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A study of energy use and associated greenhouse gas emissions in Norwegian small-scale processing of whitefish

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ABSTRACT

This study considers the energy use and associated greenhouse gas (GHG) emissions at three fish processing companies, representing a seasonal small-scale whitefish processing industry within the Norwegian coastal fisheries. The primary objective is to analyse the energy use in small-scale processing of whitefish and to provide energy requirements for primary processing, freezer and freezer storage, and drying. The study also discusses the environmental importance of the fish processing stages as compared to fishing vessels in seafood value chains. The results show that initial processing and cold storage has an average energy use of 132 kWh/ton of raw material. Freezing and freezer storage and drying have energy consumptions of 449 and 203 kWh/ton, respectively. Energy use per unit of volume decreases as the amount of raw material increases. This study finds that small-scale whitefish processing may account for a significant share of the total energy consumption and associated GHG emissions from fishing vessels and processing stages. The energy related GHG emissions are highly dependent upon the electricity mix and energy sources in general. The representativeness of the results is limited given that the three companies considered in this case study operate under very specific conditions, i.e., they are small-scale actors operating within a seasonal and geographically limited coastal fishery. Future research could utilize data from a larger number of facilities and do long-term statistical analysis of energy use in different fish processing stages. The use of advanced metering systems has proven suitable for such purposes, and could be supplemented by installation of permanent monitoring equipment such as “panel servers” to record energy use for specific processes within whitefish processing.

1. Introduction

The Norwegian fishing fleet generated approximately 863.000 ton of greenhouse gas (GHG) emissions in 2020 (Statistics Norway, 2022a). The fishing stage is usually regarded as the main contributor to environmental impacts in seafood value chains (Ellingsen and Aanondsen, 2006; Ziegler et al., 2003), but stages after landing are also important (Muir, 2015; Thrane et al., 2009b). Norwegian electric energy production is powered by 98% renewables (Statistics Norway, 2022b), and the electricity-driven processing stages are therefore often assumed to have relatively low environmental impact. However, interconnection of Norwegian and European power systems implies that the electric energy consumption in Norway is not as "green" as the national energy production would suggest. Electricity disclosures from the Norwegian Water Resources and Energy Directorate (NVE) show that only 24% of the electricity consumption in Norway can claim the carbon footprint of renewable Norwegian electricity through guarantees of origin, while the remaining 76% must accept a carbon footprint at the European level (NVE, 2021). The energy use for Norwegian land-based fish processing may therefore be more significant in terms of GHG emissions than one would expect. The global reduction of GHG emissions is outlined by The Paris Agreement on climate change, where Norway has committed itself to a 50% reduction in emissions relative to emission levels in 1990 by 2050 (United Nations, 2021).

2. Previous estimates of energy use in fish processing

While previous research and life cycle assessments (LCA) suggest that the fishing stage represents the greatest share of energy consumption and emissions throughout the value chain of fish products (Ellingsen and Aanondsen, 2006; Thrane, 2004; Ziegler et al., 2003), subsequent processing stages at land-based facilities are also given

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attention in literature. Thrane et al. (2009) argues that life cycle stages after landing have significant environmental impacts and Muir (2015) notes that energy consumption in post-harvest processes have gained increased interest with respect to LCAs and environmental footprints of seafood products. Furthermore, while Thrane et al. (2009a) documents environmental improvements through implementation of cleaner production solutions in Danish fish processing, the authors argue that more focus is needed on reduction of energy consumption.

Table 1 summarizes published specific energy consumption of land-based fish processing. The data shows variations in energy use, depending on the type of fish and degree of processing. COWI Consulting Engineers and Planners AS (1999) report energy use during whitefish filleting of 65–87 kWh/ton liveweight (LW) divided on ice (10–12 kWh/ton), freezing (50–70 kWh/ton), and filleting (5 kWh/ton). The study however state that these estimates can vary considerably between processing plants, due to processing variations due to fish species, the equipment used, the extent of processing, and the attention given to optimising resource consumption. Data for Norwegian processing plants shows higher energy use of 283–363 kWh/ton LW (Schau et al., 2009; Winther et al., 2020), representing the processing plants' total energy use. According to Muir (2015), the energy requirement for fish processing is influenced by several factors, including "the level of technical input, age and scale of a plant, the level of automation and the range of products being produced". Any cold storage, freezing and processing performed by fishing vessels prior to landing will also affect the degree of processing at land-based facilities. Literature also reports fuel consumption within fish processing industry, for instance 0.13 litre per ton LW reported by Winther et al. (2020) and 16.8 litre per ton by Ziegler (2002). The reported fuel use by Ziegler (2002) is much higher and is likely used for sustaining other major consumers in addition to processing.

Determining the energy consumption in the different stages of fish processing would be an important step in identifying opportunities for energy savings and reduction of GHG emissions. Ziegler et al. (2021) recognize that post-harvest emissions can be considerable and highlights the challenge of obtaining representative post-harvest data. Thus, documentation of specific energy use in different fish processing stages could provide valuable input to life cycle inventory data of seafood products. Existing estimates of energy use for land-based fish processing is scarce and mainly found in grey literature (Table 1).

Table 1
Specific energy use for fish processing found in literature.

Species	Processing stage	Energy use	Comment	Reference
Whitefish, demersal	Processing & cold storage/ freezing	363 kWh/ ton LW		(Winther et al., 2020)
Whitefish, demersal	Drying of saltfish to klipfish	250 kWh/ ton klipfish		(Winther et al., 2020)
Whitefish, demersal	Not defined	283 kWh/ ton LW		(Schau et al., 2009)
Whitefish	Freezing	80–150 kWh/ton	Theoretical values	(Larssen et al., 2022)
Whitefish	Filleting, ice production, and freezing	65–87 kWh/ton LW	Using average technology.	(COWI Consulting Engineers and Planners AS, 1999)
Whitefish, demersal	Processing and freezing	369 kWh/ ton gutted weight		(Ziegler, 2002)
Pelagic, herring and mackerel	Freezing	216 kWh/ ton LW		(Winther et al., 2020)
Salmon	Processing	107 kWh/ ton LW		(Winther et al., 2020)
Salmon	Processing	140 kWh/ ton LW	Per ton starved and bled salmon.	(Johansen et al., 2022)
Salmon	Processing	71, 86, and 88 kWh/ton LW	Converted to LW with conversion factor of 1.20	(Ates et al., 2017)
Salmon	Freezing	200 kWh/ ton		(Johansen et al., 2022)

3. Study setting and background

The Norwegian capture fisheries fleet consists of a deep-sea fleet of approximately 140 vessels, with length greater than 28 m, and a coastal fleet of about 2200 smaller vessel (Riksrevisjonen, 2020). While the deep-sea fleet delivers catch at a limited number of large-scale processing and freezer plants, the coastal fleet delivers to a large number of smaller processing plants distributed along the coast in areas of seasonal fisheries (Aarsæther et al., 2015). The winter fisheries that target migrating cod in the northern part of Norway, primarily associated with the Lofoten islands, supports the coastal fleet and smaller processing plants distributed along the coastline. Fig. 1 is a map of the location of all sixty processing plants in the study area. The three included in this study are highlighted. The distribution of processing plants supports the coastal fleet during the seasonal fisheries for cod that varies in location both within the season and yearly. The coastal fleet of smaller (<28 m) vessels in the north of Norway primarily targets codfish (Cod, Pollock, and Haddock), particularly the fleet with vessels of total length 15 m or less and with limited range and storage capacity compared to the deep-sea fleet.

The processing plants that serve the seasonal codfish fisheries produce products for immediate export out of the region or produce salted fish and stockfish. The seasonal fisheries carried out by the coastal fleet of smaller vessels delivered 71% of all codfish in 2020 in the municipalities shown in Fig. 1 (Norwegian Directorate of Fisheries, 2022). The catch delivered daily by vessels less than 28 m length to the processing plants in the same municipalities is shown in Fig. 2a. Both codfish and "non-codfish" exhibit a strong seasonal variation. The traditional winter fishery for codfish is possible due to the influx of Barents Sea cod that migrate south along the coast to spawning areas around the Lofoten islands. The migration increases the abundance of codfish in the area and the coastal fleet plans the operations around these rich fisheries, often moving with the cod migration. The seasonal fisheries start in January and end in April. Only small amounts of codfish are caught outside of this seasonal fishery and catches outside of the cod season consist to a large extent of pelagic species. The dependence of these processing plants on codfish is seen in Fig. 2b where most plants process codfish almost exclusively.

The catches of non-codfish are concentrated at a limited number of processing plants, which are typically processing plants of pelagic species. The smaller processing plants are an integral part of the seasonal fisheries for codfish, and they distribute the catch of the coastal fleet into value chains directed at secondary processing or consumers with different energy intensities. The influx of cod migrates south and spawn around the Lofoten islands, where the geographic distribution of the smaller processing plants allows the coastal fleet to follow the resources and adapt to smaller variations in the migration pattern, such as cod spawning to the north or to the south of the islands. The seasonal variation in resources implies a seasonal variation in processing activity and energy use, leading to large seasonal variation in electric power demands during the year. The processing plants still maintain operations for small catches and must power and operate the buildings during the off-season. This variation in electric demand requires electric grid infrastructure to accommodate the peak loads.

This study's primary objective is to analyse energy use in small-scale processing of whitefish in Norwegian coastal fisheries and to provide energy requirements for primary processing, freezer and freezer storage,

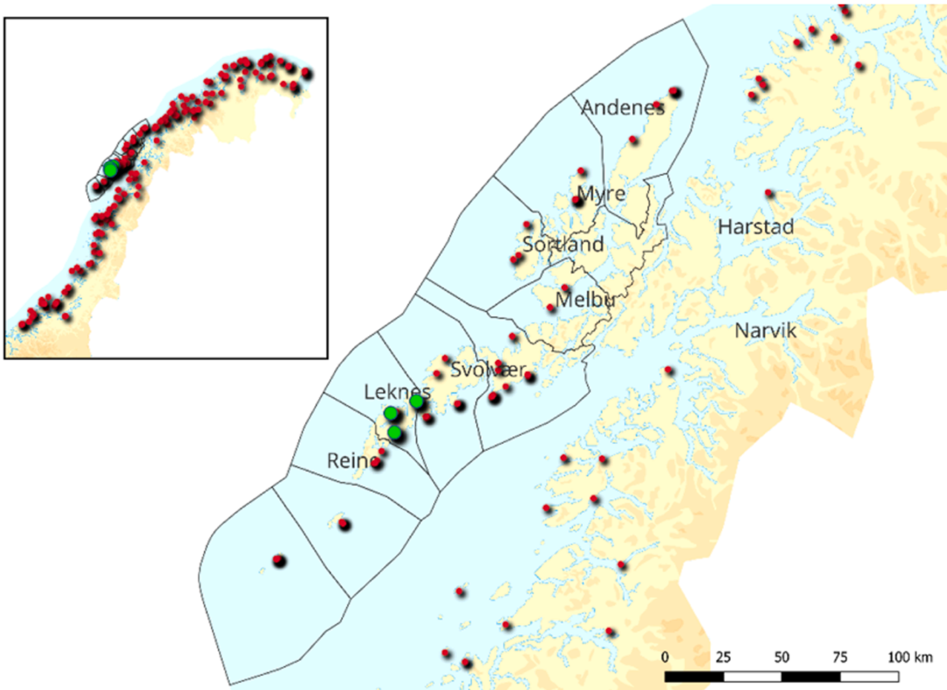
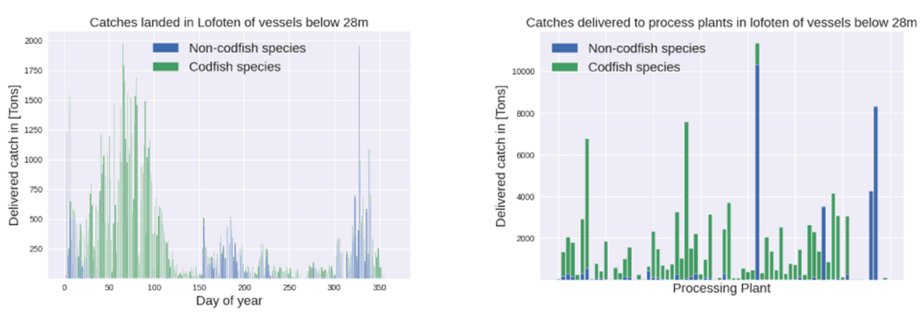


Fig. 1. Distribution of processing plants in Northern Norway as red dots. The black lines indicate municipalities where catches from the fisheries of migrating cod are delivered to processing plants. The processing plants included in this study is shown in green colour, while red shows all registered processing plants.



a) Seasonal distribution of codfish and non-codfish in 2020. The codfish fishery during the winter months is clearly visible with the majority of the catches landed during a 90-day period.

b) Distribution of codfish and non-codfish catches among the different processing plants. The importance of the seasonal codfish fisheries for the smaller plants is evident.

Fig. 2. Distribution of codfish and non-codfish catches during the year 2020 among the processing plants in the municipalities shown in Fig. 1.

and drying. We present a case study of three small-scale fish processing companies, deriving specific energy requirements for different processing stages and three common seafood products. The study discusses the environmental importance of the fish processing stages as compared to fishing vessels in seafood value chains.

4. Data and methods

A typical Norwegian fish processing plant is located adjacent to the large seasonal fisheries, close to sea for receiving products directly from vessels. Fish processing stages on shore typically include initial delivery, separation of species, gutting, separation of product and by-products, and size- and quality grading. The fish is transferred by hydraulic cranes from vessels to the processing plant quay, after which the fish is either hoisted into the processing plant by hydraulic lifts or moved by use of forklifts. Fish processing makes use of seawater that is pumped from the sea and sterilized before usage. A processing plant typically consists of conveyor belts, splitting machine, graders, and cold storage. Ice for cooling of products may be produced on site or imported to the plant. Movement of product and equipment within the processing plants is done by forklifts. Depending on the value chain, the product is then shipped from the plant for secondary processing, further processed into cut products like fillet, dried for stockfish, or frozen for storage and transport.

This study analyses the energy use of three smaller fish processing companies that support the seasonal fisheries in the Lofoten islands. The three companies, which we refer to as Company A, Company B, and Company C, have similar initial processing steps but differ in the subsequent product value chains. All three plants produce fresh and chilled product (Companies A, B, and C) and the Company A's plant also produces frozen product and dried stockfish.

The physical layouts of the processing plants differ, but all plants have similar functions along similar processing lines. The processing plant line receives product from the quay before it is lifted into the production facility with a bulk lifter. Immediately after the fish has entered the processing plant, the species of fish is recorded, and the product is weighed for statistics and quota purposes. This information is sent to the Norwegian Directorate of Fisheries. Company A's plant has additional activity with freezer storage and stockfish production. The freezing and dried stockfish production facilities are situated in separate buildings with separate electric grid connections, which makes it possible to track the energy usage of these production stages.

A diagram of the layout of the processing lines and a picture of the processing line from one of the processing plants is shown in Fig. 3. The processing equipment, quay hydraulics and forklifts used electric power delivered by the grid. The three processing plants had their processing lines for receiving catches on a single electric supply together with hydraulic motors and forklift chargers. At the end of the processing line the product is either immediately exported as chilled or salted product, prepared for stockfish production or frozen.

4.1. Data

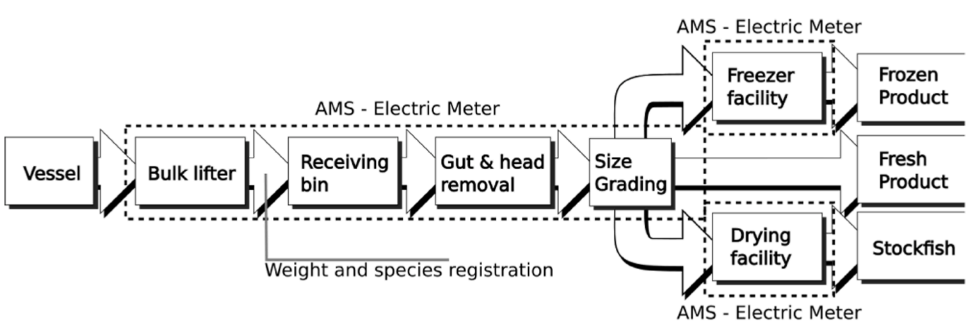
The data collection was carried out during 2020–2021 as part of a project on energy use and GHG emissions in Norwegian coastal fisheries (Høyli and Aarsæther, 2022), supplemented by minor additional data collection.

Data from the three fish processing companies were collected for the period 2019–2020. Energy and raw material data is collected for three processing plants producing fresh and chilled products (Companies A, B, and C), one freezing and freezer storage facility (Company A) and one drying facility for stockfish production (Company A). The main data sources are shown in Table 2 and consist of publicly available *contracts of sales*, advanced metering system (AMS), and semi-structured interviews. The fish processing companies were selected because they are representative for the small-scale processing of whitefish within the seasonal Norwegian coastal fisheries. Further, the three companies are situated in geographical proximity of each other, in an area known for its rich seasonal fisheries.

The contracts of sales are collected from the Norwegian Directorate of Fisheries and provide information on landed catch, such as delivery date, type and amounts of fish (Norwegian Directorate of Fisheries, 2022). Electrical energy data were accessed through the companies' AMS meters, which automatically register electricity consumption providing accurate consumption data hour by hour. Hourly information on electrical energy consumption were collected from each processing facilities' AMS meters. The semi-structured interviews provided a detailed value chain description, including fossil energy use, product matrixes, and information on additional raw materials purchase from other fish processing companies. Site surveys were conducted at the processing facilities to determine the layout of the electrical systems. The energy supply to the quayside facilities (cranes, loaders), cold storage and ice production, and processing machines were identified as

Table 2
Summary of data sources.

Data source	Description	Company A	Company B	Company C
Contracts of sales from the Norwegian Directorate of Fisheries	Amount and type of raw materials bought from fishing vessels by the companies	x	x	x
AMS energy infrastructure	Electrical energy use at processing plant	x	x	x
	Electrical energy use at freezer and freezer storage	x		
	Electrical energy use at drying facility	x		
Semi-structured interviews	Value chain description, fossil energy use, product matrixes, and purchase of raw materials from other companies	x		



a) Schematic overview of the processing line and subsequent product stages. The processing facilities for Companies B and C, which produce only fresh and chilled products, are covered by single electric meters. The processing line for Company A, which also produces other products, was on a separate sub-meter.

b) Picture showing a processing plant with a single production line. The fish arrive in the plant from bulk loaders at the left-hand side, has the head removed, is gutted, and finally graded into sizes at the right-hand side

Fig. 3. Picture showing the processing line used for whitefish processing at a smaller processing plant.

powered by the mains electrical supply. The electric energy supply to the distinct functions of processing (fresh and chilled product), freezing, and stockfish production could be isolated to specific AMS meters within Company A.

4.2. Analysis methods

The data analysis includes assessment of energy use at different processing stages and assessment of energy use and associated GHG emissions for production of common seafood products. The results shown in this paper are average values based on annual data for 2019 and 2020.

The energy use at the three processing plants was assessed by combining the respective plants' annual energy consumption with the amount of raw material bought from fishing vessels in the same period. Purchase of additional raw materials from other companies was considered when such information was available. These results are presented in terms of specific energy use (kWh) per ton of raw material and are a measure of the energy-efficiency of the processing plants.

Specific energy consumption is estimated for fresh fish, frozen fish, and stockfish products. All products go through primary processing at processing plants (Company A, B, and C), while the frozen fish and stockfish products are subjected to further treatment at the freezer facility and drying facility (Company A only). The estimation of specific energy consumption for seafood products is based on the measured energy use at processing plants ($n = 3$), freezer and freezer storage ($n = 1$) and drying ($n = 1$). These results are presented in terms of specific energy use (kWh) per ton of product (gutted weight).

The material flows through processing plant, freezer facility and stockfish production were established based on raw material data and product matrixes received from Company A. By-product generation from the processing plant were calculated based on the share of raw materials received whole and species-specific conversion factors (Table 4). It was estimated by Company A that ten percent of their generated by-products were processed into frozen by-products, the exception being by-products from Greenland halibut where no by-products are frozen. Further, it was assumed that five percent of by-products (from all species) were of no economic value, thus are not allocated input or impacts. The specific energy consumption was calculated based on the respective facilities' electrical energy consumption and the amount of material being processed at each facility. Energy use from fuel consumption related to internal transports was estimated based on an energy content of 10 kWh/l diesel.

Calculation of GHG emissions from fuel consumption considered an emission factor of 3,32 kg CO_2 per litre diesel, including GHG emissions from production and combustion (Ecoinvent, 2014). Calculation of GHG emissions from electrical energy usage considered Norwegian electricity mix with (20 gCO_2eq/kWh) and without (402 gCO_2eq/kWh) guarantees of origin (NVE, 2021). Further, as 24% of electricity purchase in Norway was bought with guarantees of origin (NVE, 2021), a *realistic* emission factor of 310 gCO_2eq/kWh is considered.

In cases where the processing facilities produce more than one product, mass allocation was used to allocate inputs and impacts. Mass allocation is the recommended allocation method according to *Carbon footprint for seafood: Product category rules* (CFP-PCR) (Norwegian Standard, 2013). An advantage over economic allocation is that mass allocation is not influenced by volatile economic values and thus allows for temporal comparison.

Specific energy use is very similar between species. Results are therefore presented at an aggregated product level, not by species. The small differences can be explained by similar conversion-factors across species, the assumption that all species generate the same amount of non-economical by-products, and the choice of mass allocation.

Table 3
Energy requirements at different fish processing steps. Data from n number of companies given in parenthesis.

Processing facility (n)	Description	Energy use [kWh/ton]	
		Mean	Min-max
Processing plant (n = 3, Companies A, B, and C)	Processing and cold storage	132	93–212
Freezer facility (n = 1, Company A)	Freezing and freezer storage	449	391–508
Drying facility (n = 1, Company A)	Indoor drying of stockfish	203	194–212

Table 4
Approximate product matrix and other species-specific information for Company A.

Fish species	Average product matrix	By-products for freezing	Sold as (conversion factor)
Cod	70% stockfish30% frozen fish	10%	Headed and gutted (1.5)
Pollock	50% stockfish50% fresh fish	10%	Headed and gutted (1.35)
Greenland halibut	100% frozen fish	0%	Whole, gutted (1.1)
Other species	100% fresh fish	10%	Headed and gutted (1.35)

4.3. System boundary and limitations

The boundary of the environmental impact considerations in this study is limited to the direct energy use in the different stages of fish processing, including processing and cold storage, freezing and freezer storage, internal transports and drying of stockfish. The study considers only energy-related GHG-emissions within the system boundary, meaning that any GHG emissions from e.g., refrigerants, infrastructure, or other potential direct or indirect GHG emission sources is outside the scope of the study. Further, it is assumed that all frozen products are stored an equal amount of time in storage.

5. Results

The results of the energy analysis are presented based on processing stages from receiving, processing, freezing or stockfish production. Production volumes were collected for all companies from contracts of sales that document the raw material input to each company. Two of the companies process the raw materials for fresh fish production (Company B and C), and the third combine production of fresh fish with stockfish production and frozen products (Company A).

5.1. Energy use in fish processing

Fig. 4 shows the seasonal energy use and received catches at the three processing plants. The seasonality of Norwegian coastal fisheries is evident through periodic peaks of higher production and energy use.

Fig. 5 shows how the specific energy consumption at processing plants varies with the amount of raw material being processed. Energy use per unit of volume decreases sharply as volume increases. The three processing plants have an average specific energy use of 132 kWh/ton LW.

Fig. 6a shows the seasonal energy use for processing plant, freezer and freezer storage, and stockfish drying (Company A). The winter fisheries are the main production period of the year, typically taking place from around March to mid-April. In this period, high energy peaks are visible at both the processing plant and freezer facility. There is no activity at the drying facility, but a significant share of the fish being processed in this period will later be sent for stockfish production. From May to June there is no production and only the energy baseload requirements are sustained. From June to July, the first of two Greenland

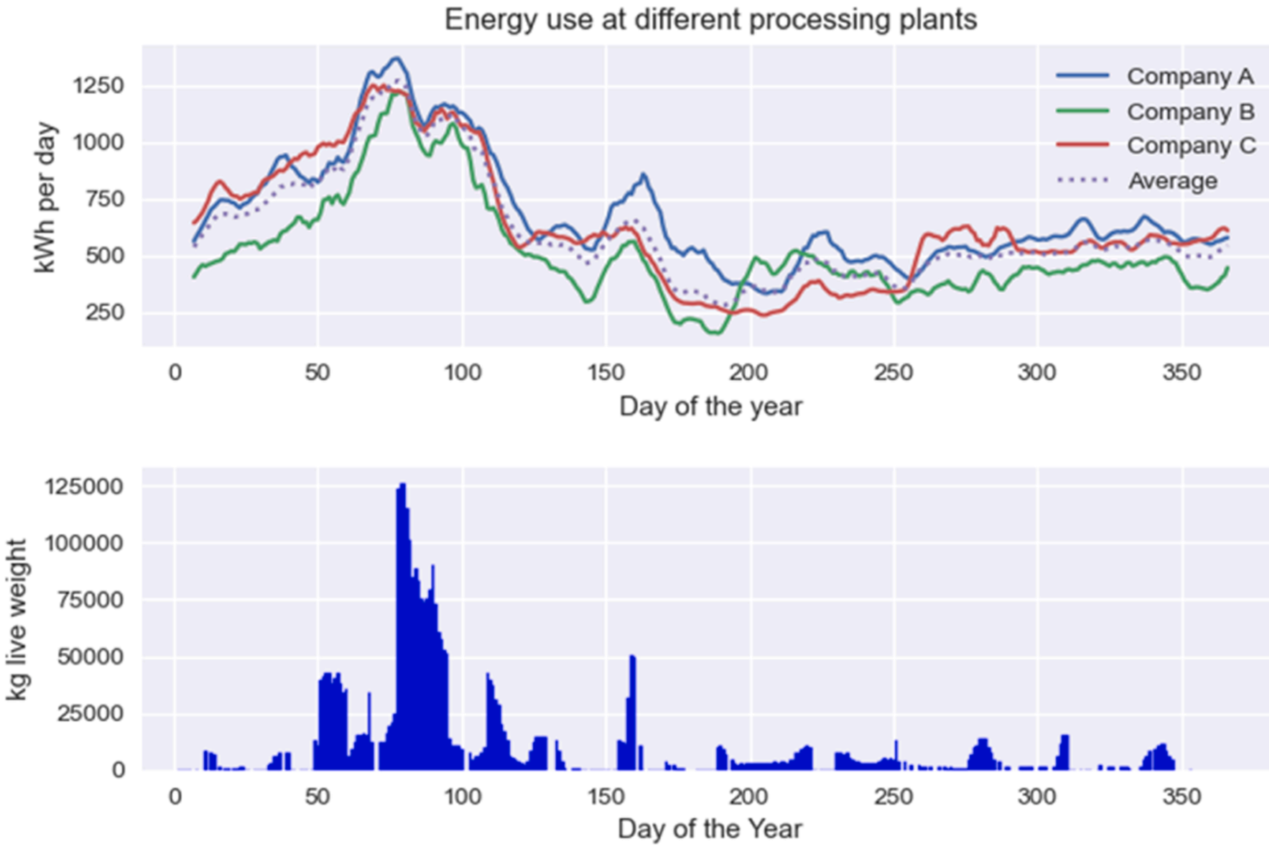


Fig. 4. Seasonal energy use and total weight of received catches for the three different processing plants on each day of the year.

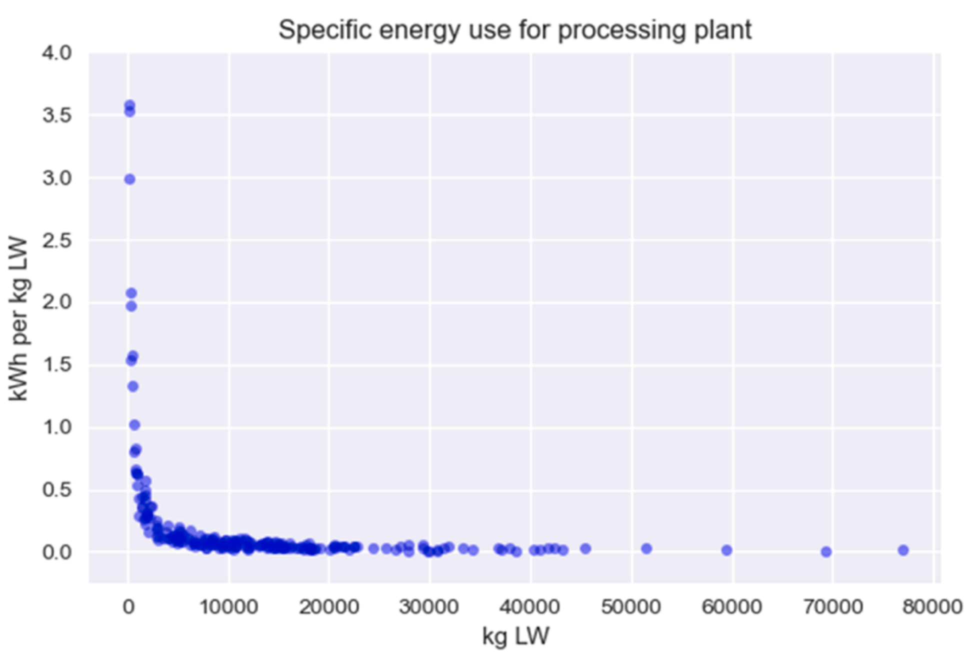
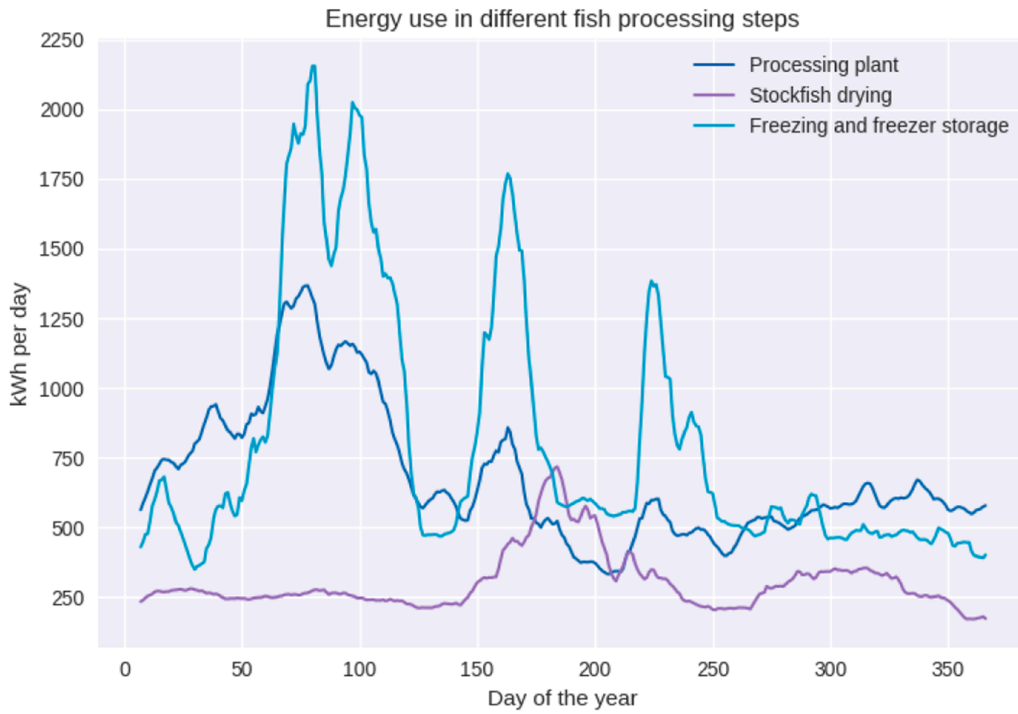


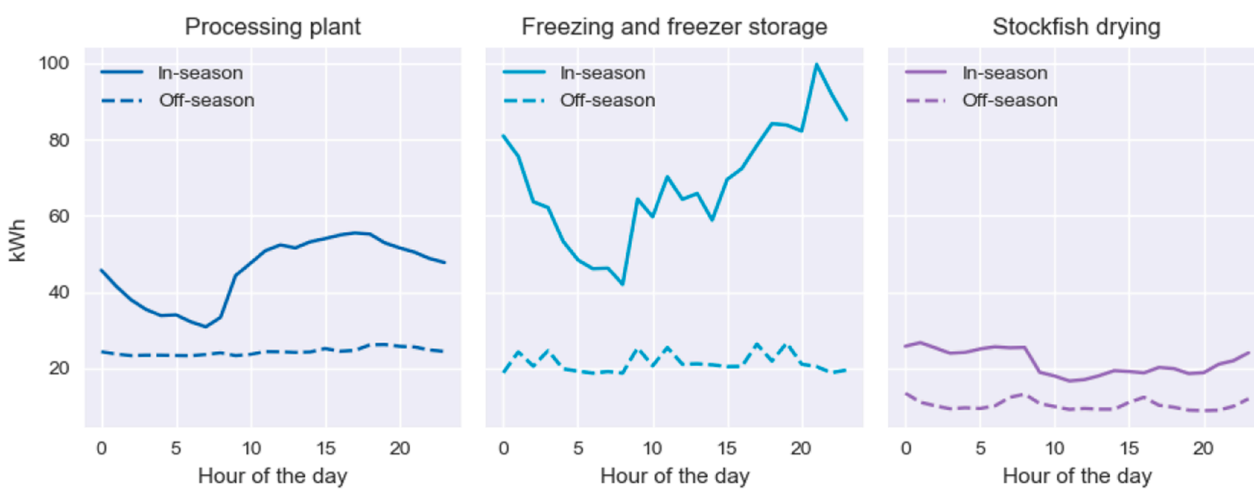
Fig. 5. Specific energy consumption at three processing plants. Each circle represents a daily average based on weekly averaged data.

halibut fisheries takes place resulting in higher energy usage for processing and freezing. In addition, the pre-dried stockfish are now ready for indoor drying. In August, the energy peaks are mainly due to the second season of Greenland halibut fisheries. No production takes places from mid-September until the pollock fishery picks up in January/ February.

Fig. 6b illustrates average hourly energy profiles of Company A, where solid and dotted lines represent high and low season, respectively. The in- and off-season periods were defined based on periods of high and low production in the data material. The processing plant and freezer profiles show clear operational patterns during high season, compared to stockfish drying which has more stable energy consumption



a) Daily energy use for processing plant, freezer and freezer storage and stockfish drying. The different facilities are supplied by different connections to the electric grid and measured separately.



b) In- and off-season energy profiles of processing plant, freezer and freezer storage and stockfish drying.

Fig. 6. Yearly energy profile, and daily energy profile in and out of production season, for Company A.

throughout the day. The off-season energy profiles are stable, indicating the energy baseload requirement the facilities must sustain regardless of how much fish is produced. The energy use during periods of no production is similar for processing plant and freezer (20–25 kW, or 500–600 kWh/day), while the stockfish drying facility require roughly half of the amount.

Table 3 presents energy requirements for different fish processing steps. The energy requirements are calculated based on the total amount of raw materials having undergone treatment at the respective facilities, and includes all by-products generated during treatment at the processing plants. The mean and min-max intervals are given across companies and calendar year.

5.2. *Energy use and GHG emissions for seafood products*

This section presents energy use and energy related GHG emissions for three seafood products, namely fresh fish, frozen fish, and stockfish. The calculations are based on the value chain of Company A involving three distinct processing facilities of processing plant, freezer facility and drying facility (see Fig. 7). The calculation of energy use at processing plant is, however, based on average data from all three companies (A, B, and C) for greater representativity. Due to the assumption that five percent of by-products are of no economic value and are not allocated input or impacts, the energy use at processing plant presented in this section will differ slightly from the energy requirements presented in Table 3.

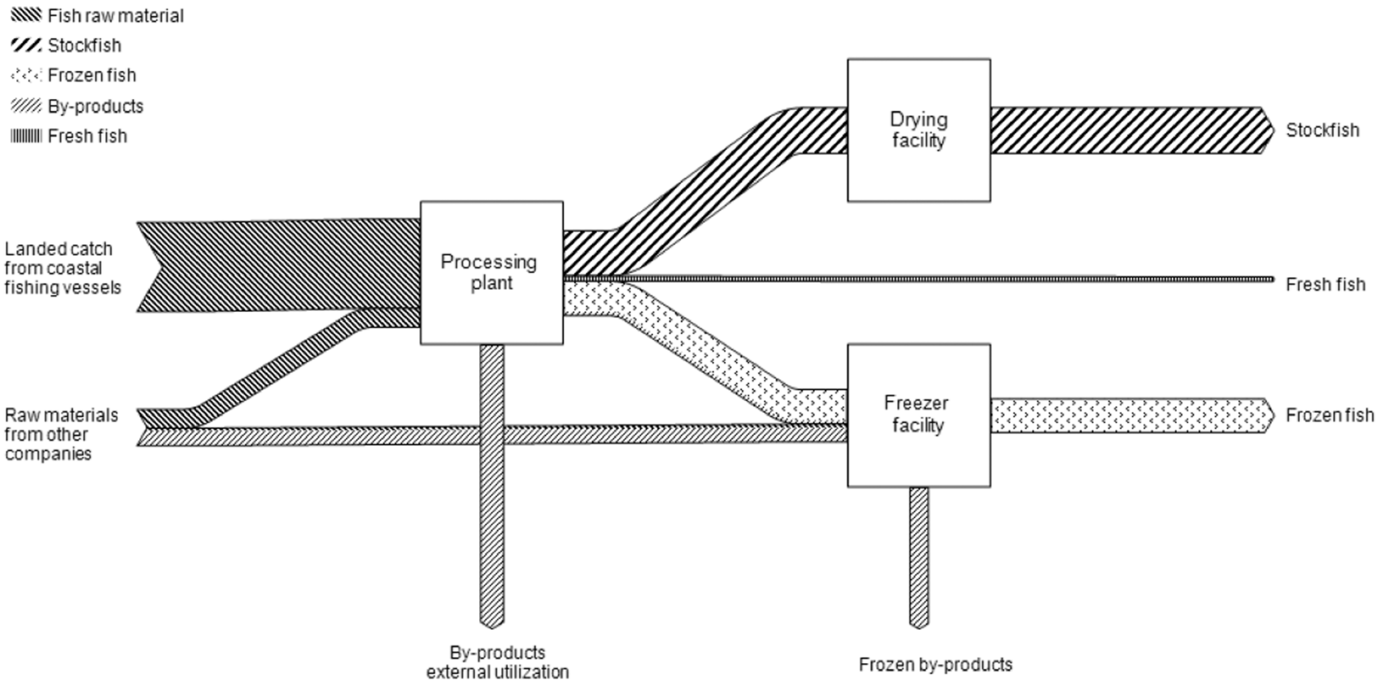


Fig. 7. Value chain flow chart, indicating the relative mass distribution of raw materials and products by thickness of material flows.

The companies' main source of raw materials is landed catch from fishing vessels, but Company A also processes raw materials (fish and by-products) bought from other fish processing companies in the region. All by-products bought by Company A from other companies are sent directly to the freezer facility. The share of by-products for freezing specified in Table 4 applies for the raw material being treated at Company A's processing plant. The remaining share of by-products from Company A is sent for *'external utilisation'*, which involves different forms of processing done by external actors.

The energy supply for all facilities is electrical energy from the electricity grid. In addition, diesel loaders are used for transport of stockfish to and from fish flakes to drying. The processing plant performs preliminary processing including gutting, beheading, and sorting of by-products. The main energy consumers are gutting lines, bulks, cold storage, ice machine, and seawater pumps. The cold storage is small and stores unprocessed raw material to the next day. The ice machine is mainly used for internal purposes, producing ice for fish in cold storage. The freezer facility's main energy consumer is the refrigeration system, which supports the freezing process and storage. Both the processing plant and freezer facility have electrical forklift chargers. The drying facility's main energy consumers are ten large drying fans, as well as a heater fan for workers.

Fig. 8 illustrates the estimated specific energy use for seafood products. The variability seen in energy requirements for different processing stages (Table 3) is transferred onto the estimated energy consumption for fresh fish (94–215 kWh/ton), frozen fish (484–722 kWh/ton) and stockfish (320–460 kWh/ton). Fig. 8 also shows the estimated energy related GHG emissions of fresh fish (41 kgCO_2eq/ton), frozen fish (181 kgCO_2eq/ton) and stockfish (115 kgCO_2eq/ton). The GHG emissions estimations considered an emission factor of 310 gCO_2eq/kWh, which was calculated based on the proportions of Norwegian electricity bought with and without guarantees of origin (NVE, 2021). Because electricity is the main energy source for all seafood products, the choice of electricity mix has significant effect on the estimated GHG emissions.

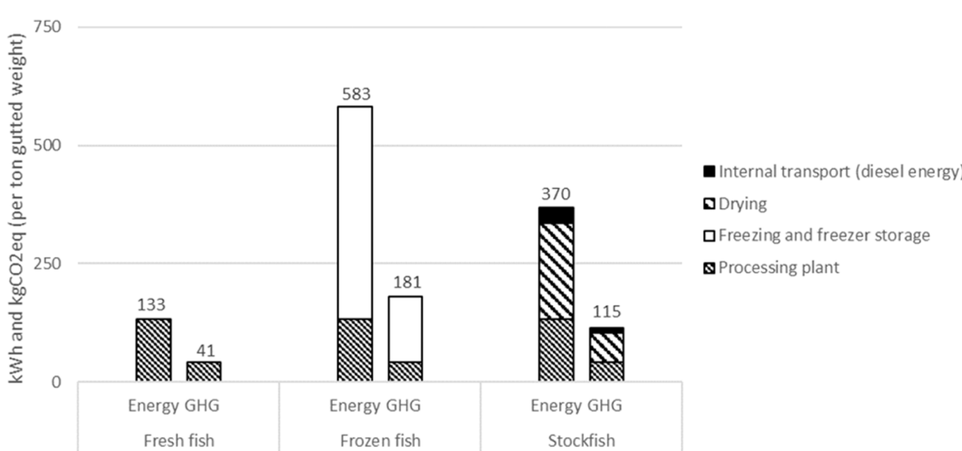


Fig. 8. Specific energy use and associated GHG emissions for production of fresh fish, frozen fish, and stockfish.

6. Discussion

6.1. Energy use and seasonality of small-scale fish processing

The energy requirements for small-scale fish processing documented in this study are higher than, but still comparable to, the energy data found in literature. Literature data ranges from 65 to 369 kWh/ton, depending on the type of species and degree of processing (Table 1). The results from the current study show average energy use for processing and cold storage (132 kWh/ton), freezer and freezer storage (449 kWh/ton), and stockfish drying (203 kWh/ton) (Table 3). In general, the higher energy results in this study compared to literature data may be influenced by the processing companies being small-scale actors subjected to seasonal operation.

The result for freezer and freezer storage (449 kWh/ton) is higher than all estimates found in the literature, even those covering several processing stages. Johansen et al. (2022) report 200 kWh/ton for freezing of salmon products, while processing and freezing of whitefish range from 363 to 369 kWh/ton (Winther et al., 2020; Ziegler, 2002). Winther et al. (2020) do not distinguish between fresh and frozen fish based on the assumption that the freezing process represents a negligible part of the total energy use. Instead, the authors regard cold storage as the main energy consumer and assume that the energy use is similar for cold- and frozen storage. This study shows higher energy use for frozen fish than fresh fish, but these results may not be comparable to Winther et al. (2020) as the cold storage is only used to store unprocessed raw material to the next day, while the freezer storage is always operational, storing significant amounts of frozen products over longer periods.

The energy use for stockfish drying (203 kWh/ton) is lower than the reported energy use for drying of saltfish to klipfish of 250 kWh/ton (Winther et al., 2020). While not representing identical products, they still share some production methods, and both require removal of moisture from the product by drying.

The result for processing and cold storage (132 kWh/ton) is higher, but still comparable to, the energy use for fresh salmon processing (71, 86, and 88 kWh/ton (Ates et al., 2017); 107 kWh/ton (Winther et al., 2020); 140 kWh/ton (Johansen et al., 2022)). Fresh fish and salmon represent relatively similar value chains, e.g., processing, cooling, and ice production, with no freezing of products. However, one could expect lower specific energy consumption within salmon processing as the salmon industry has stable operations throughout the year compared to whitefish processing.

Our results show a high degree of variability in the observed energy per unit of output. The variability in energy use for freezer and freezer storage (391–508 kWh/ton) is due to year-to-year differences in the operation of the freezing process at Company A. Company A states that "initiating one or two plate freezers will draw approximately the same amount of energy, and similarly for processing of 5 or 10 tons in the tunnel freezer. In addition, the freezer storage fans were run continuously from 2020 to avoid ice accretion on fan blades, resulting in increased operation time compared to 2019. The variation in energy use for processing and cold storage (93–212 kWh/ton) is due to differences between companies, rather than between years, where Company A has considerable higher energy use compared to Company B and C. This may be influenced by the degree of processing, by-product utilization, and building baseload energy requirement. Further, raw materials may be sold between fish processing companies, and such transactions are not covered by contracts of sales from the Directorate of Fisheries. For cases where such information is lacking, the specific energy use will potentially be underestimated for processing plants that resell raw materials, and vice versa overestimated for processing plants that buy raw materials from other companies. The extent of over- and underestimation will depend upon to what degree the raw material is processed before and after sale. In general, many factors will influence the energy use in fish processing and detailed knowledge of the specific processes is necessary to establish a holistic understanding of the cause and effect in each case.

The energy efficiency of processing plants increases with the amount of raw material being processed. Similar relationships between specific energy consumption and production volume are observed across the three processing plants (Fig. 5), which can indicate the minimum tonnage needed for optimal operation in terms of energy efficiency. The "energy-efficiency curve" may be explained by the baseload energy that the processing plants must sustain regardless of how much tonnage is processed. While some energy reduction can be expected from reduced tonnage (e.g., less operational time of equipment), the processing operation is still dependent upon machinery (e.g., seawater pumps) that will require roughly the same energy whether the processing line handles 5 or 30 tons.

6.2. The importance of energy use and GHG emissions from fish processing in seafood value chains

Table 5 shows the calculated distribution of impacts between direct energy use in land-based processing and fuel use on fishing vessels. The comparison is based on reported fuel use coefficients in the literature (Jafarzadeh et al., 2016), where vessels under 28 m burn diesel fuel corresponding to 1550 kWh/ton fish (average of 0.108 and 0.156 kg fuel/ kg fish). Combining the energy use estimate for fuel use on fishing vessels with the results on energy use for fish processing derived in the current paper shows that fishing vessel operations account for 92% of total energy use in fresh fish value chains, 81% of total energy use in stockfish value chains, and 71% of total energy use in frozen fish value chains. While this study does not consider the whole life cycle, these numbers are still comparable with Ziegler (2002) reporting that fishing vessels are responsible for 72% of life cycle energy use of frozen cod products.

The direct energy use in land-based fish processing may generate considerable GHG emissions, even when compared to fuel use on fishing vessels. For instance, processing of frozen fish is estimated to represent 26% of total GHG emissions from fishing vessels and processing stages given an electricity mix with emission factor of 310 gCO_2eq/kWh. If instead Norwegian electricity mix with guarantees of origin is considered (20 gCO_2eq/kWh), the share of GHG emissions during production of frozen fish is reduced to 3%.

The choice of electricity mix may also affect the relative distribution of GHG emissions, influencing where appropriate measures should be introduced to reduce emissions. The importance of the GHG emission contribution from the electricity mix is illustrated by stockfish production where the GHG emissions from the diesel used by loaders, a minor part of the process, contributes noticeably towards the total GHG emission level when assuming electricity with guarantees of origin. Only 24% of electricity consumption in Norway may claim the carbon footprint of Norwegian electricity produced from 98% renewable energy (NVE, 2021; Statistics Norway, 2022b). The remaining 76% of electricity consumption in Norway, i.e., electricity purchases without guarantees of origin, have a fossil energy share of 59% with considerable higher GHG emissions (NVE, 2021).

Table 5
Distribution of energy use and GHG emissions on fishing vessels and land-based processing. Share of total impact attributed to processing stages given in parenthesis. The estimation of energy use on fishing vessels is based on Jafarzadeh et al. (2016), while results for the processing stages are from the current study.

Impact across product stages	Fuel use on fishing vessels	Processing of fresh fish	Processing of stockfish	Processing of frozen fish
Energy use [kWh/ton]	1550	133 (8%)	370 (19%)	583 (27%)
GHG emissions [$kgCO_2eq$/ton]	515	41 (7%)	115 (18%)	181 (26%)

6.3. Use of advanced metering systems in energy analysis

Researchers and other professionals may access historical energy data from Norwegian fish processing companies, as well as other industry actors, where advanced metering systems (AMS) is in use. This allows for broad energy analysis across different processing companies, production methods and geographical regions. Especially if coupled with raw material data from publicly available contracts of sales, the AMS infrastructure can be useful for investigating the energy efficiency of processing plants. However, one should be aware that the contracts of sales are limited to raw material purchase from fishing vessels, thus do not provide information of transactions between fish processing companies – potentially leading to either over- or under estimation of specific energy consumption for individual companies.

The AMS meters are typically detailed to individual buildings and not specific processes, machinery, or equipment. AMS data are only available by request to the building owners, but otherwise do not require any intervention from the companies. If several processing steps (e.g., processing and freezing) are performed within the same building, it may not be possible to split the energy consumption between individual processes. This lack of detail limits the usefulness of AMS infrastructure in energy analysis. Three ways to mitigate these limitations are:

- Perform detailed energy measurements to acquire an average energy distribution on common processes and equipment. The sample size should include several fish processing companies and production methods, and could further consider categorization of companies after building type (energy standard, age, size), technologies used (age, novelty), etc. These results could then be applied to a broader energy analysis in the fish processing industry.
- Estimate buildings baseload energy requirements by considering periods of low and high production, like in Fig. 6. By this approach, AMS infrastructure can isolate the energy use for support systems like heating, ventilation, lightning, etc. A more detailed energy distribution would require knowledge of specific operational regimes and power specifications of given equipment/systems.
- Theoretical calculations of energy use for specific processes or equipment. For instance, energy use for freezing of fish can be calculated theoretically by considering specific technologies (e.g., tunnel freezer) and operational conditions (e.g., temperature before and after freezing). With knowledge of the total energy consumption from AMS meters, it is possible to isolate the freezer facility's remaining energy consumption. Any further distribution on e.g., freezer storage fans, forklift charges, lighting, etc., is not possible without making further assumptions. In addition, such energy calculations have inherent limitations limiting the accuracy of results.

In cases where actual energy measurements are not available, any approximations to estimate energy distribution on specific processes and equipment will have limited usefulness beyond the processing facility in question.

6.4. Limitations and future perspectives

The representativeness of the results is limited given that the three companies considered in this case study operate under very specific conditions. While these companies represent a diverse selection of fish processing methods (i.e., fresh, frozen, and dried products), they are all small-scale actors operating within a seasonal and geographically limited coastal fishery. For example, this study finds that processing may account for as much as 26% of the total energy-related GHG emissions from fishing vessels and land-based processing. However, these results should not be considered representative as an average for global fish processing, nor for whitefish processing in general within Norwegian fisheries, since the ocean-going fleet of larger vessels delivers a much larger volume of whitefish. These results may however be representative for the seasonal fisheries of the smaller fleet that has a yearly variation in both time and location.

This study uses background data that may have inherent uncertainties which are not fully transparent. Uncertainties in the background data are propagated to GHG emissions results by the use of emission factors for electricity (NVE, 2021), diesel fuel (Ecoinvent, 2014), and fuel use on fishing vessels (Jafarzadeh et al., 2016). The main uncertainties of GHG emissions from electricity could be related to the emission factor for electricity without guarantees of origin (GO), which is based on an estimate of the energy sources of the electricity sold without GOs in Europe called the European Attribute Mix (EAM) (AIB, 2023; NVE, 2021). The well-to-wheel diesel emission factor have inherent uncertainties related to the conditions during production and transport. However, it is the combustion process that constitute the main source of GHG emissions, and these emissions are governed by the carbon content of diesel fuel. Fuel use on fishing vessels is based on data from Norwegian fisheries in the period 2003–2012. As the data is based on a single study, the emission factors used are subjected to the limitations and uncertainties of this particular study (Jafarzadeh et al., 2016).

The AMS energy infrastructure has proved suitable for analysing an overall energy-intensity of fish processing. However, it does not allow for direct analysis of energy distribution on specific processes and equipment within fish processing. For this purpose, power clamps could be used as a temporarily solution to measure energy and power use on individual machinery and equipment. In addition, the AMS energy infrastructure could be supplemented by installation of permanent monitoring equipment such as "panel servers" that provide data logging and data distribution capabilities on individual circuit breakers. During the surveying of the energy infrastructure in preparation for this paper, it was observed that large consumers of electric energy were on individual circuit breakers. Panel servers are a recent addition to electric infrastructure and require greater intervention and minor investments from companies but could be quite valuable for future work on increasing energy efficiency in fish processing.

7. Conclusion

This study assessed the energy use of small-scale processing of whitefish through a case study of three smaller fish processing companies operating in the Norwegian coastal fishery. Specific energy requirements are presented for processing and cold storage, freezing and freezer storage, and drying. The energy results for processing and cold storage and drying are comparable to what has been reported in previous research, while results for freezing and freezer storage show greater differences from the existing literature. The use of grey literature in this study highlights the limited availability of peer-reviewed studies on energy use in fish processing.

While it is well known that the fishing stage contributes most to energy use and GHG emissions in seafood value chains, the processing stages should not be neglected. This study indicates that the energy related GHG emissions from fish processing is potentially significant, but also highly dependent upon the electricity mix and energy sources used for sustaining operations.

Fish processing plants in Norway are governed by electrical energy, making advanced metering systems suitable for investigating the energy-intensity of fish processing. Future research can consider long-term statistical energy analysis emphasizing on specific processes within fish processing.

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CRediT authorship contribution statement

Randulf Høyli: Conceptualization; Formal analysis; Investigation; Methodology; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing. **Karl Gunnar Aarsæther**: Conceptualization; Formal analysis; Investigation; Methodology; Validation; Visualization; Roles/Writing - original draft; Writing - review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Randulf Hoyli reports financial support was provided by Norwegian Environment Agency.

Data Availability

The authors do not have permission to share data.

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