for estimating the global warming impact of the refrigeration processes. As described in section 2.5.2, TEWI is the sum of direct refrigerant emissions and indirect CO_2 emissions resulting from combustion of fossil fuels to generate electric power.

3.3 SeaFish – captured fish products

SeaFish is a GHG emission profiling tool for capture fisheries. The aim is to provide a better understanding of the major contributors to the CF of seafood products along with insight into the important influence that some aspects of the seafood production chain have on final GHG emissions [24].

3.3.1 Overview

The tool broadly follows the BSI PAS2050-2, which is developed specifically for assessing GHG emissions of seafood products [24]. In Figure 3-3, a screen dump from one part of the tool is shown. The tool is freely accessible at http://profilerv2.seafish.org/index.php.



Energy consumption in the fishery

These inputs are expected to have a **significant impact** on overall GHG emissions.

Choose the fishing technique and target which most closely represents your fishing practices. ----

Refrigerant emissons in the fishery

These inputs are expected to have a **potentially significant impact** on overall GHG emissions, and should therefore be considered.

Please select the refrigerant used on your vessel, if your fishery does not involve the use of refrigerants then choose "no onboard refrigeration system" No onboard refrigeration system

Bait Consumption

These inputs are expected to have a **low impact** on overall GHG emissions, and should therefore be discreationary.

Does your fishery involve bait from other fisheries? No Bait From other fisheries

Packaging on board fishing vessel

These inputs may have an **low impact** on overall GHG emissions, and should therefore be discreationary.

Is the fish packed on board? No packaging used on board

Materials to maintain fishing operations

These inputs may have an **insignificant impact** on overall GHG emissions, and should therefore be discreationary.

Please indicate the mass of plastics used in fishing gear that are replaced annually in kilos ? kg

What is the weight of metal (steel, lead etc) used in fishing gear that is replaced annually? kg

What is the volume of lubricants and non-fuel oil used on the fishing vessel annually? kg

Construction of fishing vessel

These inputs are NOT required by the PAS2050-2 standard, but ARE required for the Norwegian NS9418 standard.

What is the weight of the vessel steel in tonnes? tonnes

What is the average landings (landed weight) made by the vessel annually? tonnes

What is the expected lifetime of the vessel? years

Energy Consumption in Processing

These inputs are expected to have a **significant impact** on overall GHG emissions.

By fish processing we mean all activities relating to the receiving, preparation, preservation and packing of fish as food products. Specifically any activity that transforms the fish material. This includes heading and gutting, filleting, salting, drying, smoking, breading etc.

If you wish to choose a fish processing option for which we have default values for electricity, please select from the list here. Otherwise, enter your own electricity values in the questions below. No further processing after fishery

Figure 3-3: Screen dump from the SeaFish GHG emission profiling tool (www.seafish.org) [24]. Used with permission from Seafish.

The major potential emission drivers addressed in the tool include direct fuel inputs to fishing, the form and scale of transport used, and the amount of time the products are held in cold storage. Also included are emissions associated with bait acquisition and storage, refrigerants, electricity usage and emission intensive packaging. Below, the method for addressing emissions related to energy consumption and refrigerants are described. A complete list of data sources to build-up the tool is available [25].

3.3.2 Energy consumption in the fishery

The following inputs are expected to have a *significant impact* on the carbon footprint:

- Ratio of the yield of fish landed to the fish caught
- Energy consumption in fishery
- Energy consumption in processing

Inputs that are expected to have a *potentially significant impact* includes:

- Refrigerant emissions
- Transports
- Ingredients for processing

The user of the tool can choose between several different fishing techniques and targets, for which the tool provides an average value of the fuel consumption per mass landed fish. In addition to the actual fishing operation, the fuel consumption also includes steaming to and from the fishing area, harbour activities and onboard processing. Table 3-1 shows the range of fuel usage, and average fuel usage, for different fish species and fishing gears. As seen, there is a huge variation between and within different fishing gear techniques and targets. This emphasize the need for more disaggregated data on fuel usage.

Table 3-1: Data of fuel usage included in the SeaFish tool. Table created based on data from SeaFish [24].

Fish type	Fishing gear /area	Range of fuel usage [l/tonne landed fish]	Average fuel usage [l/tonne landed fish]
Lobster	Trawl	760-2200	1100
Shrimp/prawn	Trawl	120-6000	1800
Small pelagic	Purse seine	8-170	53
	Trawl	45-370	140
Whitefish – finfish	Seine	230-660	480
	Trawl	208-1500	550
Whitefish -flatfish	Longline	96-1100	590
	Trawl	720-1400	930
Salmonoids	Purse seine	300-510	360
Large pelagics – tuna	Purse seine	350-700	490
	Longline	880-5000	2600
Whitefish	Norwegian coast	12-18	15
Pelagic	Norwegian coast	90-110	98
	Trawling, Norwegian ocean,	400-450	430
	Factory trawling, Norwegian ocean	290-330	310
	Longlining, Norwegian ocean	90-110	98

3.3.3 Refrigerant emissions in the fishery

Refrigerants included in the tool are R22, R134a, R717 and R744. Typical refrigerant loss, suggested by the tool, is 0.023 kg per tonnes landed fish for pelagic fisheries (corresponding to an ALR of 30 %) and 0.224 kg for demersal fisheries. Despite the lack of reported leakage rates, the lower refrigerant emissions from the pelagic fisheries are justified by the modern nature of pelagic vessels together with high catch rates. Table 3-2 shows the applied emission factor [CO_2 equivalent per kg refrigerant]. In addition to refrigerant losses, the emission factor also includes refrigerant production [24]. As seen, the HCFC (R22) and HFC (R134a) not only have a GWP that is more than thousand times larger than the natural refrigerants (CO_2 and NH_3), but also the CO_2 emissions related to their production is much larger (50 -100 times larger).

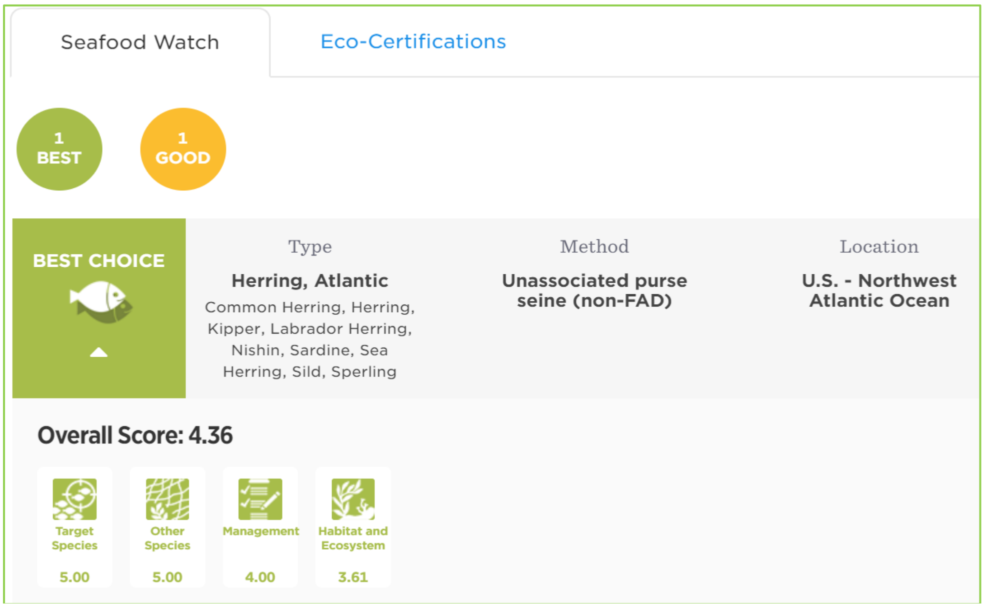
Table 3-2: GWP values and emission factors for refrigerants included in the SeaFish tool. Table created based on data from SeaFish [24].

Refrigerant	GWP	Emission factor [kg CO_{2e} / kg refrigerant produced and emitted]
R22	1810	**1913**
R134a	1430	**1533**
R717 (NH_3)	0	**2.1**
R744 (CO_2)	1	**1.8**

3.4 Seafood Watch – captured fish products

Seafood Watch, a program of the Monterey Bay Aquarium, performs research and evaluations related to the environmental impact of seafood products. The results are shared in several forms, including regionally specific Seafood Watch pocket guides, smartphone apps and online seafood recommendations. A tool (described in section3.5) has been developed together with Dalhousie University, for collecting data on carbon emissions in fisheries to better understand how these data could be used to incentivize a reduction in the fuel use related to seafood production [26].

Their "Seafood Watch Standards for Fisheries" is used to produce assessments for capture fisheries to provide recommendations for seafood customers. The resulting Seafood Watch rating includes Best Choice (green), Good Alternative (yellow), or Avoid (red), as exemplified in Figure 3-4 for Atlantic herring. It is available for free at (https://www.seafoodwatch.org/seafood-recommendations).



Type: Herring, Atlantic
Common Herring, Herring, Kipper, Labrador Herring, Nishin, Sardine, Sea Herring, Sild, Sperling

Method: Unassociated purse seine (non-FAD)

Location: U.S. - Northwest Atlantic Ocean

Overall Score: 4.36

Target Species	Other Species	Management	Habitat and Ecosystem
5.00	5.00	4.00	3.61

Figure 3-4: Example of a Seafood Watch Rating [27]. Used with permission from Seafood Watch.

The rating is based on the following assessment criteria [27]:

- Impacts of the fishery on the stock in question
- Impacts of the fishery on other species
- Effectiveness of management
- Impacts on habitat and ecosystem

Fuel consumption is not specifically addressed.

3.5 SeaFood Carbon Emission tool

The Seafood Carbon Emission Tool, available for free at http://seafoodco2.dal.ca/, includes CF estimates for 154 seafood products: 101 for fisheries and 53 for aquaculture. The CF are calculated up to the point of departure of a seafood product from primary production and before processing (cradle-to-gate). The carbon emissions presented are specific to the species and the production methods (i.e. fishing gear type or aquaculture farm type) and can be viewed per species or as aggregated averages per group of species. Figure 3-5 shows an example of results: an overview of different captured and farmed fish types [28].

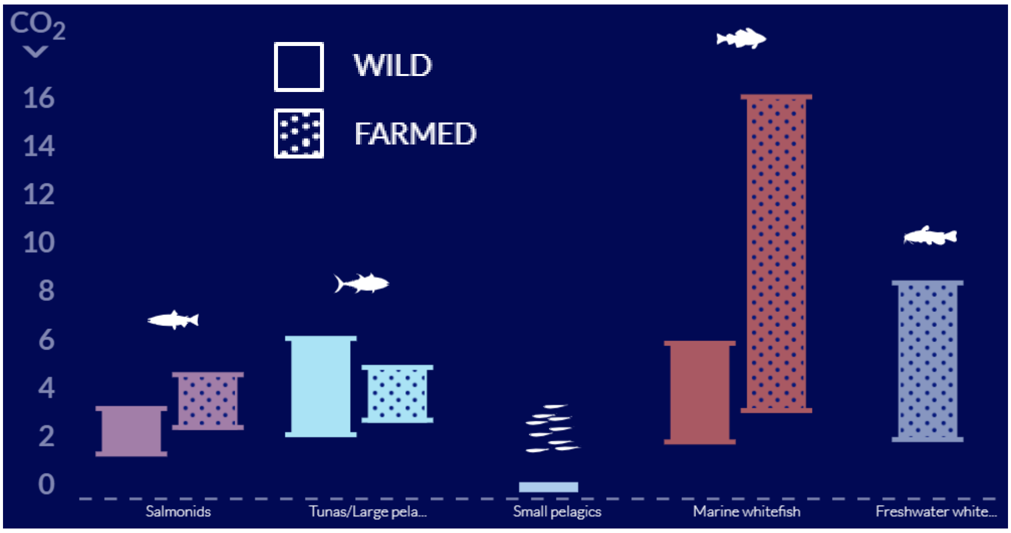


Figure 3-5: Example of results from Seafood Carbon Emission Tool [28]. Used with permission from Seafood Watch.

The estimates of carbon emissions from capture fisheries were based largely on fuel consumption rates for fishing vessels. The data were extracted from a Fisheries Energy Use Database (FEUD), which includes data from government and industry reports, direct communications with industry experts and peer-reviewed literature. Thus, the fuel use estimates come from different data source types, with different analysis years, sample sizes and methods. To help understand this variation in data, certainty scores were produced for each CF estimate, reflecting the degree to which each estimate is expected to reflect reality [28].

The fuel use values were multiplied by an emissions factor of 3.3 kg $CO_{2,eq}$ per litre fuel, which includes both emissions from burning the fuel as well as emissions from upstream processes of the mining, refining, and transportation of the fuel. The resulting quantity of fuel-related emissions was further multiplied by 1.33 to account for emission sources for which input data are scarcely available but can contribute significantly to the overall CF. These sources include the *loss of refrigerants* and emissions associated with vessel and gear maintenance and manufacture. For fisheries requiring bait, ranges of bait-related emissions were established for each fishery category: 0% - 5% of landed weight for tuna fisheries, 5% - 40% for whitefish fisheries, 40% - 60% for crab trap fisheries, and 100% - 300 % for lobster trap fisheries [28].

3.6 Pac Calculation Pro – refrigeration systems

This tool enables to compare refrigeration and heat pump systems, based on their geographic location, in terms of yearly energy consumption and CO_2 emissions as well as pay-back-time and life cycle cost. The tool includes several different configurations, among them trans-critical CO_2 (R744) systems. For example, it is possible to compare CO_2 life-time emissions between a two-stage R404A system and a R744 trans-critical system, as described in the user's guide [29].

Traditionally, refrigeration systems (and heat pumps) are dimensioned and evaluated based on a single operating point, normally around the point with the highest load. This approach ensures that the system will deliver the cooling (or heating) required but has drawbacks related to part-load performance, which are addressed in this tool. For example, it is difficult to evaluate payback time of energy saving measures based on a full load operating condition.

The following features, among others, are included in the tool [29]:

- Evaluation of system performance for every hour of the year (= 8760 operating points).
- Clear overviews on how well the system meets defined load profiles and of part load performance.
- Weather data from more than 700 locations from all around the world.
- Comparing systems at same load and ambient conditions, for evaluating energy saving measures.
- Models, based on manufacturer data, of more than 7000 commercially available compressors, giving results for off-design operation which is not based on theoretical assumptions.
- Calculation of CO_2 emissions considering the equivalent CO_2 release from electricity production (depending on the location) as well as refrigerant charge, leakage rate and recycle rate.

For personal use or use in a non-profit organization, and for educational purposes, the Pack Calculation Pro is distributed as freeware with limited functionality (https://www.ipu.dk/products/pack-calculation-pro/). For commercial use, the annual licence fee is 2900 NOK.

3.7 Fishing Vessel Energy Analysis Tool (FVEAT)

A Fishing Vessel Energy Efficiency Project (FVEEP) identified, quantified and implemented energy saving measures for fishing ships in Alaska, and developed a comprehensive tool based on data from 50 ships.

3.7.1 Description - overview

The tool provides a comprehensive model that can be used to estimate how modifications to the vessel will affect fuel consumption and to guide investment in energy conservation measures. The model will naturally be less accurate for vessels different from the 50 ones included for building up the tool. However, with customized default values, any vessel that uses diesel engines and has loads that fit into the propulsion, refrigeration, hydraulic, AC, DC and engine overhead categories can be simulated using the mathematical model and Python implementation developed for the tool [30].

The model supports different operating modes, representative of different fishing vessel types, including default values on transit speed, fishing speed, deck hydraulic loads and refrigeration systems. Six modules are included: engine, propulsion, refrigeration, hydraulics, and AC/DC electric network. The refrigeration module is briefly presented next, while a full module description is given in the model documentation [30]. Both the tool and the Microsoft Excel version that forms the basis of the tool is available for free at https://www.afdf.org/projects/current-projects/fishing-vessel-energy-efficiency/.

3.7.2 Refrigeration module

The refrigeration energy calculation depends on vessel type, operating mode (transit, fishing, anchor), refrigeration system type (refrigerated sea water (RSW), blast freeze or plate freeze) and power source (electric, hydraulic or direct drive). The energy consumed for refrigeration (E) are calculated as

$$E = P \cdot h \cdot f_{comp}/\eta$$

$$P = P_{circ} \cdot f_{circ} + P_{comp} + P_{cond}$$

- P: power consumption
- P_{comp}: average compressor power
- P_{cond}: average power for condensate pump
- P_{circ}: average power for circulation pump (e.g. in RSW systems) or fan (e.g. in blast freeze systems)
- f_{circ}: ratio of the circulation pump run time, or fan run time, to the compressor run time
- f_{comp}: fraction of time that a compressor runs in a certain operating mode
- η: efficiency factor related to the power source (hydraulic 0.55, electric 0.81 or direct drive 1.0)
- h: hours in a certain operating mode, given by the time fraction spent on transit/fishing/anchor

Default values of the required parameters are provided, as exemplified in Table 3-3 showing default values for refrigeration systems onboard seine and troll vessels [23].

Table 3-3: Default values for seine and troll vessels. Table created based on data from FVEAT [30].

	SEINE	TROLL	SEINE	TROLL	SEINE	TROLL
OPERATING MODE:	**hour fraction**		**f_{comp}**		**f_{circ}**	
Transit	0.47	0.67	0.35	0.75	1.4	1.0
Fishing	0.33	0.13	0.70	0.96	1.4	1.0
Anchor	0.2	0.2	0.27	0.92	1.4	1.0
REFRIGERATION:	**P_{comp}**		**P_{cond}**		**P_{circ}**	
RSW tanks	9.5		1.4		3.7	
Blast Freezer		5.8		0.67		0.66
Plate Freezer		3.9		0.67		0

4 Certification and eco-labelling

Various food labels are offered to help consumers make an informed choice about the sustainability of their food. Such labels are also often seen as desirable for producers as they have the potential to increase the marketable value of their products [31] [32]. However, the carbon footprint is rarely integrated into sustainability assessments such as ecolabels, certification schemes or consumer seafood sustainability guides. There are several studies highlighting the need for an eco-labelling that considers the product's carbon footprint, but also the complexity connected to accurate estimations of it. There are also studies suggesting how CF could be incorporated within seafood sustainability schemes [33].

4.1 Assessment criteria

In accordance with guidelines from the UNs Food and Agriculture Organisation (FAO), EU has suggested five criteria as minimum standards for eco-labelling of fish products from capture fisheries [34]:

- Precise, objective, and verifiable technical criteria
- Independent third-party accreditation process
- Open to all operators without discrimination
- Properly controlled to ensure compliance with minimum requirements
- Transparent, i.e. consumers should know which criteria are covered by an ecolabel and should thus have easy access to information on the certification standard

Traditionally, sustainability standards for fisheries typically evaluate three key aspects:

- The level of harvesting pressure and fish stock relative to "safe" levels
- The use or exclusion of environmentally harmful fishing practices
- The effectiveness of the fisheries management system(s).

While many certification schemes have energy and pollution consideration built into their assessment criteria, none of the most widely recognized schemes incorporate the CF in an explicit way. Including the CF into the certification criteria would provide a more holistic basis for consumers and businesses to assess the sustainability of seafood products, which is suggested as a useful next step for wild-caught seafood eco-labels. However, there are several challenges with incorporating accurate CF estimates, such as [33]:

- Agree upon a standard methodology (e.g. LCA)
- Collecting adequate and reliable data
- Establish a trusted verification process
- Determine how to best present CF information to consumers and businesses, within a certification, eco-label or consumer guide.
- High cost for the companies to be certified

4.2 MSC – Marine Stewardship Council

The scope of MSC is assessment of capture fisheries' resource sustainability, ecosystem impacts and management system robustness. It is fully compliant with FAOs guidelines, and ranges from large-scale industrial fisheries to small artisanal fisheries. As per 2019, 15% of the global marine catch was MSC certified including 361 fisheries in 41 countries, and 109 fisheries are under assessment [35]. The assessment criteria include:

- Sustainable fish stocks: ensures that fishing can continue indefinitely, and the fish population can remain productive and healthy.
- Minimised environmental impact: ensures that the fishing activity is managed carefully so that other species and habitats within the ecosystem remain healthy.

- Effective fisheries management: ensures that fisheries comply with relevant laws and can adapt to changing environmental circumstances.

Being a label considering the overall sustainability of fish products, the energy consumption/GHG emissions are to some extent incorporated, but not explicitly assessed. One often mentioned shortcoming of the MSC label is that it does not include the climate impact on transporting the fish "around the globe" before landing in the local display cabinets. For example, a MSC certified cod can be sent to China for fileting, before returning to Swedish stores. However, other aspect must also be considered. For example, fileting by hand (in China) reduces the waste with 5%, and more of the waste is reused, which partly covers for the long transport [36]. This is just one example of challenges with estimating a product's carbon footprint.

4.3 KRAV

The Swedish KRAV certification scheme is one of the few having incorporated CF into their eco-labels. To become a KRAV certified fishery (including the fishing vessel) the following criteria, among others, must be fulfilled [37]:

- The fishing vessel is MSC certified[1].
- Bottom trawling is not allowed (with a few exceptions) due to its high energy consumption.
- The capture should be stored in units marked to achieve full traceability.
- Technical requirements for fishing vessels related to, for example, fuel and refrigerants:
    - Fuel requirements:
        - Maximum 0.05% sulphur content
        - Maximum fuel use; 0.01-0.35 l/kg landed fish, depending on seafood type.
        - Documentation of annual fuel use and landed fish divided on each fishing method.
    - Refrigerant requirements:
        - Only ozone and climate-neutral refrigerants are allowed, i.e. no HFCs.
        - Approved refrigerants include CO_2, butane, propane, NH_3.

4.4 Friend of the Sea

Friend of the Sea (FoS) is a project of the World Sustainability Organization for certification and promotion of seafood from sustainable fisheries and aquaculture. Almost 800 companies are certified under FoS, including 44 approved fisheries and fleets and 3000 products from farmed and wild species [38].

The following assessment criteria are included, of which the energy management criterion includes a recommendation on calculating the carbon footprint:

- Target stocks are not overexploited
- Fisheries use fishing methods that do not impact the seabed
- Selective fishing gear (max 8 percent discard)
- No bycatch listed as ‘vulnerable’ or worse in the Red List by International Union for Conservation of Nature (IUCN)
- Compliance with legal requirements
- Waste and *energy management*
- Social accountability

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[1] The certification related to fish stocks and healthy ecosystems was previously assessed by KRAV, but since 2019 the fishery should be MSC certified.

Energy management: The organisation shall keep a register of all energy sources and their use, updated at least once a year. The register shall, as a minimum, include the following parameters:

- incoming energy sources – renewable or not
- consumption per process line – fishing, processing, transport

It is also recommended that the organisation should calculate its carbon footprint per product unit and engage to reduce it every year.

4.5 Carbon Neutral Certification

A carbon neutral footprint is one where the sum of the GHG emissions (CO_{2eq}) produced is offset by natural carbon sinks and/or carbon credits. The Carbon Trust Certification certifies organisations and products according to PAS 2060, which is the internationally recognised certification standard for the demonstration of carbon neutrality [39].

PAS 2060 builds on the existing PAS 2050 standard. It sets the requirements to be met when seeking to achieve and demonstrate carbon neutrality through the quantification, reduction and offsetting of GHG emissions from an organisation or a product. It requires robust measurement and a plan for achieving internal reductions and offsetting using high quality carbon credits.

One example of a carbon neutral certified organisation is Austral Fisheries, certified under the Australian Carbon Neutral Program. The emission sources accounted for on an organisation level include [40]:

- Scope 1: emissions arising directly from the organisation, such as fuel burned in fishing vessels
- Scope 2: emissions attributed to purchased electricity
- Scope 3: emissions arising from third party sources associated with activities of Austral Fisheries

The organisation has a yearly carbon footprint (emissions) of 32 000 tons CO_2. To become carbon neutral the organisation has offset the emissions through purchase of Voluntary Emission Reductions (VERs) from an international wind power project [40]**.** Further to the organisation-level certification, LCA has been carried out for its wild ocean-caught fish and prawn products, which are also certified as carbon neutral. The LCA scope of the products is cradle-to-gate and is described in section 5.13.

4.6 Global Sustainable Seafood Initiative (GSSI)

The aim of GSSI is to ensure confidence in the supply and promotion of certified seafood as well as to promote improvement in the seafood certification schemes. GSSI increases comparability and transparency in seafood certification and enables informed choices for procurement of certified seafood. GSSI's Global Benchmark Tool, which is based on international reference documents, identifies and recognizes robust and credible certification schemes and supports other schemes to improve.

As per Dec 2019, GSSI has recognized five certification schemes related to captured fish [41]:

- Alaska - Responsible Fisheries Management (RFM) Certification Programme
- Iceland Responsible Fisheries Management (IRFM) Certification Programme
- Marine Stewardship Council (MSC)
- Audubon Gulf United for Lasting Fisheries (G.U.L.F.) RFM Certification Program
- Marine Eco-Label Japan (MEL) V2 Scheme for Aquaculture and Fisheries

5 Carbon footprint of fisheries – previous studies

This chapter gives examples of previous studies on CF estimations of fisheries around the world. First, some general conclusions are given, followed by summaries of studies, with focus put on results related to the fishing vessels' fuel consumption and refrigerant emissions. More systematic reviews are found in [4] [42].

5.1 General conclusions

Most studies confirm the capture phase being the most significant contributor to the CF of fishery products. The main exception observed is the use of air transport. Seafood LCAs typically shows that 75% – 95% of the overall GHG emissions are related to the fishing stage of the product [43]. This high contribution is primarily caused by emissions from diesel fuel to power the fishing vessel. In some fisheries refrigerant leakage also has a noticeable effect. Whether products are fresh or frozen mainly affects the CF if it requires a change in transport mode. The significant contribution of the fishing vessel's fuel consumption to the overall CF implies that the fishing method and gear type have a considerable impact on the CF. In general, pelagic fisheries are efficient while demersal trawling is one of the most energy intensive [44].

Processing is generally found to have a minor contribution to the CF, but the location of processing, i.e. onboard ship or onshore, may have a non-negligible effect. The electricity for running onboard facilities are normally produced with diesel fuel, resulting in a higher CF compared to most onshore plants. However, the CF for electricity use for onshore plants can vary largely between countries. Also, the amount of waste in processing facilities of various countries and, consequently, CF per kg of edible fish may also differ [31].

It is important to highlight that the results of impact assessments from different studies are often rather incomparable, given different assumptions and methodological choices. It is more feasible to compare critical inventory items such as fuel, refrigerants, water and chemicals use for individual processes (e.g. fishing), which can be contrasted per functional unit [42].

5.2 EU fishing fleet

Figure 5-1 (left) shows a comparison of the average fuel consumption (litres per kg landed fish) for different gear types in the EU fishing fleet. Figure 5-1 (right) shows the potential reduction in fuel consumption by using alternative gears (compared to trawl) in three different fisheries [2].

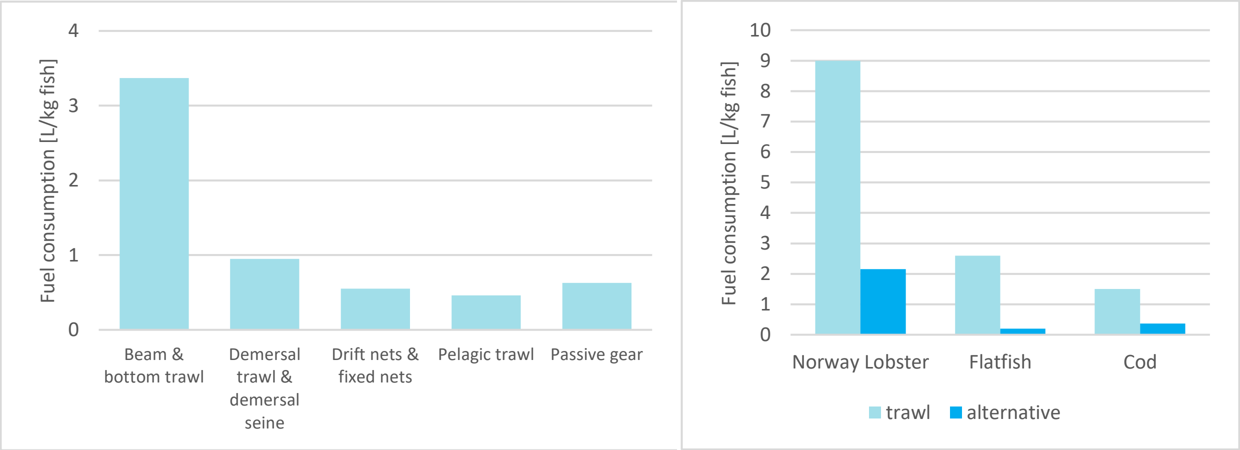

Figure 5-1: Average fuel consumption per kilo fish for different gear types in EU (left), and for trawling and alternative gears in three Nordic fisheries (right). Figure created based on results presented from Seas at Risks [2].

As seen, the fuel needed for catching and landing one kilo of Norwegian lobster can be reduced with a factor of 5 by switching from conventional trawl fisheries to creel (trap) fisheries. Such a switch also come with the advantages of reduced by-catch of non-target species, reduced impacts on the seabed, and improved quality of the caught lobster. In Danish flatfish fisheries, the amount of fuel per kg caught fish could be reduced by a factor of 15 by switching from beam trawling to Danish seine, in addition to a reduced impact on the seabed. In Sweden cod is caught both in trawls and with gillnets. During trawling over 4 times more fuel is used per kilogram landed cod than during gillnet fishing [2].

5.3 Norwegian Seafood

In 2009, a CF analysis of 22 Norwegian seafood products (fisheries and aquaculture) was performed [45]. Some of the products were compared with the CF of European terrestrial animal proteins. The conclusions were that Norwegian seafood were competitive with other seafood products and terrestrial animal products from a CF and energy use perspective. Since then, several analyses of parts of the Norwegian seafood industry have been carried out. For captured fish, the energy consumption, energy efficiency, refrigerant use and CF of the Norwegian fishing fleet and Norwegian fisheries have been studied [46] [47]. Figure 5-2 illustrates the main findings from a follow-up study of the 2009 analysis, published in 2020 [48].

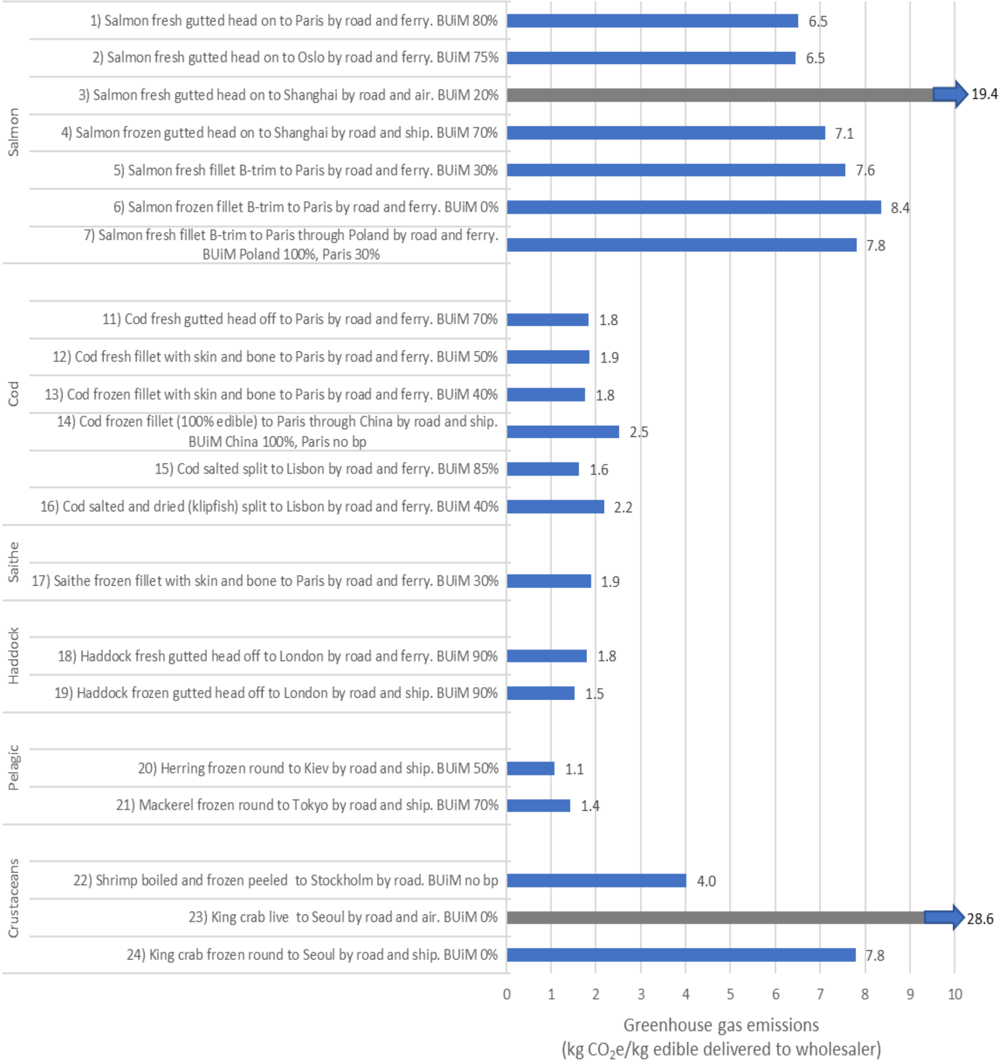

Figure 5-2: GHG emissions of the selected seafood products (kg $CO_{2,eq}$/kg edible product delivered to wholesaler). BUiM stands for by-product use in market [48].

Since the study performed in 2009, Norwegian fisheries and aquaculture have gone through several changes that may affect the GHG emissions. For instance, there has been a shift towards the use of more climate-friendly refrigerants in fisheries and more airfreight of fresh seafood, especially salmon. In addition, the seafood sectors gradually find it more important to document the CF of their products. As a result, an update to the 2009 study was made in 2020, with some methodological changes (e.g. different methods for estimating energy efficiency of fishing vessels and including effects of land use change on CF of salmon feed). Even if the results are not directly comparable, the 2020 report presents a simplified approach for comparison over time [48].

The GHG emissions of Norwegian seafood products range from 1 to 29 kg CO_2/kg edible product delivered to wholesaler (Figure 5-2). Various factors affect the GHG emissions, such as species, fishing gear, product form, transportation mode, distance to market, edible yield and utilisation of by-products. Pelagic fisheries (herring and mackerel) have the lowest emissions. Demersal fisheries (cod, saithe and haddock) also have relatively low emissions. Crustaceans (shrimp and king crab) are the most fuel intensive species, mainly due to the low catch per unit of effort. Among the studied products, farmed salmon has the highest emissions at landing/harvest, with or without accounting for land use change. This is mainly due to the feed [48].

5.4 United Kingdom - typical seafood chains

In this study, the GHG emissions related to ten typical UK seafood chains where evaluated, from the point of origin (capture or farm) to UK distribution. The method applied is largely consistent with the Carbon Footprint Measuring Methodology (CFMM) published by the Carbon Trust [44]. The main results are presented in

Figure 5-3 and summarised below [49].

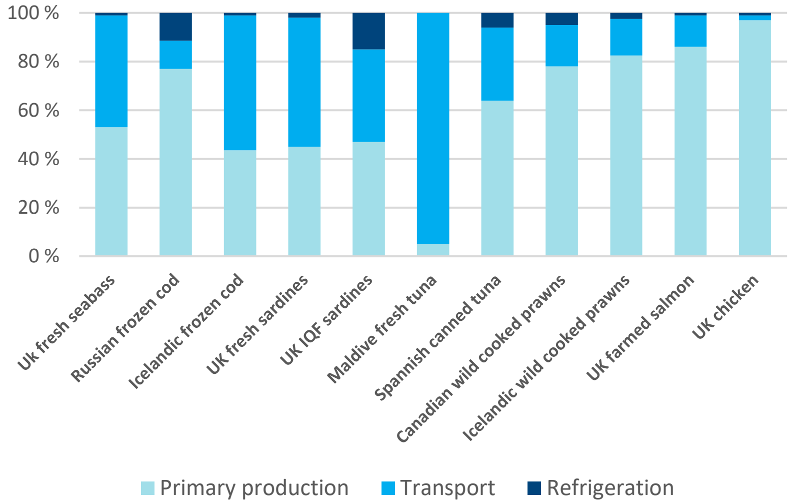

Figure 5-3: Relative importance of primary production (capture or farm), transport, and refrigerants on the GHG emissions generated from ten UK seafood chains. Figure created based on results presented in [49].

- Primary production is typically the main contributor to GHG emissions, generated from fuel use and refrigerant leakage for captured fish, and from feed provision for farmed fish.
- Fuel consumption varies with stock abundancy, fishing technology and distance to fishing ground
- Since the UK imports most of their seafood, transport plays an important role, especially when fresh products are transported by air, or frozen products are transported over long distances.
- Processing and packaging generally have a small (< 10%) contribution to the GHG emissions, except when emission-intensive materials are used (e.g. metal cans) or where cooking is involved.

5.5 Sweden - frozen cod fillet

An LCA study of Swedish frozen cod fillet, from fishery to household, was performed using ISO 14040. Findings include the fact that all environmental impact categories assessed (Global Warming Potential, Eutrophication Potential, Acidification Potential, Photochemical Ozone Creation Potential and Aquatic Ecotoxicity) are dominated by the fishery. Thus, any measures decreasing the use of energy in the fishery will have a positive impact on the overall environmental performance of the product.

The CF (expressed as GWP) is clearly dominated by the fishery stage, the major part being related to fuel consumption on the fishing vessel. Three fishery methods were assessed: pure gillnet, pure trawling and combined gillnet and trawl, showing a considerable difference in GHG emissions, mainly due to the difference in fuel consumption onboard. When fishery is excluded, transports and consumers are the most important phases [50]. Note that refrigerant emissions were not included in this study.

5.6 Shetland – pelagic trawlers (Atlantic mackerel)

This study estimates the carbon footprint related to capture, processing, storage and packing of pelagic fish, based on the guidelines in PAS 2050-2 . The pelagic fish, caught by RSW trawlers, are landed directly to a processing plant, the fish being pumped from the vessel holding tanks into the holding tanks in the processing plant. All discards of unwanted bycatch are passed on to a fishmeal processing plant [31].

At the time of study, R22 was used as refrigerant onboard the trawlers. A loss of 0.064 kg R22 / tonne landed fish was assumed, corresponding to a CO_{2eq} emission factor of 0.122 kg CO_2 / tonne landed fish. Freezing (onshore) is also a significant step in the processing section of the chain, but since ammonia is used as refrigerant, there are no direct emissions related to refrigeration. As seen in Figure 5-4 ("high R22 leakage"), the capture phase (fuel and refrigerant) represents over 70% of the carbon footprint [31].

The leakage rate of 0.064 kg can be considered as a worst-case scenario. If, instead, assuming a leakage rate of 30%, corresponding to a loss of 0.024 kg R22, the CF is decreased with more than 10% ("low R22 leakage" in Figure 5-4). All ships included in the study confirmed their intention to convert to ammonia by 2015 to comply with legislation requirements. The use of ammonia will decrease the CF with 10% - 20% compared with R22 for a low and high leakage rate, respectively ("ammonia" in Figure 5-4).

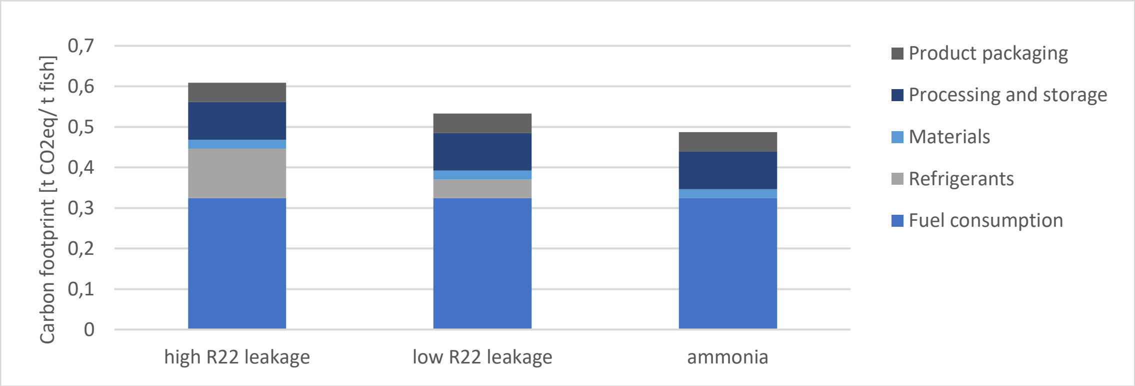

Figure 5-4: Carbon footprint for Shetlands pelagic fishery, distributed between different stages and for various refrigerants and leakage rates. Figure created based on results presented in [31].

5.7 Philippines – tuna fishery

Figure 5-5 presents the results from an initial CF estimate of Philippines' tuna fisheries. The analysis was performed based on a top-down approach, using input-output tables from Philippine economy. As seen, more than 50% of the CF is related to "direct emissions" from fishing fleet operations, i.e. fuel use [51].

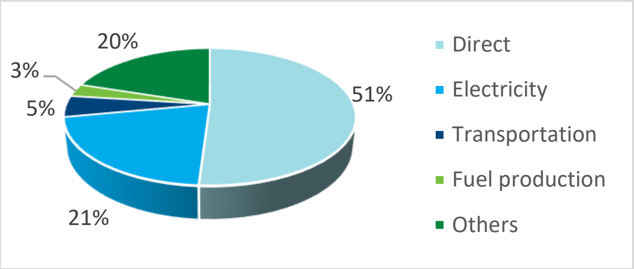

Figure 5-5: Breakdown of carbon footprint contribution (0.25 – 0.3 kg CO_2 / kg tuna) for Philippines' tuna fisheries. Figure created based on results presented in [51].

A refined CF estimate was derived from actual fleet data. This bottom-up approach includes activity- and process-based data for different fishing gears (purse-seine, long-line, pump boats) and various scenarios for downstream processing and logistics (cold storage, cooking, canning, transport by land, sea or air) [51].

Figure 5-6, shows the results for an optimistic scenario characterised by high yields, low energy use, and transport by sea. The fishing stage is the significantly largest CF contributor, primarily related to fuel consumption for propulsion and auxiliary on-board equipment, such as refrigeration. Purse seine fishing shows the lowest CF per kg of landed catch, while long-line gear has the highest CF. The contribution of cold storage (60 days) is much smaller than those of all other major activities in the tuna supply chain. Note also that canning represents a non-negligible contribution.

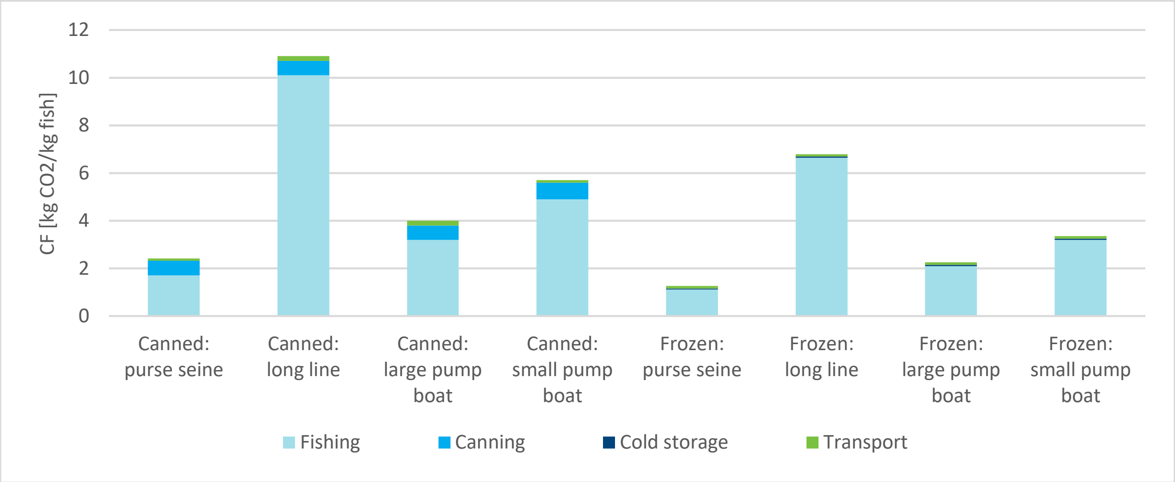

Figure 5-6: Contributions of four major activities to the CF / kg tuna delivered to consumer, for an optimistic scenario. Figure created based on results presented in [51].

Figure 5-7 shows the results for a conservative scenario with low yields, high energy consumption, and air freight transport. As seen, there is a marked increase in the CF contribution from transportation, but the fishing stages are still the dominant contributor. For canned fish, the cannery operation is the second largest contributor, while for frozen fish the transportation is the second largest contributor. For both scenarios, the CF contribution of refrigeration is relatively small. It was also pointed out that since CF is highly sensitive to yields, a CF reduction is compatible with increasing profitability [51].

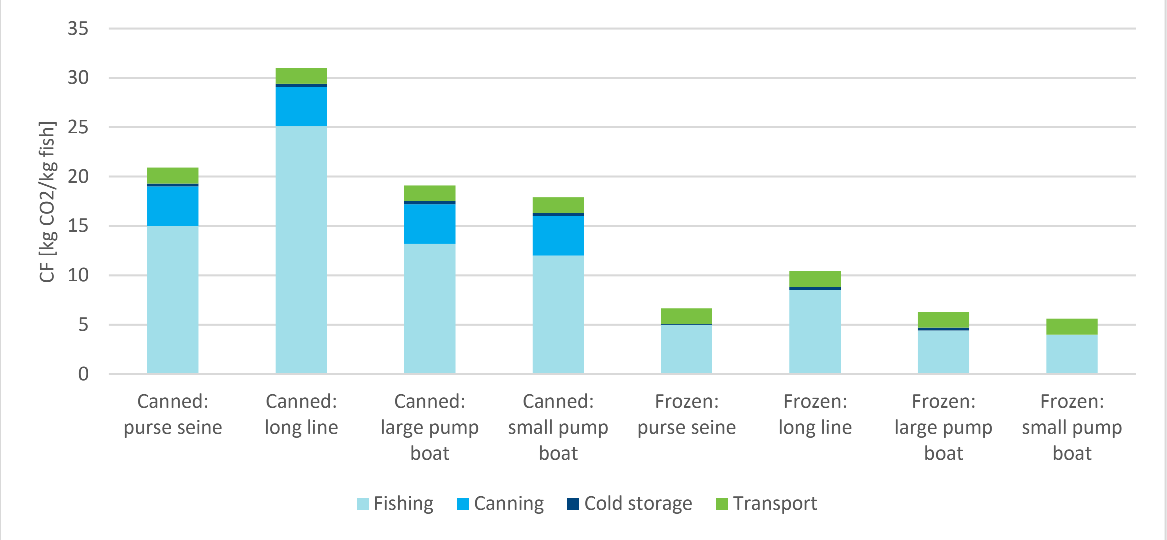

Figure 5-7: Contributions of four major activities to the CF / kg tuna delivered to consumer, for a conservative scenario. Figure created based on results presented in [51].

5.8 Global purse seine tuna

This study evaluated the carbon footprint of the global purse seine tuna fleet (yellow-fin tuna and skipjack). The results indicate a global average fuel consumption of 368 litres/tonne landed tuna, corresponding to a fuel related CF of 1.1 kg CO_2 / kg landed tuna. As seen in Figure 5-8, the CF of the packaging stage are almost as large as the CF for the fishery stage (fuel use), mainly due to the high emissions related to tin can production. Note that the post-landing emissions from processing, packaging and transport are assumed to be constant across regions [52].

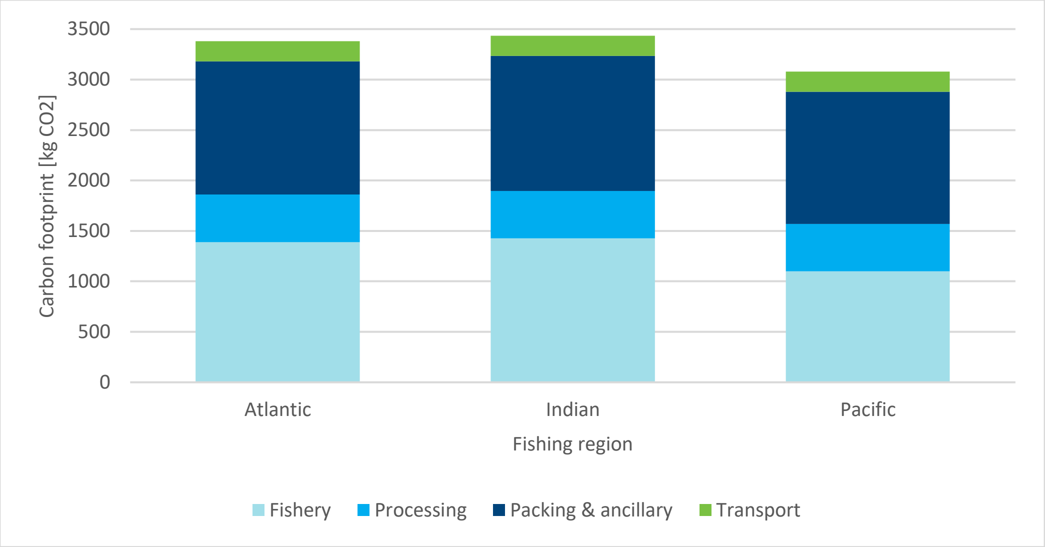

Figure 5-8 Carbon footprint of canned skipjack tuna at retail, fished in Atlantic, Indian and Pacific oceans. Figure created based on results presented in [52].

A comparison to previous studies was also made, in terms of comparing tuna fisheries employing other gears than purse seine (trawling, long-line) and/or targeting other species. Longline tuna fisheries, generally targeting more valuable tunas (e.g. bluefin), consume significantly more fuel than tuna fisheries employing purse seine [52].

5.9 Galician fishing activity

This study comprises the GHG emissions from capture stage, covering also onboard processing activities, to landing in Galician ports. Apart from diesel use onboard, the analysis also include diesel production, anti-fouling production and other input-related processes to the fishing vessel operation [53]. Refrigerants were originally not included, but the study was later updated to include refrigerant emissions [54].

The analysis includes species from coastal fishing (e.g. horse mackerel, Atlantic mackerel, European pilchard and blue whiting), offshore fishing (e.g. European hake, megrim and anglerfish) and deep-sea fishing (skipjack and yellowfin tuna). Figure 5-9 summarises the results from both the initial study and the study updated with refrigerant emissions. From the initial study (i.e. neglecting refrigerant emissions), the following main results were presented:

- For coastal fishing (C) the average CF is 1.46 tonne $CO_{2,eq}$/tonne fish, ranging between 0.6/0.7 tonne $CO_{2,eq}$/tonne fish for seining/trawling mackerel up to 4.0 tonne for trawling hake.
- For off-shore fishing (O) the average CF is 5.65 tonne $CO_{2,eq}$/tonne fish, ranging from 2-6 tonne for several different species (caught by lining), 13 tonne for lining big-eye tune and up to 25 tonne for trawling Norwegian lobster.
- For deep sea fishing (D), equivalent to tuna seining, the CF is 1.36 tonne $CO_{2,eq}$/tonne fish, taken as an average for various fishing areas (Atlantic, Indian, Pacific).

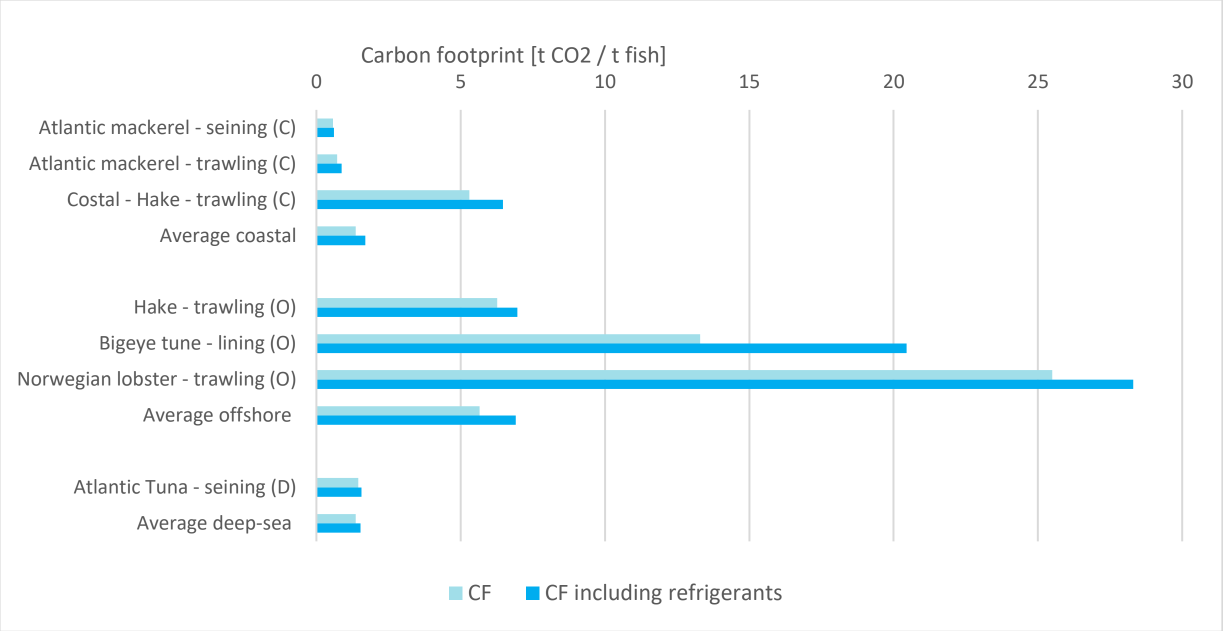

Figure 5-9: CF for different species in the Galician fishing activities (from capture to port), showing the influence of including refrigerant emissions in the CF analysis. Figure created based on results in [53] [54].

From the study updated with refrigerant leakage, the following main results were presented:

- Most of the ships were at the time of study using R22, with a very slow shift to R507A and R404A, and in very specific cases NH_3.
- The reported annual R22 leakage per ship is 150 kg for coastal trawlers and 10 kg for coastal purse seiners. For offshore vessels and deep-sea purse seiners it is 200 kg and 500 kg, respectively.
- Including refrigerant emissions means an increase in CF of 15% for coastal, 22% for offshore and 7% for deep sea fishing, with an overall increase of 13%.
- Further efforts should be made for providing robust data regarding refrigerant emissions.

- The gradual shift from R22, which was to be completed in 2015, may generate considerable changes in GHG emissions. For example, it can either be reduced to zero by switching to ammonia (R717) or increased by switching to high-GWP refrigerants (R404A, R507) [54].

5.10 Greek fishing fleet

The Greek fishing fleet was evaluated in terms of energy efficiency, fuel intensity and carbon footprint. Data was collected and compiled during 2004-2008, under the EU Data Collection Regulation. The CF includes only fuel consumption, with an assumed emission factor of 2.66 kg CO_2/litre of fuel burned [55].

The results show an average CF of 1.94 t CO_2/t fish, average fuel intensity of 0.72 l fuel/kg fish and average energy use of 30.8 GJ/t fish. (Otter) bottom trawler shows the highest values with a CF 3.69 t CO_2/t fish and a fuel intensity of 1.39 l/kg. The purse seiner, being some of the largest fuel consumer, is still efficient (fuel intensity of 0.35 l/kg), by making good use of the energy through catching a large amount of fish. The small-scale coastal fleet (> 17000 vessels), mostly netters and long-liners is characterised by old vessels with low catches at a very high energy use [55].

5.11 Tasmanian fishing vessels - scallops

GHG emissions for the Tasmanian fishing fleet, capturing scallops, were evaluated based on the BSI specific fisheries LCA guide (PAS 2050:2011). The analyses consider the four production stages: fishing activity, landing/auctioning, processing and distribution. Inputs to the fishing activity stage includes diesel use, refrigerants, engine oils, grease and antifouling.

The results, presented in Figure 5-10, show that fuel use in the fishery stage, together with the landfill in the processing stage, are the major factors that should be investigated to improve the CF. For the fishing stage, the CF is related to diesel usage[2] (95%) and refrigerant[3] emissions (5%) [56].

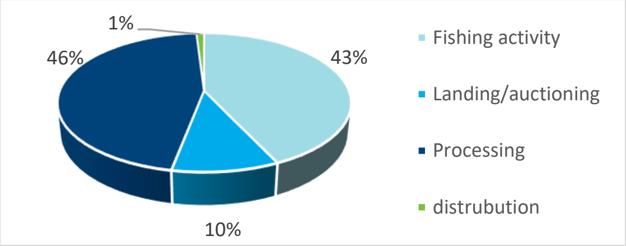

Figure 5-10: GHG emissions breakdown for Tasmanian fishing vessels. Figure created based on [56]

5.12 Southern Africa Fisheries

In 2018, a GHG emission inventory was performed for several fishery companies operating in the southern Africa fishing industry. Emissions were measured in accordance with the GHG Protocol Corporate Standard using the operational control approach, including catching, processing, and transport.

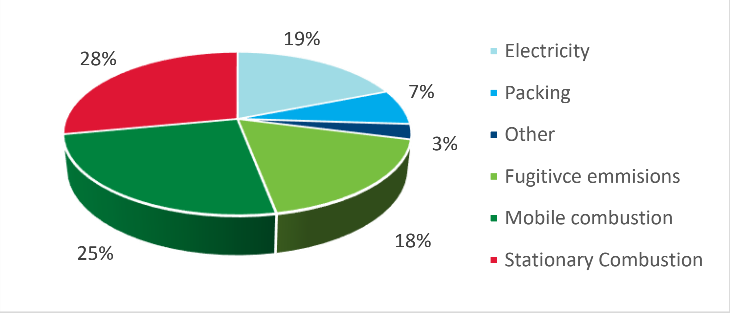

Figure 5-11: Breakdown of GHG emissions from African fisheries. Figure created based on [57].

Figure 5-11 summarises the results, showing that 48% of the GHG emissions arise from fishing vessels and 52% from land-based operations. Refrigerant (R22) emissions constitute in total 18% [57].

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[2] Engines installed includes a main engine of 480 kW and two auxiliary engines of 50 and 115 kW.

[3] The ships having typically 15 litres of R134a installed onboard.

5.13 Carbon neutral – Austral Fisheries

In the process of becoming certified as carbon neutral, Austral Fisheries carried out an extensive LCA for its wild ocean-caught fish and prawn products, in accordance with the requirements of *National Carbon Offset Standard for Products and Services* (2017) and *GHG protocol product life cycle accounting and reporting protocol*. The analysis is divided in four main stages for which a number of processes are defined, either related to energy use (E) or material use (M). The four stages are [40]:

- Material acquisition & pre-processing:
    - pre-processing of fuel, lubricants, bait, packaging, other equipment used for capture (E, M)
    - water supplied to vessel (M)
    - transport of materials and equipment to vessel (E)
- Production:
    - *Production at sea: catching, processing, packing (E), freezing of product - refrigerant (M)*[4]
    - Refrigerated transport and land-based processing (E)
    - Sales processes – office electricity (E)
- Distribution & storage:
    - Refrigerated transport, cold storage, refrigerated transport to wholesaler purchaser (E)
- Use:
    - Cold storage, refrigerated transport, cooking in restaurant (E)

The main results are as follows:

- For a fish catch, the production at sea (no freezing applied) has a CF of 5.1 t CO_{2eq} / t fish, which represents 80% of the total CF.
- For a prawn catch, the CF related to energy use for production at sea is 7.04 t CO_{2eq} / t prawn. Together with the CF for freezing the product (use of refrigerants) of 1.03 t CO_{2eq} / t prawn, the capture stage represents 89% of the total CF.

5.14 TEWI analysis - Australian prawn fleet

This study evaluates replacement options for R22 systems onboard Australia's Northern prawn fleet [18]. An energy audit was performed to enable a proper TEWI analysis. More than 30% of total fuel consumption is attributed to the auxiliary engine for generating power onboard and an estimated 75% of the fuel consumed by the auxiliary engine is for refrigeration. Three options for replacing R22 were evaluated:

Option 1 – base case: A new, but conventional, system using R507A (240 kg). No energy efficiency upgrades are included, but improved containment practices reduce the leakage rate from 35% to 15%.
Option 2 – best case: A cascade system with NH_3 and CO_2, offering zero direct emissions and an improved energy efficiency of 10% - 20%. For safety reasons, a sealed refrigeration plant room is required.
Option 3 – future case; A system with HFO blends, enabling the use of a conventional system but with a total re-build. With improved equipment efficiencies a 10% increase in energy efficiency is assumed.

The input parameters for the TEWI analysis are shown in Table 5-1. Figure 5-12 presents the results, in terms of direct and indirect emissions of $CO_{2,eq}$ over 20 years lifespan.

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[4] The energy-related process "Production at sea" includes energy usage for fishing fleet steaming to and from the fishing ground, catching the fish or prawn and any processing, freezing and packaging onboard. The material related process "Freezing of product", includes material use of refrigerant gases (leakage).

Table 5-1: Input parameters for TEWI analysis. Table created based on [18].

Options to replace R22	Input parameters to TEWI analysis		
	Refrigerant(s)	**Leakage [%]**	**Efficiency [%]**
Option 1 – base case:	R507A	15	100
Option 2 – best case:	$CO_2 + NH_3$	n.a.	120
Option 3 – future case:	HFO blends	15	110

Not shown in the results presented in Figure 5-12 is that the TEWI for the R507 system is similar to that for the existing R22 system. The reduced leakage rate for the upgraded system does only lead to a marginal improvement in TEWI since R507A has a higher GWP (3300) [58].

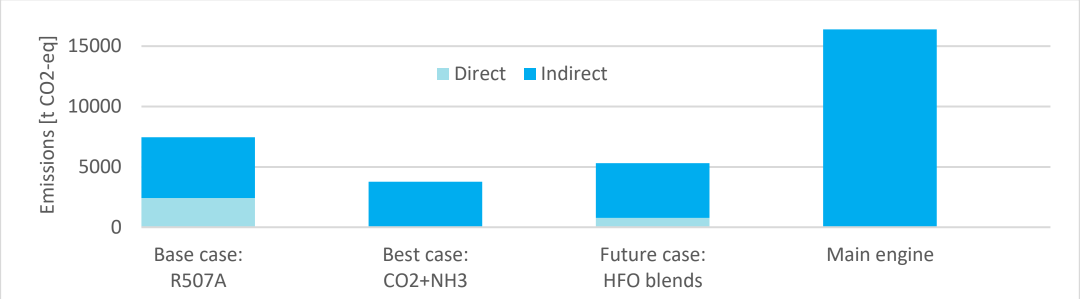

Figure 5-12: Results from a TEWI analysis of refrigeration system onboard the Australian prawn fleet. Figure created based on results presented in [18].

5.15 Cold chains - chilling and super-chilling technologies for salmon

This study exemplifies how LCA can be used for comparing the carbon footprint of two cold chains differing in the refrigeration technology applied for chilling of salmon: super-chilling with impingement blast freezer and conventional chilling by ice production. Table 5-2 specifies the stages in the two cold chains (the harvesting and filleting stages are identical). As seen, including a super-chilling stage enables a lower operating temperature for the packaging and storage stages. The refrigerant used in both cold chains is primarily NH_3. For the harvesting process R22 is also used, with an assumed leakage rate of 5% [59].

Table 5-2: Specification of cold chain stages for chilled and super-chilled salmon. Table created based on [59].

	CHILLED cold chain				SUPER-CHILLED cold chain			
Process	**Temp. in**	**Temp. out**	**Time**	**Refrigerant**	**Temp. in**	**Temp. out**	**Time**	**Refrigerant**
Harvesting	10 °C	2 °C	1.5 h	R717, R22	10 °C	2 °C	1.5 h	R717, R22
Filleting	2 °C	3.5 °C	0.5 h	R717	2 °C	3.5 °C	0.5 h	R717
Super-chilling	n.a.				3.5 °C	-1.7 °C	0.05 h	R717
Packing	3.5 °C	0°C	1 h	R717	-1.7 °C		1 h	R717
Storage	0 °C		24 h	R717	-1.7 °C		24 h	R717

Table 5-3 provides results from the CF analysis of various production stages for the two cold chains. Even though the electricity use for refrigeration is about twice as large for the super-chilled chain there is almost a 20% reduction in CF compared to the chilled chain. This is mainly due to a reduced need of expanded polystyrene (EPS) material for packaging and a better utilization of available volume for transportation, since no ice is needed. Looking at the CF for the total product chain, i.e. including production, transport, distribution, display cabinets and domestic fridge, it is the production and transport stages that are clearly dominating the CF. For the super-chilling chain, these stages constitute 90% (45% each). Comparing the total CF for the two different chains, the super-chilling technology offers a 15% reduction in CF [59].

Table 5-3: Results from CF analysis of chilled vs super-chilled salmon cold chain. Table created based on [59].

Cold chain	Electricity use [5] [kJ]		Ice use, transport [kg]	EPS use, packing [kg]	Cold storage [kJ/kg]	CF [g $CO_{2,eq}$]
	Harvesting	Refrigeration				
Chilled	339	37.6	0.25	0.033	1 (at 0°C)	91
Super-chilled	339	72	0	0.026	1.2 (at -1.7°C)	73

5.16 Marine Fish PEFCR

The Marine Fish PEFCR project aimed at developing recommendations for a product environment footprint category rule (PEFCR) for seafood products on the EU market. A PEF screening of EU pelagic and demersal fisheries was performed with the goal of identifying environmental hot spots and studying methodical choices [5]. The PEF screening included data on fuel use, refrigerant emissions, construction and end-life of vessel, as well as production and waste handling of fishing equipment. Input data of fuel and refrigerants are shown in Table 5-4. The input data on fuel use is based on the Norwegian fishing fleet (2009-2013). However, for the pelagic fleet, the fuel use of 0.095 l/kg fish landed was corrected to 0.22 l/kg, since 40% of EU consumption of pelagic fish is tuna (tuna-like) [5] [60].

Table 5-4: Input data for fuel use and refrigerant emissions. Table created based on [5] [60].

	Fuel use [litres/kg landed fish]	Refrigerant leakage [kg R22 / kg landed fish]
Pelagic	0.22	0.023
Demersal	0.245	0.224

The screening, in terms of cradle to grave assessment (i.e. from fishing to delivery at retailer) confirmed existing knowledge from LCAs and PEFs; The most important life cycle stages for wild caught products are the fishing activities, the transport of fish and packaging materials. The main challenge identified, both for the development of a PEFCR and for the whole application of the PEF method within the seafood sector, is the lack of databases including life cycle inventory data (mass- and energy balance) for different production systems. Thus, a life cycle inventory database covering all different technologies, methods and regional differences should be established for the seafood sectors [5] [60].

Recommendations related specifically to refrigeration systems include the following:

- Electricity (fuel) consumption for on-land ice production are today often assessed independently but on-board ice production, and other refrigeration systems, is based on the ship's total fuel (diesel consumption). The energy (fuel) use to run the refrigeration system should be specified.
- The refrigeration capacity should be allocated to inputs of fish handled.
- For accurate emissions of refrigerants to air a more precise definition of refrigerant volume and leakage rate is needed, i.e. more stringent documentation of refrigerant use is required. It is also important to consider the change in energy efficiency when changing refrigerant.
- Generic data can be applied for production of the refrigerant.

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[5] For the production step, the Norwegian electricity mix was applied, while the French mix was applied for the other steps.

6 Conclusions and further work

From the review of standards, certification schemes, tools and previous studies related to carbon footprint (CF) assessments of seafood products, the following conclusions were drawn:

- Only a few of the available standards for estimating the CF of a product are specifically developed for seafood. The British Standard PAS2050:2 contains requirements for the CF assessment of seafood products and the Norwegian standard NS-9418 provides product category rules for calculating and communicating the CF of seafood products.

- Sustainability certification schemes for fisheries typically evaluate harvesting pressure, fishing practices and fisheries management. Even if energy and emissions considerations are often built into the assessment criteria, the CF is rarely integrated in an explicit way. The Swedish KRAV is one of the few having specified criteria directly related to CF.

- There are on-line tools that could be used for estimating the CF of seafood products or parts of the seafood product chain. For assessment of the fishery stage default data are provided on total fuel consumption. The data are based on conventional diesel propulsion and the refrigeration system is not addressed specifically, except from default values on refrigerant leakage. Tools developed for assessing the CF of different refrigeration systems are mostly developed for land-based applications.

- Previous studies related to CF assessment of captured sea-food products clearly show a significant CF contribution from the fishing vessel's fuel use. Direct emissions from refrigeration systems using synthetic refrigerants can also play an important role, as can air transportation. Several studies emphasize the need for disaggregated data on fuel use, e.g. propulsion and refrigeration, for proper evaluations of CF reductions when introducing more climate-friendly refrigeration systems.

Based on this review, and on the current development towards more energy-efficient and climate-friendly propulsion systems, fuels and refrigerants, the following topics for further work in CoolFish are suggested:

- Estimate the share of fuel use between propulsion and refrigeration, for different types of fishing vessels and different operational modes. This could be done by a combination of compiling any existing data, encourage such onboard measurements and develop numerical models.

- Develop models for estimating the fuel-related CF for propulsion systems other than conventional diesel-mechanic (such as diesel-electric, gas-electric and hybrid propulsion including batteries).

- For a reference ship, compare changes in CF for different propulsion systems/fuels and innovative refrigeration systems.

- For the global small-scale fleet, estimate the impact on CF by changing to natural refrigerants

- Suggest appropriate ways to communicate the CF of a fishery/fishing vessel.

7 Acknowledgements

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