The effects of the Icelandic demersal trawling fleet renewal on product carbon footprint

Áhrif endurnýjunar fiskiskipaflotans á kolefnisspor afurða

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Innihald skýrslu	Skýrsla þessi greinir frá bakgrunni, framkvæmd, niðurstöðum og annarri umfjöllun sem fram kemur í ritrýndri vísindagrein sem kom út í tímaritinu ***Journal of Cleaner Production*** í nóvember 2024. Vísindatímarit setja ströng skilyrði um lengd greina og því var ekki unnt að koma á framfæri öllum þeim atriðum sem höfundar hefðu óskað eftir. Þessi skýrsla veitir því auka upplýsingar sem ekki var pláss fyrir í: Guðrún Svana Hilmarsdóttir, Jónas R. Viðarsson, Birgir Örn Smárason, Sæmundur Elíasson, Friederike Ziegler & Ólafur Ögmundarson. (2024). Is renewing Icelandic demersal trawling vessels resulting in lowergreenhouse gas emissions**?** ***Journal of Cleaner Production***, 484(2024) 144245. https://doi.org/10.1016/j.jclepro.2024.144245		
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Summary in English

There has been a major renewal of the Icelandic trawler fleet since the turn of the century, while the number of such vessels has decreased by almost half. It has been claimed that the new vessels are much more fuel-efficient and that the carbon footprint of the products must therefore have decreased as results. Data on oil imports to fishing vessels seem to support these claims.

To better analyse the impacts of the fleet renewal on the carbon footprint of fish catches, several representatives from the Icelandic bottom trawler sector joined forces with experts from Matís, the University of Iceland and the University of Akureyri that work on assessing the environmental impacts in production systems. Data was collected from 11 trawlers over a 10-year period and a Life Cycle Assessment (LCA) methodology was applied to analyse their carbon footprint per unit of catch, and then a comparison was made between older and newer vessels to examine if there is a statistically significant difference. The vessels in the sample were chosen to provide a good cross-section of the Icelandic bottom-trawl fleet in terms of size, age, catch composition and location around the country. The sample included four new vessels that were purchased to replace older vessels, i.e. a comparison was made between old and newer vessels from the same fishing company, with the same catch quotas and even the same crew.

The results of the analysis revealed that the renewal of the trawl fleet alone has not had a significant impact on the carbon footprint per unit of catch. Three of the four new vessels examined did not show lower carbon footprint than the older vessels they replaced. The fourth vessel, however, showed a significant reduction in the carbon footprint, but that may be because it replaced two older vessels. The most likely explanation is therefore that since the catch quotas of two vessels were combined on one new vessel, it is the quota status and fishing pattern that had the dominant effect, rather than the age of the vessels. These results consistent with previous studies in Iceland, which have shown that the state of fish stocks, catch quotas, and fishing patterns are by far the most important factors when it comes to greenhouse gas emissions per unit of catch. Thus, the concentration of catch quotas and the reduction in the number of vessels have had a decisive effect on reducing the carbon footprint, rather than fleet renewal. However, it is worth bearing in mind that comparisons between years can be difficult as stock abundance and distribution, as well as catch patterns can vary greatly from year to year.

The results of the life cycle analysis also provided information on the average carbon footprint per unit of catch for the vessels in the sample. This is very important information, as such a comprehensive analysis of the carbon footprint of bottom-trawl catches has not been carried out in Iceland before. Previous data only covered individual trawlers over much shorter periods. The results show that the carbon footprint of a landed cod catch is 0.7 kg CO_2 equivalent/kg catch, 0.8 kg when the carbon footprint is allocated to the edible part of the catch, and 4.5 kg when it is allocated to protein content of the edible parts. Similar results were shown for haddock and saithe, but the carbon footprint of redfish is much higher as the fishing itself is more energy-intensive and the utilisation for human consumption is much lower. These results are similar to comparable studies that have been conducted in recent years in the countries the Icelandic seafood industry prefers to compare with. When these values are compared to other protein sources, it is clear that Icelandic bottom-trawl catches are among the protein sources in the world with the lowest carbon footprint. For example, poultry has more than 12 times the carbon footprint per protein unit than the Icelandic cod, pork has 17 times the footprint, and beef has 80 times the footprint. It should be noted, however, that these are global averages.

It should be noted that the life cycle analysis only covered the fishing part of the value chain and that it did not take into account the effects that have been shown in previous studies to have a negligible effect on the carbon footprint of trawling. It also did not take into account the effects of trawling on the seabed, although in recent years it has been suggested that trawling releases large amounts of CO_2 that is captured in bottom sediments. However, the scientific community has not agreed on what these effects actually are. The analysis was carried out in accordance with international standards, ISO 14044, and the results are therefore fully comparable with other studies where the same standards have been followed.

Summary in Icelandic / Ágrip á íslensku

Frá aldamótum hefur átt sér stað mikil endurnýjun í íslenska togskipaflotanum, samhliða því sem fjöldi skipa í útgerðarflokknum hefur fækkað um nánast helming. Hefur verið látið að því vaka að nýju skipin séu mun sparneytnari og því hljóti kolefnisspor afurðanna að hafa dregist saman af þeim völdum. Gögn um olíuinnflutning til fiskiskipa virðast styðja þessa ályktun.

Til að greina betur áhrif endurnýjunar flotans á kolefnisspor fiskafla tóku því saman höndum nokkrir fulltrúar togaraútgerða, ásamt sérfræðingum Matís, Háskóla Íslands og Háskólans á Akureyri í mati á umhverfisáhrifum framleiðslukerfa. Safnað var gögnum frá 11 togskipum yfir 10 ára tímabil og aðferðafræði vistferilsgreininga (*e. Life Cycle Assessment*) beitt til að greina kolefnisspor á aflaeiningu, og þá hvort samanburður á milli eldri og nýrri skipa sýndi tölfræðilega marktækan mun. Skipin í úrtakinu voru valin til að gefa gott þversnið að íslenska togskipaflotanum hvað varðar stærð, aldur, aflasamsetningu og staðsetningu umhverfis landið. Voru í úrtakinu fjögur ný skip sem keypt voru til að koma í stað eldri skipa þ.a. samanburður fékkst milli eldir og nýrri skipa hjá sömu útgerð, með sömu aflaheimildir og jafnvel sömu áhöfn.

Niðurstöður greiningarinnar leiddu í ljós að erfitt sé að fullyrða að endurnýjun togaraflotans ein og sér hafi haft áhrif á kolefnisspor á aflaeiningu. Þrjú af þeim fjórum nýju skipum sem til skoðunar voru sýndu ekki marktækt lægri kolefnisspor en eldri skip sem þau komu í staðinn fyrir. Fjórða skipið kom hins vegar í staðinn fyrir tvö eldri skip, og þar var um marktæka lækkun að ræða. Líklegasta skýringin þar er hins vegar sú að þar sem aflaheimildum tveggja skipa var safnað saman á eitt nýtt skip sé það kvótastaða og útgerðarmynstur sem hafi ráðandi áhrif, frekar en aldur skipanna. Þessar niðurstöður eru í nokkuð góðu samræmi við fyrri rannsóknir hér á landi, sem sýnt hafa fram á að ástand nytjastofna, aflaheimildir, útgerðarmynstur skipta langsamlega mestu máli þegar kemur að útblæstri gróðurhúsalofttegunda á aflaeiningu. Þannig hafi samþjöppun aflaheimilda og fækkun skipa haft úrslitaáhrif varðandi lækkun kolefnisspors, frekar en endurnýjun flotans. Rétt er hins vegar að hafa í huga að samanburður á milli ára getur verið erfiður þar sem fiskigengd og aflabrögð geta verið mjög mismunandi á milli ára.

Niðurstöður vistferilsgreiningarinnar gáfu einnig upplýsingar um meðaltals kolefnisspor á aflaeiningu fyrir skipin í úrtakinu. Eru það mjög mikilvægrar upplýsingar þar sem svo yfirgripsmikil greining á kolefnisspori togaraafla hefur ekki farið fram hér á landi áður. Fyrri gögn náðu einungis yfir einstök togskip yfir mun styttri tímabil. Niðurstöðurnar sýna að kolefnisspor landaðs þorskafla er 0.7 kg $CO2$ ígildi/kg afla, 0.8 kg þegar kolefnissporinu er úthlutað á þann hluta aflans sem verður að matvælum, og 4.5 kg þegar því er úthlutað á prótein einingar. Svipaðar niðurstöður fengust fyrir ýsu og ufsa, en kolefnisspor karfa er mun hærra þar sem veiðarnar sjálfar eru orkufrekari og nýting til manneldis mun lægri. Þessar niðurstöður eru í nokkuð góðu samræmi við sambærilegar rannsóknir sem gerðar hafa verið á undanförnum árum í þeim löndum sem við viljum helst bera okkur saman við. Þegar þessi gildi eru svo borin saman við aðra próteingjafa er augljóst að íslenskur togarafiskur er meðal þeirra próteingjafa í heiminum sem bera hvað minnst kolefnisspor. Þannig er t.d. kjúklingur með meira en 12 sinnum stærra kolefnisspor á prótein einingu en þorskur, svínakjöt með 17 sinnum stærra spor og nautakjöt 80 sinnum stærra spor. Rétt er þó að taka fram að þar er um alheims meðaltöl að ræða.

Hafa ber í huga að vistferilsgreiningin náði einungis til veiðihluta virðiskeðjunnar og að ekki var tekið með í reikninginn áhrif sem sýnt hefur verið fram í fyrri rannsóknum að hafa léttvæg áhrif á kolefnisspor togveiða. Ekki var heldur tekið með í reikninginn áhrif togveiða á sjávarbotninn, en á síðustu árum hafa verið leiddar líkur að því að togveiðar losi um mikið magn af CO2 sem fast er í botnsetum. Vísindasamfélagið hefur hins vegar ekki komið sér saman um hver þau háhrif séu í raun og veru. Greiningin var gerð í samræmi við alþjóðlega staðla ISO 14044 og eru niðurstöðurnar því að fullu samanburðarhæfar við aðrar rannsóknir þar sem sömu stöðum hefur verið fylgt.

matís

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1 Introduction

The Icelandic seafood industry has invested heavily in modernising its bottom trawler fleet in recent years, with the aim to improve handling, increase value and optimise its operations. This has resulted in significant reduction in number of vessels, as the new trawlers are generally more efficient than those that they replace. At the turn of the century the trawler fleet consisted of 84 vessels, and in 2023 the fleet had been reduced down to 39 vessels, which is a 54% reduction in number (Statistics Iceland, 2024a). This fleet renewal started in 2017, when eight new trawlers were added to the fleet. Figure 1 shows how the number of vessels has been reducing in recent years, and how the average age of the bottom trawler fleet has been going down since 2017.

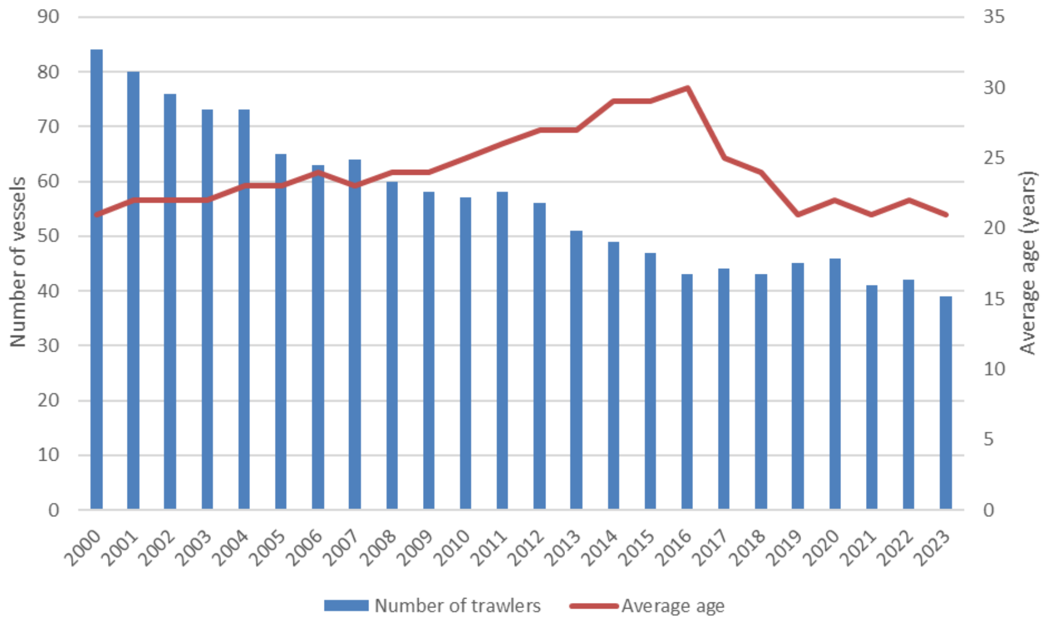

Figure 1: Total number of vessels in the Icelandic demersal trawler fleet and the average age 2000-2023

The reduction in number of trawlers is not solely explained by the renewal of the fleet, because the investment in the vessels is a part of ongoing consolidation and optimisation within the Icelandic seafood industry. The larger companies in the sector have been buying quotas or merging with other fishing companies, which have therefore been able to make better long-term plans. These plans have included investment in new trawlers, which are often replacing trawlers from the 70's and 80's. Quite often, the companies have invested in one new trawler to replace two or three older.

One of the assumed effects of the fleet renewal is reduction in environmental impacts, as the newer vessels are more energy efficient and fewer in number. Fisheries Iceland have calculated that the Icelandic fishing sector as a whole has reduced its oil consumption by 38% since the turn of the century, as shown in Figure 2 (Fisheries Iceland, 2022).

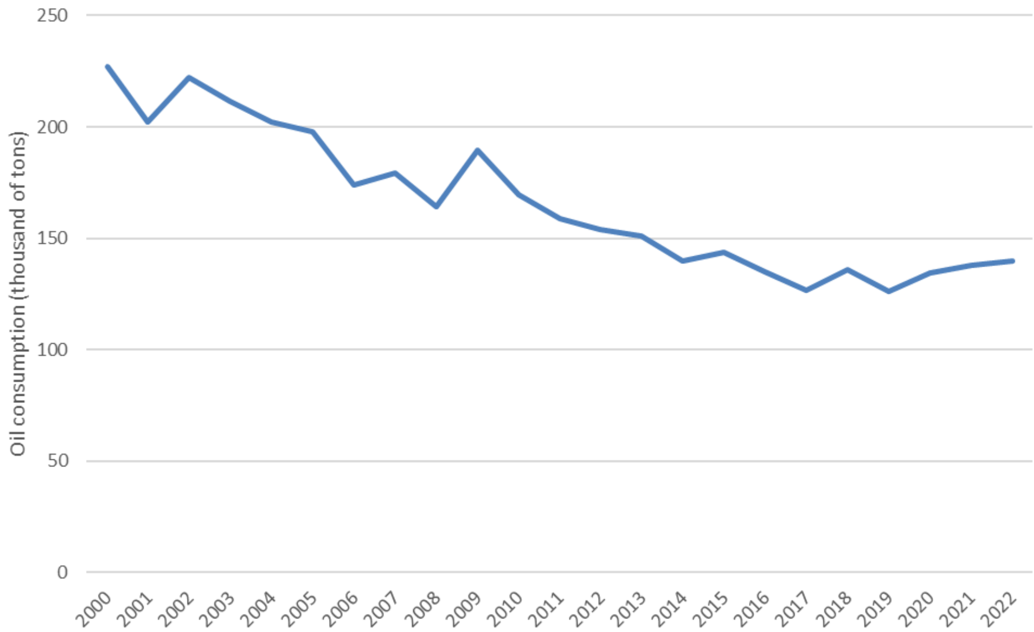

Figure 2: Oil consumption of the Icelandic fishing sector 2000-2022

Kristofersson, Gunnlaugsson and Valtýsson (2021) compared the CO_2 emissions of the different fleet sectors in Iceland during two periods, 1997-2000 and 2015-2018. They found that weighted average CO2 eq / kg cod eq had decreased from 1,47 to 0,89 between the two periods, or by 40%. Their conclusion was that "overall catches and abundance are by far the most important factors determining emissions, the bigger the catches and the greater the abundance, the smaller the emissions per unit of output. Fuel prices are a distant third factor and technological change has played a minor role in this development. In addition, the importance of different factors affecting emissions, varies between vessels depending on types of fishing gear. The results indicate that building up fish stocks not only increases output but also increases profitability and reduces emissions per unit of output, as long as the fisheries management system preserves incentives for efficient fishing".

The aim of this report is to dig deeper into these numbers by taking concreate examples of individual vessels where older trawlers have been replaced by new. The focus will be both on oil consumption per kg catch and kg CO_2 eq./kg product calculated using Life Cycle Assessment (LCA). The report follows up on a similar study published in 2014 where LCA was carried out on seven Icelandic fishing vessels, two of which were demersal trawlers built in the 70's (Smárason, Viðarsson, Þórðarson, & Magnúsdóttir, 2014). Key output from this work, in addition to this report, is a peer-reviewed journal article that was published in the Journal of Cleaner Production in December 2024 (Hilmarsdóttir, et al., 2024). The independent peer-reviewing process further validates the methodology applied, results and conclusions.

2 Materials and methods

The objective of the study was to analyse the effects of vessel renewal and fleet reconstruction on the fuel use intensity (l/kg) and Greenhous Gas (GHG) emissions of Icelandic demersal trawl fisheries, based on the Life Cycle Assessment (LCA) methodology. The study followed the International Standard Organizations (ISO) 14040 (ISO, 2006a) and 14044 (ISO, 2006B), as well as best practice guidelines (Hauschild, Rosenbaum, & Olsen, 2018), with focus on climate change impacts. It also complied with ISO 22948 for GHG calculations, expressing GHG emissions as kg CO_2 equivalents. This is a common practice in LCA, in a step called impact assessment, to convert amounts of other GHG to the equivalent amount of carbon dioxide, to aggregate GHG based on their global-warming potential (GWP) (Eurostat, 2024).

Data was gathered first-hand from fisheries companies in Iceland, where data for eleven demersal trawlers over the period 2012-2022 was collected.

Due to large uncertainty and inconsistency in available data on benthic carbon emissions due to trawling, and because the focus of this study is on assessing the GHG emissions of old and newly renewed vessels, this study did not engage in incorporating potential carbon release due to benthic layer disturbance.

2.1 Goal and scope

This study aimed to:

1) provide an up-to-date estimation of the GHG emissions of Icelandic demersal trawled fish,
2) evaluate the importance of fleet renewal and onboard processing on fisheries GHG emissions in relation to other factors

The functional unit assessed was “*1 kg of demersal trawled fish at landing”.*

The focus of the study was on global warming potential, referred to as GHG emissions. The functional unit was chosen to cover potential differences in impacts based on catch composition and to investigate if the GHG emissions varied between the old trawlers and the renewed trawlers studied. The allocation method chosen for the base case was mass allocation. To demonstrate sensitivity towards choosing the allocation method when comparing the edible part of the different species, economic allocation was applied in a *scenario* as the fish species differ in price and ratio of the fish utilized for human consumption (edible part ratio; Table 2).

2.2 Data collection and system boundary

Data was collected first-hand from eleven trawlers owned by four major seafood companies in Iceland to represent cross-section of the Icelandic demersal trawl fleet, with respect to age, size, catch composition and operation. The eleven vessels account for approximately 25% of the Icelandic demersal trawl fleet during the study period. Fuel consumption was collected first-hand, where catch composition data was obtained both first-hand and from the open official catch-registry of the Directorate of Fisheries database (Directorate of fisheries, 2024). The vessels are presented in Figure 3.

Trawler 1: Páll Pálsson ÍS 102
Built in 1972
Length: 53,68 m.
Widith: 9,5 m.
GT: 809 t.
Hp: 2.300
Home port: ísafjörður, Iceland
Owner: Hraðfrystihúsið - Gunnvör hf

Trawler 2: Páll Pálsson ÍS 102
Built in 2018
Length: 51,29 m.
Widith: 13 m.
GT: 1.222 t.
Hp: 2.407
Home port: ísafjörður, Iceland
Owner: Hraðfrystihúsið - Gunnvör hf

Trawler 3: Klakkur SK 5
Built in 1977
Length: 51,83 m.
Width: 10,76 m.
GT: 745 t.
Hp: 2.200
Home port: Sauðárkrókur, Iceland
Owner: FISK-seafood ehf

Trawler 4: Málmey SK 1
Built in 1987
Length: 56,50 m.
Width: 12,60 m.
GT: 1.470 t.
Hp: 2.991
Home port: Sauðárkrókur, Iceland
Owner: FISK-seafood ehf

Trawler 5: Drangey SK 2
Built in 2017
Length: 62,55 m.
Width: 13,50 m.
GT: 2,081 t.
Hp: 2.172
Home port: Sauðárkrókur, Iceland
Owner: FISK-seafood ehf.

Trawler 6: Jón Vídalín VE 82
Built in 2072
Length: 55,52 m.
Width: 9,50 m.
GT: 809 t.
Hp: 2.300
Home port: Vestmannaeyjar, Iceland
Owner: Vinnslustöðin hf.

Trawler 7: Gullberg VE 292
Built in 2000
Length: 37,00 m.
Width: 10,40 m.
GT: 600 t.
Hp: 1.436
Home port: Vestmannaeyjar, Iceland
Owner: Vinnslustöðin hf.

Trawler 8: Breki VE 61
Built in 2018
Length: 51,29 m.
Width: 13,00 m.
GT: 1,222 t.
Hp: 2.407
Home port: Vestmannaeyjar, Iceland
Owner: Vinnslustöðin hf.

Trawler 9: Drangavík VE80
Built in 1991
Length: 28,98 m.
Width: 7,92 m.
GT: 356 t.
Hp: 1.000
Home port: Vestmannaeyjar, Iceland
Owner: Vinnslustöðin hf.

Trawler 10: Bergey VE 544
Built in 2007
Length: 28,93 m.
Width: 10,39 m.
GT: 486 t.
Hp: 699
Home port: Vestmannaeyjar, Iceland
Owner: Bergur Huginn ehf.

Trawler 11: Bergey VE 144
Built in 2019
Length: 28,93 m.
Width: 12,32 m.
GT: 611 t.
Hp: 788
Home port: Vestmannaeyjar, Iceland
Owner: Bergur Huginn ehf.

Figure 3: The eleven trawlers that took part in the study

The earliest data was from 2012 and the latest from 2022. All data was aggregated and used as an annual average for the years provided by the companies. Hence, not all trawlers included the same reference years, as shown in Table 1, although some years did overlap between the trawlers. However, resource use has been shown to vary both within each year and between years (Ziegler, Groen, Bokkers, Karlsen, & de Boer, 2018).

Table 1: Information about the trawlers studied and years data was collected for the current study. Trawlers are numbered, where subscription indicates the same trawler. Old vessels are indicated with blue colour and new vessels with green colour. Coloured numbers indicate fuel intensity (Liters oil per kg catch)

Trawler	Owner of the vessel	Building year	Length (m)	Width (m)	GT	Hp	Fuel intensity (l/kg) during the reference years for the trawlers										
							2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
1[a]	A	1972	53.7	9.5	809	2300	0.17										
2[a]	A	2018	51.3	13	1222	2407									0.17	0.18	
3[b]	B	1977	51.8	10.8	745	2200	0.35	0.30	0.23	0.28	0.29	0.28					
4[b]	B	2017	62.6	13.5	2081	2172							0.23	0.21	0.25	0.26	0.25
5	B	1987	56.5	12.6	1470	2991				0.22	0.23	0.23	0.23	0.25	0.29	0.30	0.29
6[c]	C	1972	55.8	9.5	809	2300			0.53	0.43							
7[c]	C	2000	37	10.4	600	1436				0.35	0.34						
8[c]	C	2018	51.3	13	1222	2407								0.24	0.28		
9	C	1991	29	7.9	356	1000									0.24		
10[d]	D	2007	29	10.4	486	699							0.17				
11[d]	D	2019	29	12.3	611	788									0.19	0.19	

[a-d] indicate replacement of trawlers, before and after changes

Trawlers have been renewed during different time periods ([a-d] in Table 1). Trawler 2 replaced Trawler 1 in 2018, a 46-year younger vessel that was built to ensure better quality of the catches, better working conditions, and lower fuel consumption. Similar reasons led to the replacement of Trawler 3 by Trawler 4, and for Trawler 10 by Trawler 11. Trawler 8 replaced two older vessels, Trawler 6 and Trawler 7, while Trawler 5 and Trawler 9 are still in operation although being older vessels, thereby providing a benchmark for the newer vessels. Fuel intensity (l oil/kg catch) at each reference year for each of the trawlers can be seen in Table 1.

Annual data regarding steaming and catching for Trawler 4 and Trawler 5 was provided first-hand where litres of oil were measured both during steaming and during catching, to investigate if trend of longer catching distance appeared with later years. Furthermore, the impact of changing Trawler 5 from a freezer trawler to fresh-fish trawler was investigated.

The system boundaries included datasets of fuel consumption, catching ground, catch composition and the descriptions of the trawlers studied, of the eleven different bottom-trawlers, as shown in Figure 4.

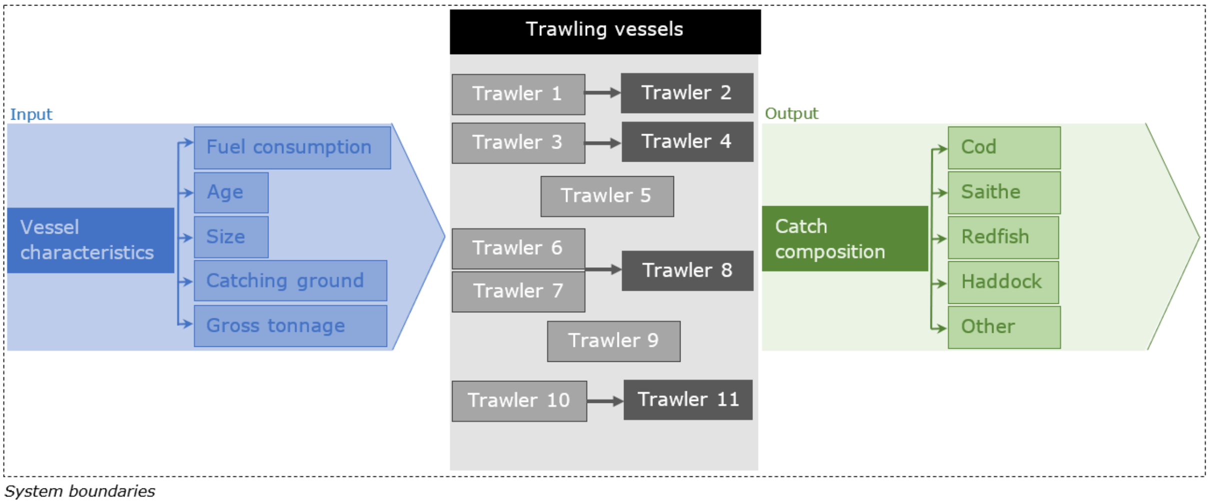

Figure 4: System boundaries of the Life Cycle Assessment of producing 1 kg of demersal trawled fish at landing. The trawling vessels are described in Table 1.

The construction of the vessel itself, use of coolants, anti-fouling, cleaning agents and other resources were included in the data collection and preliminary analysis but were in the end not kept within the system boundaries because Inconsistent data registration, and as they have shown to have minimal influence on the results. Previous studies (Ziegler, Jafarzadeh, Skontorp Hognes, & Winther, 2022) have for example shown that 86% of the GHG emissions of bottom trawlers targeting cod In Norway are caused by the fuel use. There have however been published studies that have shown up to 40% increase in GHG emissions due to severe coolant leaks, repairs and services in onboard cooling systems (Winter, et al., 2009) & (Ziegler, Groen, Bokkers, Karlsen, & de Boer, 2018). The use of more environmentally friendly coolants and better maintenance of cooling systems in the Icelandic fleet however makes severe coolant leakages very unlikely.

2.3 Life Cycle Impact Assessment (LCIA)

Calculations were performed using SimaPro version 9.1.0.8 software (PReConsultants, Amersfoort, Netherlands) in conjunction with the ecoinvent 3.8 Life Cycle Inventory Database (Wernet, et al., 2016).

The environmental impact of focus in this study was global warming potential (GWP100a) although all the impact categories are also presented (Table X1 in *Appendix)*. The average fuel consumption yearly during bottom trawl fishing was modelled for each trawler and year in the software. The impact assessment method used in the current study was CML-IA baseline V3.08 / EU25 and was chosen to be able to compare with Smárason et al. (2014), which already compared long-liners to trawlers within the Icelandic fishery. However, the fleet renewal impact had yet to be investigated, as well as the general GHG emission estimate for Icelandic trawling updated.

2.4 Sensitivity analysis

A sensitivity scenario was identified to evaluate the sensitivity of the results. The allocation method chosen as the *base-case* was dependent on the mass of the catch (mass allocation), but as the different species vary both in value and utilization ratio, a *scenario* describing economic allocation was added when comparing the edible part (eatable part) of the different species studied, as shown in Table 2.

Therefore, economic allocation *scenario* was assessed, as both value of the fillets and the byproducts vary across the species studied, affecting the economically based allocation *(scenario*) compared to the mass allocation (*base-case*) (Svanes, Vold, & Hansen, 2011). Hence, the *scenario* showed if the GHG emissions were allocated based on monetary value (The Icelandic currency, ISK) as the fish is often caught due to the relatively high price of the fillet.

Table 2: Ratios of the different streams from target species where the values represent edible pars, except values in brackets, without further food processing. The total value both in base case and scenario are expressed in kg/kg and ISK/kg and collected from Statistics Iceland.

<table>
<tr><th></th><th>Fillet</th><th>Head and backbone</th><th>Liver and roe</th><th>Skin and cut-offs</th><th>Total mass for fillets only (Base-case) (kg/kg)</th><th>Total value for fillets only (Scenario) (ISK/kg)</th></tr>
<tr><td>Cod</td><td>39%</td><td>41%</td><td>14%</td><td>(6%)</td><td>39%</td><td>90%</td></tr>
<tr><td>Haddock</td><td>36%</td><td>42%</td><td>(14%)</td><td>(7%)</td><td>36%</td><td>92%</td></tr>
<tr><td>Saithe</td><td>38%</td><td>40%</td><td>(14%)</td><td>(8%)</td><td>38%</td><td>88%</td></tr>
<tr><td>Redfish</td><td>35%</td><td colspan="3">(65%)</td><td>35%</td><td>79%</td></tr>
</table>

Further details regarding prices of the different parts of each fish species are listed in Table 3, and are based on average export prices (FOB) from Statistics Iceland.

Table 3: The value (ISK/kg) of each part of the target fish species, used in economical allocation (scenario)

<table>
<tr><th>ISK/kg</th><th>Cod</th><th>Haddock</th><th>Saithe</th><th>Redfish</th></tr>
<tr><td>Fillet</td><td>1,684</td><td>1,809</td><td>1,014</td><td>1,246</td></tr>
<tr><td>Head</td><td>109</td><td rowspan="2">102</td><td rowspan="2">90</td><td rowspan="5">178</td></tr>
<tr><td>Backbone</td><td>71</td></tr>
<tr><td>Skin</td><td>135</td><td>130</td><td>130</td></tr>
<tr><td>Liver and roe</td><td>165</td><td rowspan="2">318</td><td rowspan="2">282</td></tr>
<tr><td>Cut-offs</td><td>450</td></tr>
</table>

The study period covers eleven years, but the monetary values used do only apply to the annual average in 2023. The assumption is however that relative values remain similar between years.

2.5 Statistical analysis

Statistical and regression analyses were conducted utilizing Microsoft Office 365's Excel software (Microsoft, Redmond, WA, USA). Results were presented as mean values ± standard deviation (SD), with a significance threshold of $p < 0.05$ to ascertain statistical significance.

Multivariable linear regression model was developed to assess the outcomes for the various trawlers, and to identify the most influential contributing variables (Montgomery & Runger, 2014). Prior to developing the model, the authors selected the most relevant explanatory variables to analyse their impact on the trawlers GHG emissions. The model was fitted with the response variable GHG data, evaluated by R^2 metrics and the explanatory variable parameters significance tested with p-values. The resulting model is described with the following equation:

$$GHG = b_0 + b_1 CATCH + b_2 AGE + b_3 SIZE + b_4 GT + b_5 ZONE \ + \ e$$

where GHG emissions is the response variable, and catch, age, size (length/width), GT (gross tonnage), and zone (effort due to fishing zone, ranked from 1 to 5) are the selected explanatory variables, and b the model parameters.

3 Results

The Data used for the analysis were compiled from eleven vessels and represented 43 annual datasets, spanning from one year per vessel to eleven years. The total catches represented in the study were 255 thousand tonnes of demersal catches, and the fuel used were 53.500 tonnes, amounting to an average fuel intensity of 0,21 kg oil / kg catch. When converted to litres of oil per kg catch the average fuel intensity is 0,26 l oil / kg catch. The fuel intensity of the vessels for each year in the study is shown in Table 4.

Table 4: Fuel intensity (litres of oil / kg of catch)

Year	Trawler 1	Trawler 2	Trawler 3	Trawler 4	Trawler 5	Trawler 6	Trawler 7	Trawler 8	Trawler 9	Trawler 10	Trawler 11
2012	0,135		0,355		0,327						
2013			0,305		0,303						
2014			0,231		0,374	0,449				0,290	
2015			0,279		0,225	0,390	0,343			0,286	
2016			0,289		0,227		0,322			0,247	
2017			0,285		0,233					0,204	
2018				0,231	0,227					0,166	
2019				0,213	0,247			0,240		0,190	
2020		0,176		0,255	0,288			0,237	0,206		0,226
2021		0,169		0,264	0,302						0,209
2022				0,248	0,291						0,203

Trawler 5 was operated as a factory vessel until 2015, when it was converted into a fresh-fish trawler, resulting in severely (40%) reduced fuel intensity between the years 2014 and 2015. An important factor when considering fuel intensity is the total catch and subsequent catch per unit effort (CPUE). Table 5 shows the total annual catches of the study vessels, in thousands of tonnes.

Table 5: Total catches in wet-weight by vessel and year during the study period (thousand tons)

Year	Trawler 1	Trawler 2	Trawler 3	Trawler 4	Trawler 5	Trawler 6	Trawler 7	Trawler 8	Trawler 9	Trawler 10	Trawler 11
2012	6.411		4.404		8.499					3.172	
2013			4.973		9.254					2.520	
2014			6.681		5.475	2.178				3.719	
2015			4.908		7.016	2.606	4.360			4.124	
2016			5.655		8.551		4.233			4.791	
2017			5.017		7.323					4.702	
2018				7.273	8.178					5.917	
2019				9.085	7.852			7.964		4.756	
2020		6.411		7.899	7.494			7.648	3.289		4.980
2021		6.359		8.052	6.850						5.655
2022				7.218	6.663						5.024

Comparing the two tables above show a relationship between total catches and fuel intensity, although other factors are evidently in play. Each fishing vessel displays unique operational patterns and catch compositions, and no clear trend can be noticed in fuel efficiency for newer vessels compared to the old vessels. Figure 5 shows for example how Trawler 2 and Trawler 11 have a slightly higher fuel use intensity than the vessels they replaced, while Trawlers 4 and 8 have a lower fuel use intensity. The GHG emissions are demonstrated along with the kg CO_2-eq and fuel intensity (l/kg) of both the old and the renewed vessels in Figure 5.

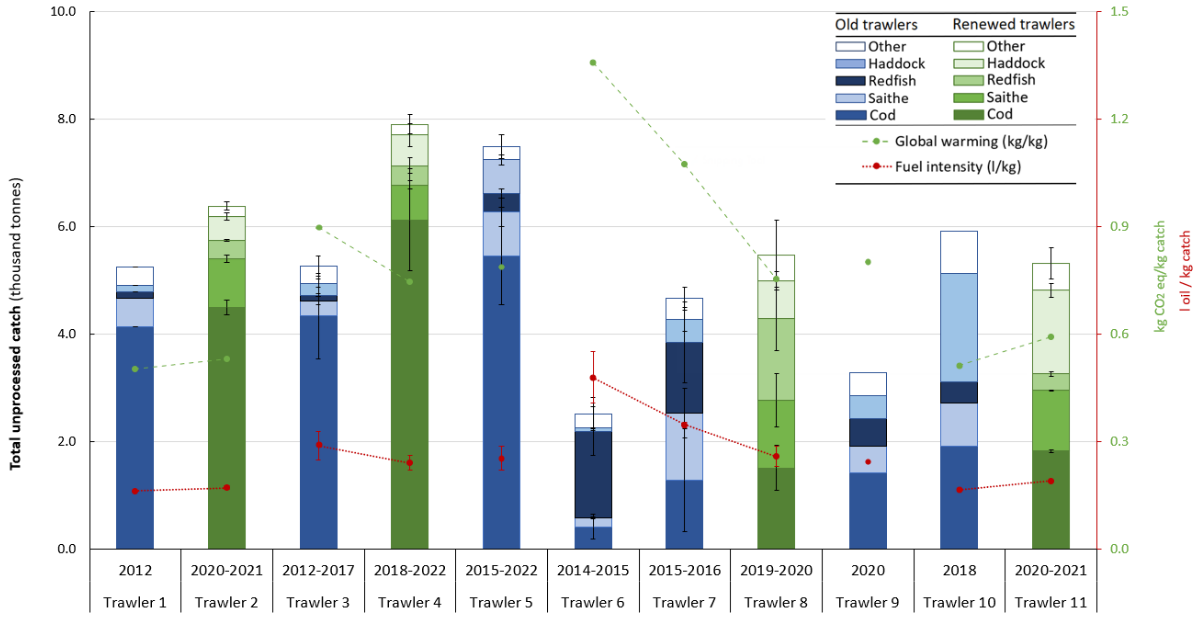

Figure 5: Catch composition of each trawler in reference years are displayed in the figure bars. Different colours in bars present a different species including old or renewed trawler (see figure legend). The global warming potential (green dashed coloured line) of unprocessed catch for each trawler and the catch composition along with fuel intensity (red dotted coloured line). Global warming potential and fuel intensity are expressed on the right y-axis and total unprocessed catch on the left y-axis. Standard deviations are expressed as error bars when more than one reference year is in the dataset.

The results show varying GHG values from 0.50-1.35 kg CO_2-eq per kilo unprocessed catch, depending on the trawler, years and catch composition, as shown in Figure 6.

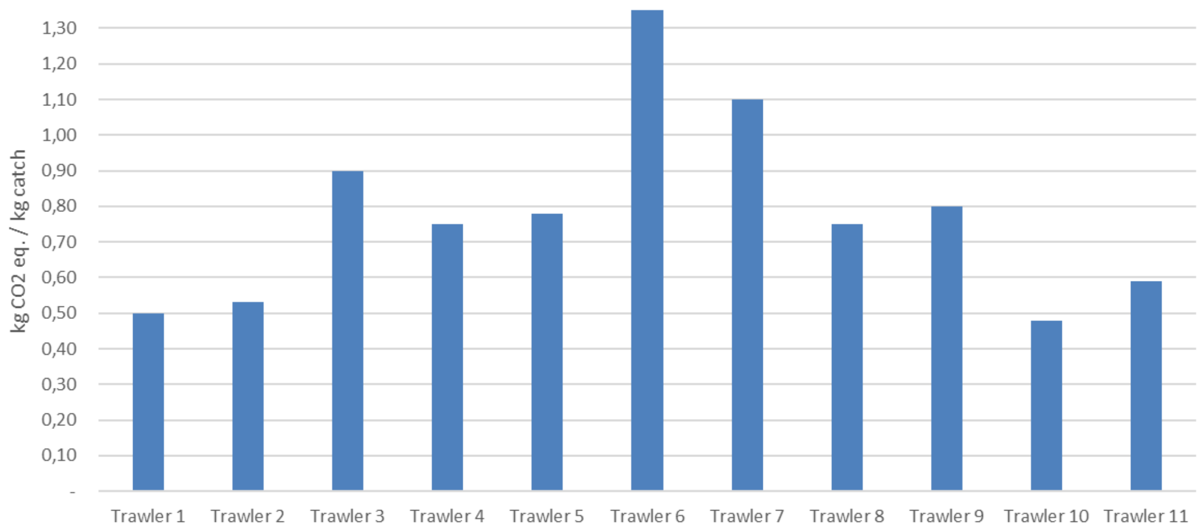

Figure 6: Average kg CO_2 eq./kg catch of the eleven vessels

Previously reported GHG emissions in Icelandic demersal trawl fisheries from 2014 were around 1.0 kg CO_2-eq per 1 kg demersal fish landed (Smárason, Viðarsson, Þórðarson, & Magnúsdóttir, 2014). This variation could explain a trend of lower GHG emissions with target species such as cod, saithe and haddock, and higher GHG emissions for redfish. As shown in Figure 5 the trawlers targeting redfish the most, trawler 6 and trawler 7, have by far the highest GHG emissions. The reason for a higher GHG emissions in vessels with high redfish catch composition could be due to redfish being generally caught at considerably more depth than cod, haddock and saithe.

3.1 Comparison between mass – and economic allocation

To evaluate GHG emissions on the edible part of the catch, mass – and economic allocation was estimated, as the target species varied both in value and ratio utilized for human consumption. As the mass allocation (base-case) measured the mass of each stream, such as cod fillets being 39% of the cod (Table 2), the economic allocation of cod fillet was 90% of the cod's value (Table 3). Along with varying fillet prices for the species studied, valorisation of the side-streams varies, affecting the GHGs. Further details regarding prices for each part of the fishes are shown in Table 6 (Statistics Iceland, 2024).

Table 6: Average 2023 values of the different parts of the target fish species

ISK/Kg	Cod	Haddock	Saithe	Redfish
Fillet	1.684	1.809	1.014	1.246
Head	109	102	90	178
Backbone	71			
Skin	135	130	130	
Liver & roe	165	318	282	
Cut-offs	450			

The GHG emissions from the unprocessed catch landed was allocated to the edible part of each fish species, including kg CO_2-eq per kg protein of the edible parts calculated from the Icelandic Food Composition Database - ISGEM (Matís, 2024). Furthermore, in the current study, edible parts of the fish do not include feed or bait, only parts that are edible and sold directly for human consumption.

Currently, redfish is only caught for its fillets, although the side-streams are processed into fishmeal- and fish oil, and/or used as bait. The GHG emissions of redfish are estimated at 2.7 kg CO_2-eq per kg edible product and around 15.1 kg CO_2-eq per kg protein, estimated with mass allocation Table 7. For the other species, the emissions varied as more than the fillet was considered edible, where cod, saithe and haddock ranged from 3.8 to 5.9 kg CO_2-eq per kg protein if the GHG emissions were allocated on edible part of the fish. The reason for a higher emissions of redfish protein could be due to higher emissions of the unprocessed redfish catch at landing, alongside the low utilization ratio as the fillet is currently the only part being utilized for human consumption.

Table 7: GHG emissions allocated on unprocessed catch landed compared to allocation on edible fish parts and fillet. Values represent the base-case, which is with mass allocation, where economic allocation scenario in brackets.

	Cod	Haddock	Saithe	Redfish
GHG emissions (kg CO_2-eq/kg unprocessed catch)	0.7 (0.8)	0.5 (1.0)	0.8 (1.0)	1.0 (0.8)
Edible product	87%	78%	78%	35%
Allocating only to edible parts*	0.8 (0.9)	0.7 (1.2)	1.1 (1.2)	2.7 (2.3)
Allocating all to the fillet*	1.8 (2.1)	1.4 (2.7)	2.2 (2.5)	2.7 (2.3)
kg CO_2-eq per kg protein edible parts **	4.5 (5.2)	3.8 (7.3)	5.9 (6.9)	15.1 (12.5)

** Numbers from the regression model*
***calculated from the ISGEM database*

Previous studies calculated with economic allocation have reported 1.0-1.7 kg CO_2-eq per kg demersal fish landed (Parker, et al., 2018) and 2.4 kg CO_2-eq per kg cod (Ziegler & Hanson, 2003). These values are relatively higher than presented in Table 7, where the GHG emissions for edible part of cod is 0.7 when using mass allocation and 0.8 when using economic allocation. However, if the emissions were allocated solely to the fillet, emissions would range from 1.4 to 2.7 kg CO_2-eq per kg of demersal fish fillet, which would be closer to previously reported values from Parker et al. (2018) and Ziegler & Hanson (2003). Hence, one important explanation for the relatively low emissions resulting for Icelandic seafood from demersal trawling is the very high rate of utilization.

When comparing the GHG emissions between mass- and economic allocation, the ratio for cod and haddock shifts i.e. Haddock has lower GHG emissions than cod when using mass allocation, but higher when applying economic allocation, as shown in Figure 7.

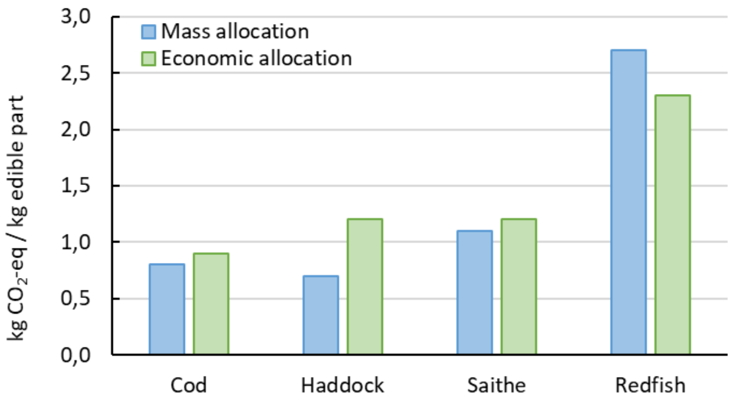

Figure 7: Average GHG emissions for the edible part of each fish species compared between mass and economic allocation.

This is likely due to higher utilisation rates in cod processing and difference in prices of the side streams. Furthermore, for redfish being the target species, Trawlers 7-9 show that with mass allocation, the GHG emissions for redfish are <10% higher if allocated by mass compared to value, and <6% for saithe. The reason might be both due to the ratio of side-streams being valorised, and the price for each of the side-streams, as edible parts of saithe and redfish are nearly half of the value for edible parts of cod and haddock (Statistics Iceland, 2024). Therefore, an opportunity to utilise a higher ratio of redfish and saithe could result in lower GHG emissions allocated to the fillet, distributing the emissions to other side-streams, and possibly increasing the value of the fish species.

Higher utilisation ratios of the demersal species can lower emissions of the edible part, by valorising higher ratio of the side-streams for human consumption. Cod utilisation has increased over the years, and today even higher part of the cod is utilised, skin and guts, where the skin is sold and used for added value products such as collagen production, pharmaceuticals, nutraceuticals and even medical applications (Iceland Ocean Cluster, 2024). However, as utilisation of by-products is often part of the newer trawlers it can lead to increased energy intensity onboard the vessels and as long as fishing vessels operate on fossil fuels, onboard processing is generally more climate intensive than processing on land, if using non-fossil energy sources (Hilmarsdóttir, Ögumundarson, Arason, & Guðjónsdóttir, 2022). That can result in allocating impacts to higher ratio usage of side-streams which can lead to a higher GHG emissions of individual trawlers. As an example, use of refrigerants in onboard cooling systems have shown to be responsible for up to 30% of the total GHG emissions in landings (Ziegler, Groen, Bokkers, Karlsen, & de Boer, 2018), and results from this study might therefore be underestimated for some fish species. However, that data collected did not include the use of coolants, and it therefore falls outside the system boundaries. The results from Ziegler et al. (2018) demonstrates that valorising side-streams are not "free” of environmental impacts as it often claimed, e.g. it requires the use of additional energy for processing and chemicals. Hence, applying LCA remains critically important when exploring valorisation options and changes within production processes.

3.2 Evaluating the importance of fleet renewal on GHG emissions

The average CO_2 emissions per unit of catch have been reported to have reduce by approximately 40% in Iceland's demersal fisheries, between 1997 to 2018 (Kristófersson, Gunnlaugsson, & Valtýsson, 2021). That study also concluded that technological change has played a minor role in this development, as the main explanations for the reduction in GHG emissions are stock abundance and overall catches i.e. the bigger the catches and the greater the abundance, the smaller the emissions per unit of output. The current study reaches similar conclusions, as fleet renewal does not appear to have significant impact on GHG emissions. Although the average emissions of the older vessels were 0.84 CO2-eq per kg catch compared to 0.67 CO2-eq per kg catch of the newer vessels, amounting to 20% average reduction, the results are not statistically significant, as shown in Figure 8.

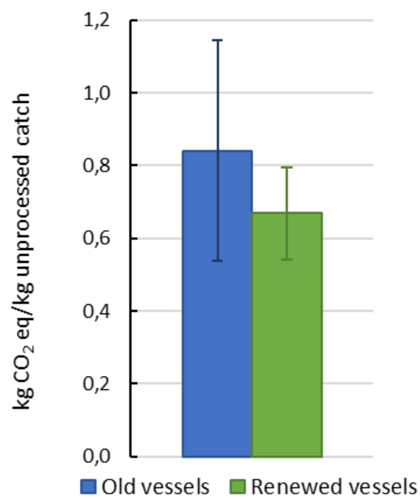

Figure 8: Average GHG emissions per kilo unprocessed catch in old (blue colour) and renewed vessels (green colour) during the reference years. Error bars represent standard deviation

The average fuel intensity (l/kg) was also higher for the older vessels (0.28±0.11) compared to the renewed vessels (0.22±0.0). Fuel intensity was further investigated in relation to steaming, catching and onboard processing.

Fuel intensity remained similar in the current study as previously reported (0.2-0.5 l) (Ziegler, Jafarzadeh, Skontorp, & Winther, 2022), although many factors can affect fuel consumption during fishing (Hilmarsdóttir, Ögumundarson, Arason, & Guðjónsdóttir, 2022). Two trawlers (*Trawler 4* and *Trawler 5*) were further compared to investigate if fuel intensity would vary between *steaming* and *catching* phases of the trawler. Additionally, onboard processing was investigated in *Trawler 5*, as it used to have onboard processing (freezer trawler) from 2012-2014 but was converted to a fresh fish trawler in 2015.

As seen in Figure 9, both trawlers showed increased GHG emissions from 2018 to 2021. This increase could be due to multiple factors, including steaming and/or trawling distances, less efficient engines, or more energy or cooling media needed for optimal chilling. The comparison between GHG emissions of fresh fish and onboard processing operations is obvious, as expected.

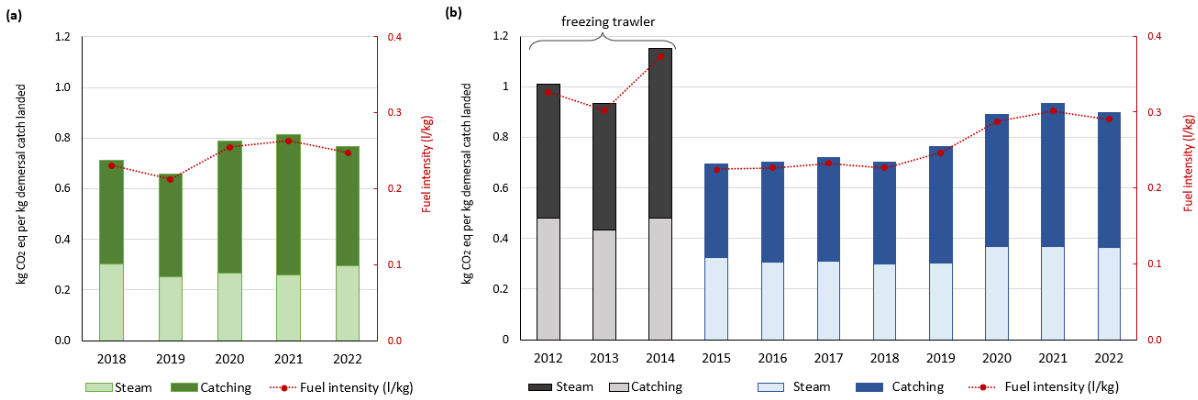

Figure 9: GHG emissions (kg CO2-eq) for Trawler 4 (a) and Trawler 5 (b), of 1 kg demersal fish landed, by trawling during various years. Emissions were divided between steaming and catching during trawling and compared with fuel intensity (l/kg) of the second x-axis marked in red. Trawler 4 has been renewed (green colour) but not Trawler 5 (blue colour).

On average, GHG emission originated 60% from the catching phase (58% for old and 63% for the newer trawlers) and 40% from steaming during fresh fish operations. This ratio was reversed during the onboard processing operations, where the steaming phase was responsible for 55-60% of GHG the emissions.

Around a 24% reduction of the GHG emissions during catching was noticed when *Trawler 5* was changed from onboard processing and freezing, to fresh fish operations (from 2012-2014, and 2015-2022). Changing the trawler from freezing trawler to a fresh fish trawler not only resulted in reduction of GHGs, but also increased the value of the catch, as fresh fish has generally a higher price than frozen fish; as for example the average export prices of fresh Icelandic skin & boneless cod fillets exceeded the average prices of frozen-at-sea counterparts by 25% in 2023 (Statistics Iceland, 2024). Furthermore, newer trawlers could possibly process and cool the catch quicker along with better general working conditions for the crew depending on vessel design. Moreover, emission standards and fishing zone access can vary depending on the vessel length. Therefore, not only can handling onboard and other onboard processing affect the GHG emissions, but also vessel design due to less strict length regulations (rather than regulating beam/width), which is an example where regulations can counteract technological improvement and could be a future concern. However, currently stock size is reported to have greater effect on fuel efficiency rather than vessel size (Byrne, Agnarsson, & Davíðsdóttir, 2021), (Kristófersson, Gunnlaugsson, & Valtýsson, 2021) & (Ziegler & Hornborg, 2014).

3.3 Trawler variables influencing GHG emissions - a regression analysis

To identify parameters impacting the GHG emissions and to evaluate the influence of key variables, a regression analysis was performed. All the selected explanatory variables in Eq.1 influence the GHG emissions to some level and the regression analysis suggests that R^2=94.3% of the variation in the GHG emissions can be explained by the explanatory variables *catch (p=0.039)*, *age (p=0.027), size (p=0.032), GT (p=0.065),* and *zone (p=0.002)*. The explanatory variables *catch, age, size* and *zone* were found to have most effects, p<0.05 in the model, while the explanatory variable *GT has* a higher p value of 0.065. These results indicate that the weight of the trawlers (gross tons) influences the GHG emissions less than the catch, trawler age and fishing zone. Trawler size and shape influenced the GHG emissions.

Icelandic regulations limit trawler length to 30 m, leading to wider designs that increase drag and fuel use. These regulations also limit engine size, potentially reducing fuel efficiency.

Figure 10 shows graphs locating the trawlers investigated in terms of total GHG emissions and total catch for the reference years. The graphs are shown for different fish species (cod, saithe, haddock and redfish) and the slope of a best-fit regression line can represent the kg CO_2-eq/kg catch ratio. The comparison does not show a clear trend for GHG emissions for newer vs older trawlers during the reference period.

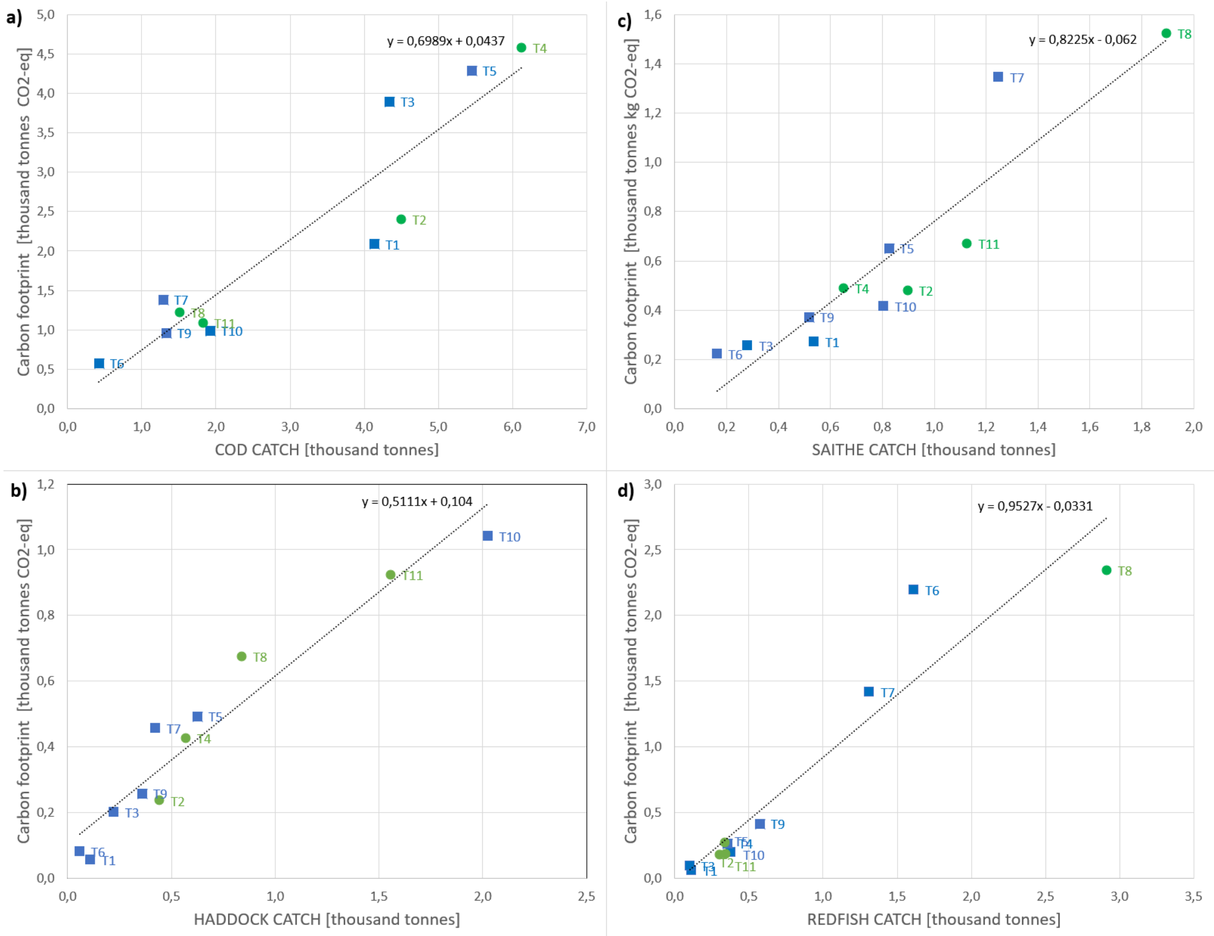

Figure 10: Comparison between the different trawlers for total GHG emissions and the total amount caught in the reference years. The relation is presented in four graphs for different fish species cod (a), haddock (b), saithe (c), and redfish (d). Old vessels are indicated with blue colour boxes and new vessels with green colour dots.

Comparison between the fish species indicated that a kg of redfish gave an average of 0.95 kg CO_2-eq, cod 0.70 kg CO_2-eq, saithe 0.82 kg CO_2-eq, and haddock the lowest or 0.51 kg CO_2-eq, if GW was divided for all the unprocessed catch per each trawler. For comparison results from Ziegler et al. (2022), with average values for the period 2007-2017, showed greenhouse gas emissions in Norwegian fisheries in kg CO_2-eq/kg catch at landing for cod of 0.68, for saithe 0.75 and haddock 0.79. When comparing the total catch of all the trawlers, previously published data from Ziegler et al. (2022) showed less than 3% increase in GHG emissions for cod, 55% lower for haddock, and 9% higher for saithe. Values calculated with the total catch was similar to more refined data with only the target species (over >1000 tons/year). These comparisons are shown in Table 8.

Table 8: Values based on the regression analysis, expressing kg CO_2eq/kg catch and average for each fish species depending on catch volumes.

Fish species kg CO_2-eq/kg catch	**All the trawlers** Total catch	**Trawlers by target species** >1000 tons catch	**Comparison** with Ziegler et al. 2022
Cod	0.70	0.72	0.68
Haddock	0.51	0.55	0.79
Saithe	0.82	0.83	0.75
Redfish	0.95	1.08	-

As Figure 10 shows there are trawlers with low catch quantity for each of the studied species, this is most apparent for redfish where there are only three trawlers (T6, T7 and T8) that are targeting redfish to any extent during the reference period. For cod, however, only one trawler (T6) catches less than 1000 tons/year and for saithe and haddock the catches are more evenly distributed between trawlers.

The regression model showed that catch, age and fishing zone account for approximately 94% of the GHG emissions from trawlers, with CO_2 emissions varying across fish species. As the fishing industry continues to evolve, regression models could help identify which variables to prioritize for reducing GHG emissions.

4 Conclusions

The main question the study was intended to answer is whether the renewal of the Icelandic demersal trawl fleet has had concreate impact on the fleets GHG emissions and carbon footprint. The answer to that question is no, as the GHG emissions of unprocessed catch did not show significant difference after vessel renewal. This does not necessarily mean that the newer vessels are not more energy efficient than the older vessels. There are simply other factors that overshadow the impact of the fleet renewal (if there indeed is an impact).

The study showed that average GHG emissions of unprocessed catch varied from 0.5 to 1.4 kg CO_2-eq per kilo, depending on the trawler, years and catch composition, and that GHG emissions for cod, haddock, saithe and redfish varied from 0.7 to 2.7 kg CO_2-eq per kilo edible part, depending on the species and valorisation ratio of each species.

It is also revealed by the study that onboard processing at sea and certain types of vessel regulations can lead to increased fuel usage. Evaluation of the GHG emissions should consider the trawler's target catch species along with influencing factors, such as the trawler age and shape.

Of the variables analysed the weight of the vessels influenced the GHG emissions less than the catch, trawler age and fishing zone. The regression analysis however did not show a clear trend for older vs newer trawlers in terms of GHG emissions.

The utilization of by-products was more impactful in reducing GHG emissions compared to the vessel renewal. However, valorising side-streams can increase emissions and hence, LCA methodology is highly recommended to explore options and estimate the effects of the changed process beforehand

The authors recommendations for the industry are to investigate onboard processing steps for energy required additionally for the vessels, utilise the by-products at a higher rate for most species. Furthermore, following points are suggestions for future research and actions that aim to enhance the sustainability of bottom trawling practices by leveraging technology, policy and comprehensive data analysis:

- **Enhanced Data Collection** would include implementation of real-time monitoring systems for fuel consumption and emissions to improve the accuracy of GHG impact models which could be linked to different species caught at each time for more exact calculations of impacts for each caught species.
- **Low-Carbon Technologies** would reduce fossil fuel reliance and emissions.
- **Optimized Fishing Practices** would reduce bycatch and therefore environmental impacts by adopting fuel-efficient and selective trawling methods.
- **Sustainable Fishing Policies** would require incentives and regulations for energy-efficient vessels and low-emission technologies as well as sustainable utilization of fish stocks, which build on thorough environmental assessments based on detailed validated data to reduce risk of implementing less sustainable fishing policies.
- **Comprehensive Life Cycle Assessments** would identify areas for reducing environmental impacts if all stages of the fishing process were included.

5 Discussions

The aim of this study was to analyse the effects of vessel renewal and fleet reconstruction on the fuel use intensity and GHG emissions of Icelandic demersal trawl fisheries, based on LCA methodology. The general assumption in the seafood industry has been that new vessels and engines play a key role when it comes to fuel saving and reduction of GHG emissions. The results of the study however indicate that the age of the vessels have minor impact on fuel use intensity and GHG emissions. The deciding factors are catch volumes, catch composition, quota possession, and stock status. When allocating fuel intensity and GHG emissions on eatable product or eatable protein, the utilisation ratio to human food becomes a key factor.

These results should not come as a total surprise, as they are in line with the results of Kristófersson et al. (2021) who studied the CO2 emissions of the entire Icelandic fleet during the period 1997-2018. They observed that emissions per unit of catch fell around 40% during the study period but concluded that overall catches and abundance were by far the most important factors determining emissions, the bigger the catches and the greater the abundance, the smaller the emissions per unit of output.

Although the results of the study do not indicate that fleet renewal on its own plays a significant role in fuel saving and reduction of GHG emissions, there are concreate examples from the study showing that optimisation made possible because of fleet renewal can lead to reduced fuel intensity. The example in question is where Breki VE (Trawler 8) replaced two older vessels Jón Vídalín VE and Gullberg VE (Trawlers 6 and 7) contributing to 36% reduction in fuel intensity.

The study also provides information on fuel intensity and GHG emissions of the Icelandic bottom trawler fleet that can be used for benchmarking against other seafood- and protein sources. The average GHG emissions amounted to 0,70 kg CO_2-eq/kg unprocessed catch of cod when applying mass allocation, as shown in Table 7. This is similar to the results of Ziegler et al. (2022), which showed average values of 0,68 kg CO_2-eq/kg catches of landed Norwegian cod. When allocating the GHG emissions on edible part of the cod the average values increase to 0,80 kg CO_2-eq/kg fish. When benchmarking with other protein sources, a common praxis is to use GHG emission per the available protein, as mass allocation can be deceiving when comparing with food that can have large mass but little nutritional value, or if only little part of the produced volume is used for human food. This is for example apparent when comparing the GHG emissions of the four species focused on in this study, where the redfish sticks out due to low utilisation ratio info human food, as shown in Figure 11.

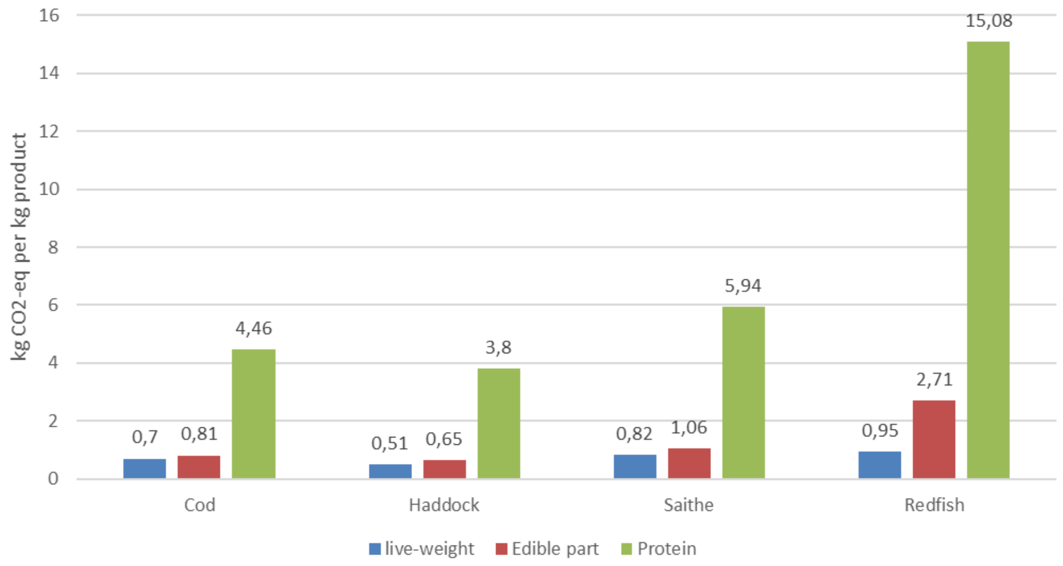

Figure 11: GHG emissions of the four species focused on in the study allocated to mass of live-weight, edible parts and edible protein

The approach of allocating the GHG emissions to total mass, edible products, edible protein or value of individual products can of course be debated. Focusing solely on production into human food does for example disregard that side streams can be utilised into products that are even be more valuable than the fillets, such as pharmaceuticals, cosmetics, food supplements, textiles etc. This is however a universally adopted approach with allows for benchmarking between protein sources and countries.

The average GHG emissions of the trawled Icelandic cod amounted to 4,5 kg CO_2-eq per kg protein of edible parts, which is low in comparison with most other protein sources. HGH emissions per protein units of various food items are shown in Figure 12, along with the results of this study, for comparison (United Nations, 2025) (Our World in Data, 2025) (Oceana, 2021).

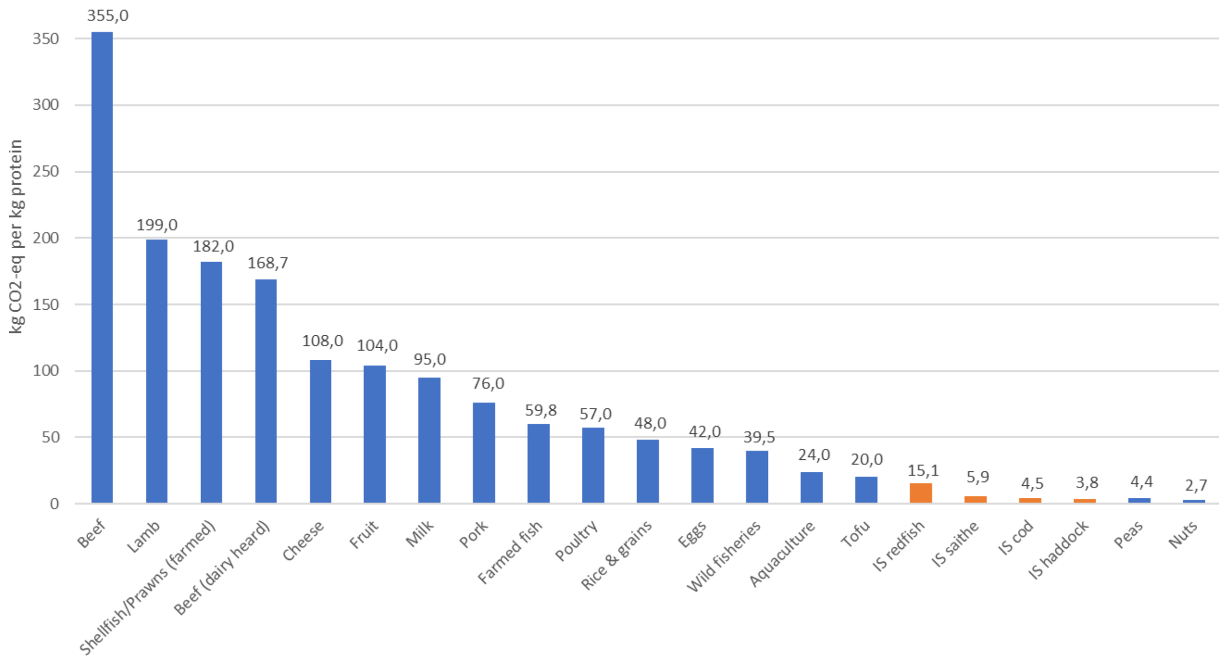

Figure 12: kg CO_2-eq per kg protein edible parts

The numbers only include the farming or harvesting/catching part of the production, but the part in between it reaches the plate of the consumer is missing, which can have significant impact on the GHG emissions. Smárason et al. (2014) showed for example that the catching phase represented 50% of the total GHG emissions of Icelandic trawl caught cod loins when reaching retail stores in mainland Europe when sea freighted and trucked to its destination, but only 20% when airfreighted. It is however apparent from the evidence presented in this report that Icelandic trawl caught seafood is low carbon protein when compared with other food protein sources.

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7 Appendices

Table X1: The environmental impacts of each trawler per one kg of unprocessed catch, as an average at years ranging from 2012-2022

Environmental impacts per kg unprocessed catch													
Impact category	**Unit**	**Total average**	**Trawler 1** 2012	**Trawler 2** 2020-2021	**Trawler 3** 2012-2017	**Trawler 4** 2018-2022	**Trawler 5** 2015-2022	**Trawler 6** 2014-2015	**Trawler 7** 2015-2016	**Trawler 8** 2020-2021	**Trawler 9** 2019-2020	**Trawler 10** 2018	**Trawler 11** 2020-2021
Abiotic depletion	kg Sb eq	1.3E-07	8.7E-08	9.2E-08	1.5E-07	1.3E-07	1.4E-07	2.3E-07	1.9E-07	1.2E-07	1.4E-07	8.9E-08	1.0E-07
Abiotic depletion (fossil fuels)	MJ	1.1E+01	6.9E+00	7.3E+00	1.2E+01	1.0E+01	1.1E+01	1.9E+01	1.5E+01	9.9E+00	1.1E+01	7.1E+00	8.2E+00
Global warming (GWP100a)	kg CO2 eq	7.8E-01	5.0E-01	5.3E-01	9.0E-01	7.5E-01	7.9E-01	1.4E+00	1.1E+00	7.2E-01	8.0E-01	5.1E-01	5.9E-01
Ozone layer depletion (ODP)	kg CFC-11 eq	1.4E-07	8.9E-08	9.4E-08	1.6E-07	1.3E-07	1.4E-07	2.4E-07	1.9E-07	1.3E-07	1.4E-07	9.0E-08	1.0E-07
Human toxicity	kg 1,4-DB eq	1.3E-01	8.2E-02	8.7E-02	1.5E-01	1.2E-01	1.3E-01	2.2E-01	1.8E-01	1.2E-01	1.3E-01	8.4E-02	9.7E-02
Fresh water aquatic ecotox.	kg 1,4-DB eq	1.9E-02	1.2E-02	1.3E-02	2.2E-02	1.8E-02	1.9E-02	3.3E-02	2.6E-02	1.8E-02	2.0E-02	1.3E-02	1.5E-02
Marine aquatic ecotoxicity	kg 1,4-DB eq	5.2E+01	3.4E+01	3.6E+01	6.0E+01	5.0E+01	5.3E+01	9.1E+01	7.2E+01	4.8E+01	5.4E+01	3.4E+01	4.0E+01
Terrestrial ecotoxicity	kg 1,4-DB eq	4.0E-04	2.6E-04	2.7E-04	4.6E-04	3.8E-04	4.0E-04	6.9E-04	5.5E-04	3.7E-04	4.1E-04	2.6E-04	3.0E-04
Photochemical oxidation	kg C2H4 eq	3.9E-04	2.5E-04	2.7E-04	4.5E-04	3.8E-04	4.0E-04	6.9E-04	5.4E-04	3.6E-04	4.1E-04	2.6E-04	3.0E-04
Acidification	kg SO2 eq	1.7E-02	1.1E-02	1.2E-02	2.0E-02	1.6E-02	1.7E-02	3.0E-02	2.4E-02	1.6E-02	1.8E-02	1.1E-02	1.3E-02
Eutrophication	kg PO4 eq	2.3E-03	1.5E-03	1.6E-03	2.7E-03	2.2E-03	2.3E-03	4.0E-03	3.2E-03	2.1E-03	2.4E-03	1.5E-03	1.8E-03

Table X2: The value (ISK/kg) of each part of the target fish species, used in economical allocation (scenario)

<table>
<tr><th>ISK/kg</th><th>Cod</th><th>Haddock</th><th>Saithe</th><th>Redfish</th></tr>
<tr><td>Fillet</td><td>1684</td><td>1809</td><td>1014</td><td>1246</td></tr>
<tr><td>Head</td><td>109</td><td rowspan="2">102</td><td rowspan="2">90</td><td rowspan="5">178</td></tr>
<tr><td>Backbone</td><td>71</td></tr>
<tr><td>Skin</td><td>135</td><td>130</td><td>130</td></tr>
<tr><td>Liver and roe</td><td>165</td><td rowspan="2">318</td><td rowspan="2">282</td></tr>
<tr><td>Cut-offs</td><td>450</td></tr>
</table>

Table X3: Base-case (a) and scenario (b) for the edible part of different fish species, as a percentage of the total catch during the reference period for different trawlers. Darker red colour indicates higher GHG emissions compared between the trawlers for the same fish species.

Base-case (mass allocation)

(a) **Edible part** **GHGs**	**Trawler 1** 2012	**Trawler 2** 2020-2021	**Trawler 3** 2012-2017	**Trawler 4** 2018-2022	**Trawler 5** 2015-2022	**Trawler 6** 2014-2015	**Trawler 7** 2015-2016	**Trawler 8** 2019-2020	**Trawler 9** 2020	**Trawler 10** 2018	**Trawler 11** 2020-2021
Cod	84%	73%	88%	80%	75%	19%	30%	50%	30%	37%	38%
Saithe	11%	15%	6%	8%	11%	7%	29%	17%	25%	16%	23%
Redfish	2%	6%	2%	5%	5%	71%	31%	18%	30%	7%	6%
Haddock	2%	7%	5%	7%	9%	3%	10%	15%	14%	39%	32%

Scenario (economical allocation)

(b) **Edible part** **GHGs**	**Trawler 1** 2012	**Trawler 2** 2020-2021	**Trawler 3** 2012-2017	**Trawler 4** 2018-2022	**Trawler 5** 2015-2022	**Trawler 6** 2014-2015	**Trawler 7** 2015-2016	**Trawler 8** 2019-2020	**Trawler 9** 2020	**Trawler 10** 2018	**Trawler 11** 2020-2021
Cod	87%	76%	89%	81%	77%	23%	35%	54%	27%	37%	39%
Saithe	8%	11%	4%	6%	8%	6%	24%	13%	20%	11%	17%
Redfish	2%	4%	2%	4%	4%	66%	27%	14%	20%	5%	5%
Haddock	3%	9%	5%	9%	11%	4%	14%	19%	32%	46%	39%

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