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Energy flow analysis of an industrial ammonia refrigeration system and potential for a cold thermal energy storage

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ABSTRACT

There is an increasing effort to reduce energy demand at food processing plants, mainly to reduce the total carbon footprint. The energy demand of a fish processing plant (using ammonia as refrigerant) has been evaluated in this study. Results show that production follows a seasonal cycle throughout the year, with no (or very low) production in the spring (Mar-May), and peak production in the autumn (Sep-Nov). By investigating data from the plant's energy management system, it was revealed that the refrigeration systems are responsible for about 75% of the total electric power demand and the compressors for 90-95% of that. Because of the large discrepancy in energy demand over the year, and also daily variation within production periods, there is a good potential for installing a cold thermal energy storage. An initial evaluation on how a CTES system can be implemented at the plant is included, discussing type of storage, choice of PCM (e.g. solid CO2) and effect on heat production, but this evaluation will be developed further.

Keywords: industrial refrigeration, fish processing, energy analysis, energy demand, cold thermal energy storage, peak power requirements

1. INTRODUCTION

The per capita consumption of fish in 2017-2019 was stable at 24 kg in the EU and the wild-caught species account for most of this (EUMOFA, 2021, 2019). The oceans provide billions of people with healthy and nutritious food, with a smaller environmental footprint than land-based products (Stuchtey et al., 2020). Emissions from the seafood industry vary according to processing procedures, transport, and fish species. Cooling is done either with use of ice or refrigerated seawater (RSW) depending on if the fish is wild-caught or from aquaculture. The fish is then repacked in retail packaging or consumer packaging. Depending on distance to the final market it is either frozen in freezing equipment with following frozen storage or placed in chilled storage rooms. Winther et al. (Winther et al., 2009) assesses the emissions from 22 different fish food chains and found that emissions across the chain post slaughter could vary significantly. Cooling was particularly significant post slaughter, often accounting for at least 50% of the emissions and this was related to the use of high GWP refrigerants. However, many fish processing plants use ammonia as refrigerant, which has no global warming potential and the GHG emissions is therefore mainly connected with energy demand. Previous reports have shown that the refrigeration system is responsible of about 70 % of the total energy usage at seafood processing plants (Helgerud, 2007; Walnum, 2010).

The energy demand of Norwegian fish processing plants has been addressed in several research papers. Widell and Eikevik (2010) described and evaluated a system with several screw compressors and showed that there was a large potential of reducing energy usage by better operation of the system, including installing frequency converters. Hafner et al (2011) showed a theoretical saving potential of 30 % when using a cold thermal energy storage with CO_2 in the refrigeration system. Walnum et al. (2011) and Widell et al. (2012) analysed the operation of air fans in freezing tunnels and showed that energy usage can be reduced by

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lowering the rpm of the fans or turning off air fans towards the end of the freezing time. Nordtvedt er al. (2015) summarized different alternatives for reducing energy demands.

Fish processing plants for pelagic fish have often large variation in the production profile, from day to day and during the year, depending on the varying seasons and availability of the fish. The main pelagic fish species (for consumption) caught outside of Norway are Atlantic Mackerel (Scomber Scombrus) and Atlantic Herring (Clupea Harengus). Most of the fish is frozen whole, but some are also filleted before being frozen. The majority of the fish is exported. (Widell and Nordtvedt, 2019)

The main objective of this paper is to describe and analyse data from a Norwegian fish processing plant which freezes Mackerel and Herring in air blast freezing tunnels. Many processing plants measure and log data, but it is not often published. By analysing data for energy usage and production, certain patterns can be revealed and suggestions for improvement can be found. Based on the identified patterns of energy utilisation, suggestions and benefits of implementing cold thermal energy storage (CTES) technology into the refrigeration system is proposed.

2. MEASUREMENTS AND METHODS

The procedure at the plant is to pump the fish (Herring or Mackerel) together with RSW (refrigerated sea water) into the factory. Thereafter it is either put as a whole (round) fish into cardboard boxes, or it is filleted and put into plastic bags together with some water/brine and then into cardboard boxes. Each box contains 20 kg of fish and they are frozen in freezing tunnels, each tunnel with the capacity to freeze 125 tonnes of fish per batch. Freezing time is 22 h and the products are afterwards palletized and moved to a freezing storage. Centre temperatures of boxes in several locations in the tunnels are measured, to check if they have reached the intended temperature (-18°C, requirement from *Norwegian Food Safety Authority*[1]).

2.1. Refrigeration system description

The original refrigeration system (Ref. sys. 1) was installed when the processing plant was built in 1993 and it has been upgraded during the years, most recently in 2017 when they added a new system (Ref. sys. 2), with three new compressors and additional freezing tunnels. The refrigeration system includes components for cooling, freezing and storage and the original system is illustrated in Figure 1. It has also been described previously by Widell (Widell, 2012). The total cooling capacity of the refrigeration system is more than 4 MW, but the entire unit is only required during days with high production. The refrigerant in use is only ammonia and the refrigerant charge is more than 30 tonnes. The refrigerant is circulated with pumps from liquid separators to the evaporators.

The processing plant has 11 freezing tunnels, where the five original tunnels are in the processing hall (tunnels A) and the 6 newer tunnels are located inside one of the freezing storages (tunnels B). The plant has also two freezing storages. There is an additional large freezing storage next to the fish processing plant, which also stores fish from other plants. It has a separate refrigeration system which has constant head load and constant energy usage.

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[1] https://www.mattilsynet.no/language/english/

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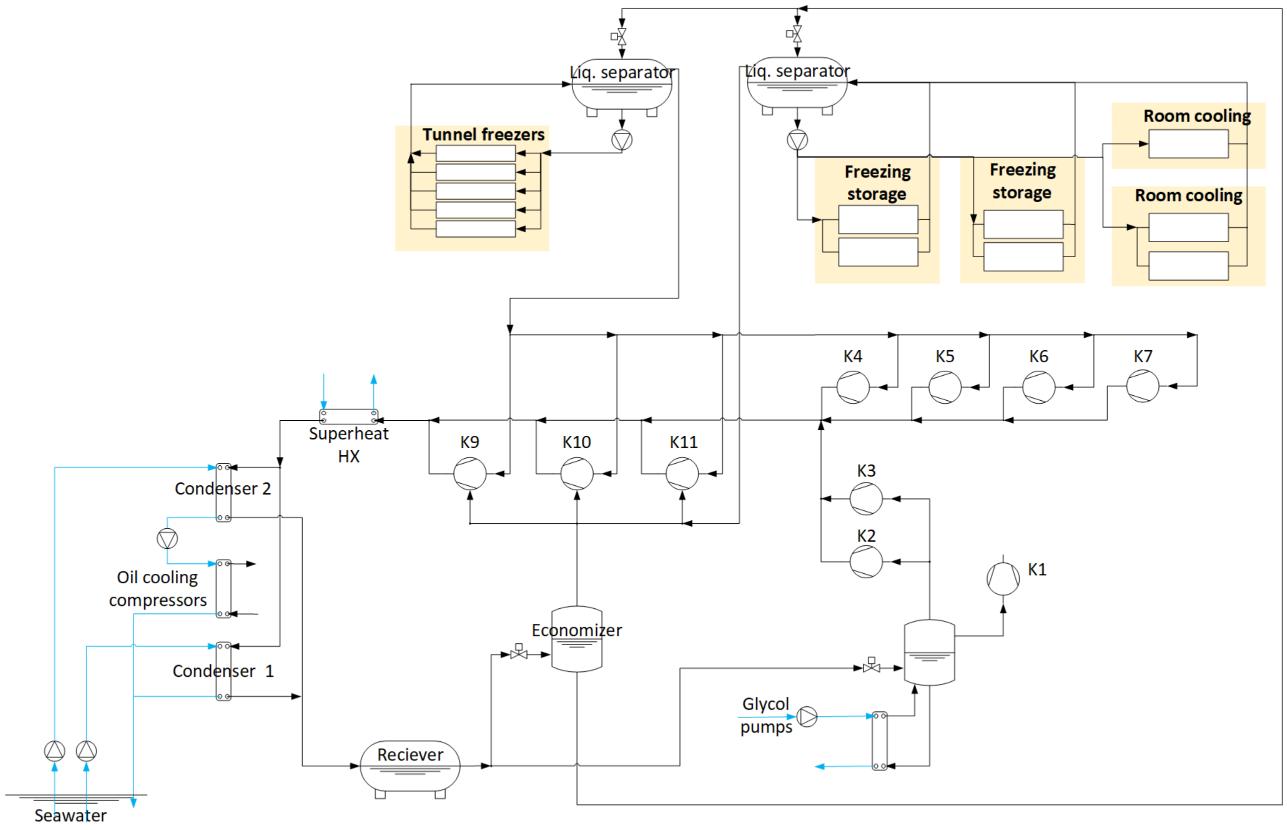

Figure 1. Illustration of the original refrigeration system (refrigeration system 1).

The refrigeration systems have 13 compressors, ranging from a refrigeration capacity of 221 kW to 1164 kW (-40 / +25,0 °C). Some of them have frequency converters, allowing much more energy efficient operation than capacity regulation with slide regulation. The slide regulation is only used during start-up of the compressors. K1 to K11 belong to refrigeration system 1, A1 to A3 to refrigeration system 2.

The surplus heat from the refrigeration systems is utilized for several purposes. It is used in ventilation, floor heating, domestic hot water production, and heated water for cleaning of the plant. Some of the heat is also used for melting of ice outside. Heat is collected both from the oil cooling of the compressors and the superheat heat exchanger (desuperheaters). Water for cleaning of processing equipment is further heated to 75 °C by an electrical boiler. The boiler also heats water when there is not enough surplus heat i.e., at periods of low production.

2.2. Logging and data managing system

The processing plant has several separate data acquisition and storage systems, which measures and logs temperatures, pressures, energy, and other process variables. In this study, data from the system logging energy data was analysed. Data for production rates has also been included.

Historical energy data for the plant were acquired for the period 2017-2021 for a total of 50+ loggers, with a sampling rate of 1 hour, resulting in approximately 2.5 million data points. A python script was developed both to aggregate and transform the data (which was stored in monthly files) from wide format to a more convenient long format, clean the data and perform exploratory data analysis. The latter included the possibility to create interactive visualisations on the fly by employing the 'plotly' package, and subsets of the data (time periods of interest) could be transferred to Excel for final analysis and static plot productions.

Several components and entire sections of the plant shared the same logger, meaning that, e.g., the energy demand of a single compressor could not be separated from the total recorded energy value. Therefore, sections were defined and are used throughout this paper, as listed in Table 1. No changes in the metering configuration were done during the period of data investigated, i.e., sections could be compared on year-to-year basis. Refrigeration system 2 came online in May 2017.

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Table 1: Sections of the plant, defined on the basis of metering configuration

Section	Description
Refrigeration system 1	Energy usage of 7 screw and 3 reciprocating compressors, lighting in freezer storages and misc. auxiliary equipment. Covers refrigeration demand for the 5 original freezing tunnels and frozen storages.
Refrigeration system 2	Energy usage of the newest (2017) refrigeration system, including 3 screw compressors and misc. low-consumption equipment (lighting etc.). Covers refrigeration demand for 6 freezing tunnels.
RSW	Energy demand of 2 reciprocating compressors dedicated for RSW chilling and RSW pumps at the plant.
Electrical boiler	Energy demand of electrical boiler (sole component)
Fillet sections	Energy usage of machinery and equipment at the two fillet sections of the plant
Other	Everything else that doesn't fall into sections described above, e.g. common areas, air compressors etc.

2.3. Calculations

Data from the processing plant is described in the results section directly or they have been used in calculations. Accumulated production volume is the sum of all fish that has been processed at the plant (going into the freezing storage). Overall energy usage are the energy data from all loggers summarized.

Specific energy consumption (SEC) is an important measure when comparing different processing plants or to see if a change to a system has led to a more energy efficient production. It should be noted that the wording 'specific energy consumption' is a bit misleading as energy is not consumed but converted, and that 'use' or 'demand' would be more precise. However, for the sake of staying consistent with the term as it is used in literature, SEC is used in this paper. For buildings and food storage, specific energy use is often kWh/m^2, but for food production it is often more important to apply kWh/kg of produced food. In this paper the SEC is calculated per tonnes of (output) product.

$$SEC = \frac{\sum Total\ energy\ demand\ of\ plant\ (kWh)}{\sum Total\ production\ of\ plant\ (tonnes)}$$

3. RESULTS AND DISCUSSION

3.1. Production data

Figure 2 shows the average monthly production volume at the fish processing plant for the years 2017-2021. The values are relative, which means that they are normalised against the month with highest production volume within the period (which is not shown in the graph). The graph shows that production follows a seasonal cycle throughout the year, with no (or very low) production in the spring (Mar-May), and peak production in the autumn (Sep-Nov). The cycle is linked to the seasonal availability of fish.

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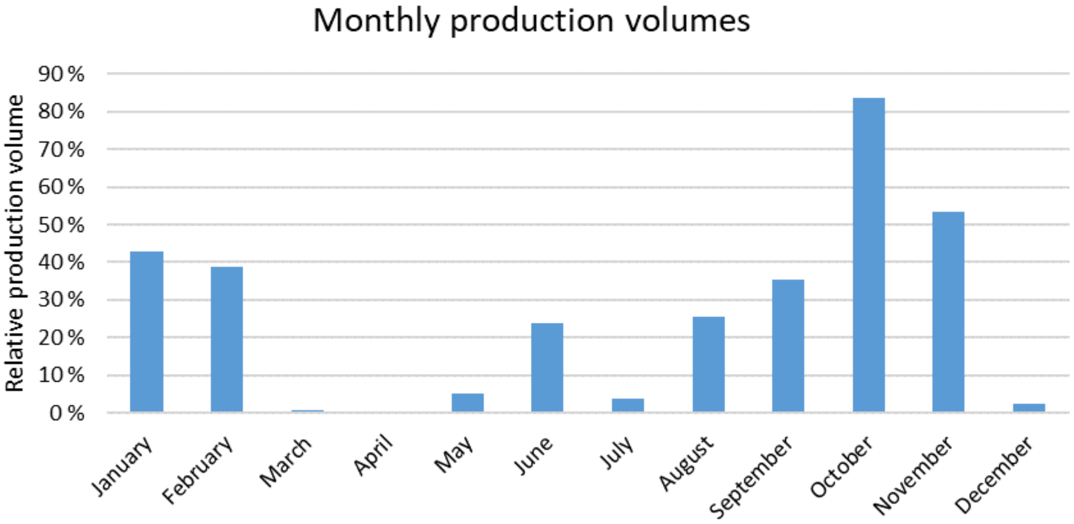

Figure 2: Monthly production volume at the fish processing plant 2017-2021. Relative volumes, normalised against the month with higehst production volume within the period.

Figure 3 displays the accumulated production volume for the years 2017-2021 by category and shows that it is mainly whole frozen fish that is processed at the plant, thereupon frozen fillet products. Roe (spawn) is also processed at the plant but holds a very small share of the total overall production.

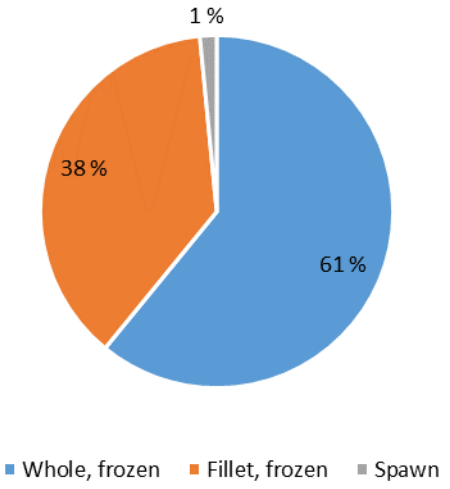

Figure 3: Production volume shares accumulated 2017-2021

3.2. Overall energy demand

Figure 4 shows the share of total energy demand for each section of the plant for 2021, including shares during months of production and non-production. Even though 2021 was chosen as sample for this figure, data for 2017-2021 shows that the pattern is similar for other years.

The two refrigeration systems are demanding most of the electric power, with refrigeration system 1 accounting for almost half of the plants total energy demand and a quarter by refrigeration system 2. By investigating into loggers within the ref. sys 1 section, it was revealed that the compressors were the main consumers (90-95% of section), which were in line with expectations. Due to configuration of measurement loggers a more detailed data exploration could not be made for the newest refrigeration system (Ref. sys 2), but a similar assessment is assumed. The RSW section, i.e., chilling of fish before processing, has a very small share compared to the refrigeration systems, which more than anything else reveals the different levels of energy intensity between the two thermal processes.

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Surplus heat from the refrigeration system is utilized to pre-heat water, but the final temperature lift is done in an electrical boiler. The figures show that the boiler is a relatively large consumer on an annual basis. Comparing production vs non-production periods, the refrigeration system 1 is still the largest consumer providing cold for the frozen storages, while refrigeration system 2 and RSW system is more or less shut off.

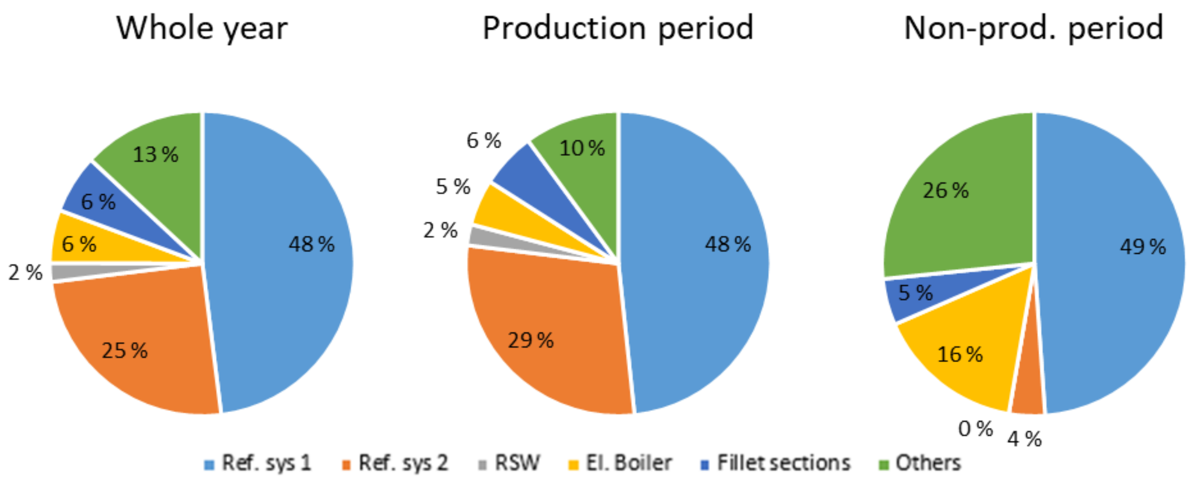

Figure 4: Plant total energy demand for 2021 by sections. Left: annual basis. Middle: During a production month. Right: During a month with no production

Figure 5 shows the total daily energy demand at the plant for 2021, and shows that the variation throughout the year is, as expected, heavily linked to the seasonal production cycle. During the periods January to February, and September to November, daily energy usage is measured at levels almost tenfold compared to the non-production period March to May. The monthly peak power is also shown in the figure, i.e., the hour of each month with highest measured power demand. During production periods the peak power is measured to be around 5-5.5 MW compared to less-than 1 MW for non-production periods.

The figure reveals that even within periods of production there is a significant day-to-day variation in energy usage. For example, January consists of daily levels at both above 100 MWh and as low as 10 MWh. Although some of the low-demand days seems to be set during weekends, there is no definite pattern as production seems to take place whenever raw material is available and must be processed. An important prerequisite for a successful implementation of a CTES system is knowledge of the production cycle and being able to predict days of high cooling demands. Historical data cannot be used to make pinpoint predictions, meaning this information must be inputted from processors knowledge. However, the knowledge of variation in energy demand in different time periods indicates a potential for peak shaving by CTES implementation.

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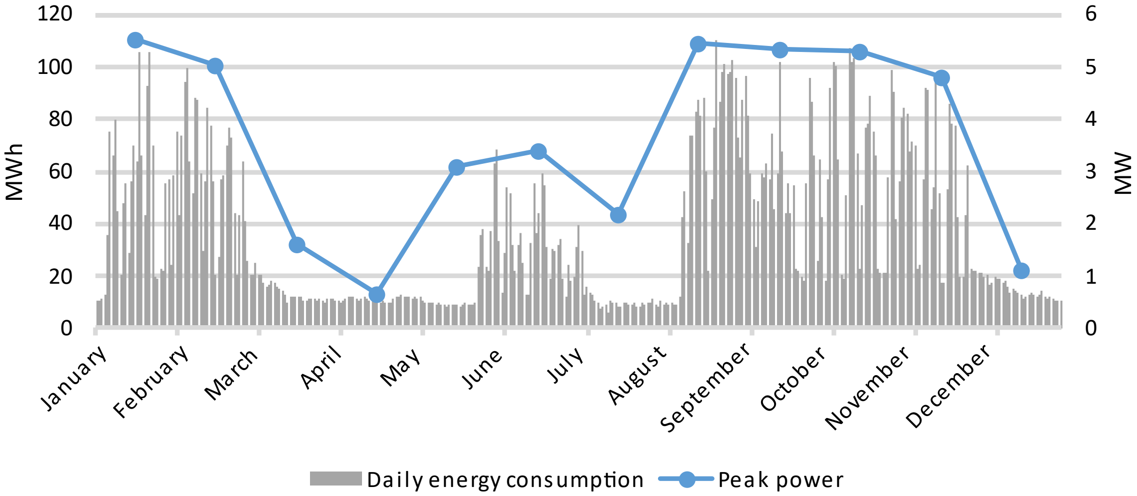

Figure 5: Total daily energy demand at the plant for 2021, including monthly peak power

3.3. Specific energy demand

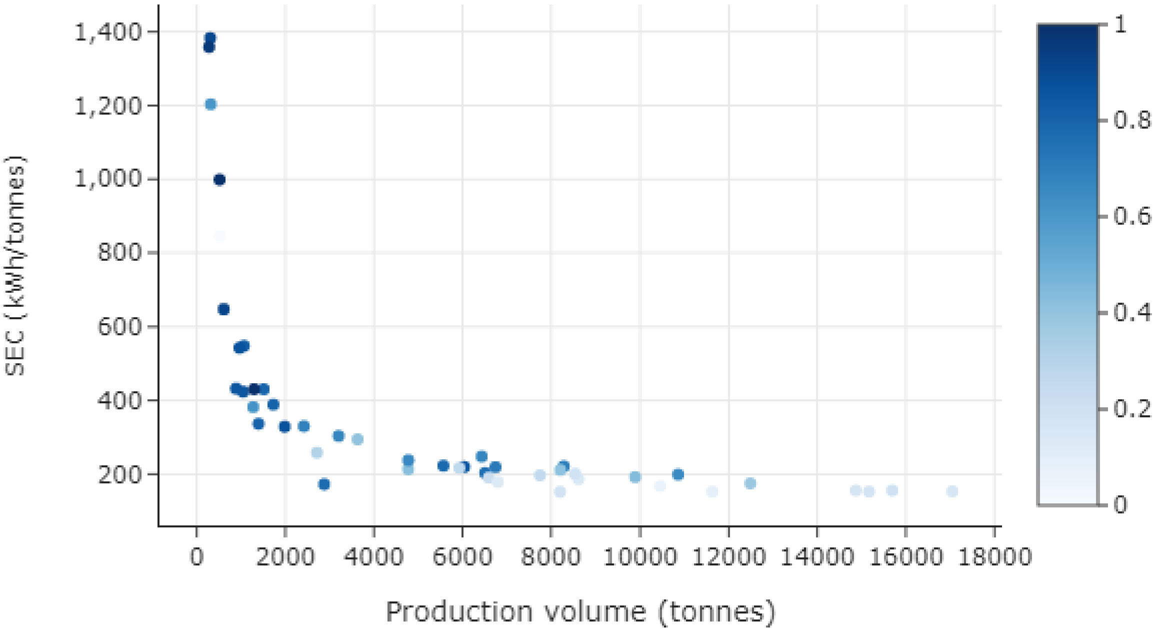

Figure 6: Relationship between SEC, production volume and share of fillet production

Figure 6 shows the relationship between SEC and production volume (monthly) based on energy and production data for the period 2017-2021. In addition, the share of fillet production (of total monthly production) is shown as a colorscale, where the dark blue colors indicate a high share of fillet production. What is apparent by looking at this graph is that there is a power law relationship between SEC and production volume. Secondly, there is a relationship between share of fillet production and production volume; a larger share of fillet production lowers the total production volume. This is easily understood by the fact that the production yield from fillet products is half that of round production, while supply volume remains unchanged. Furthermore, fillet production is more energy demanding compared to round production. This is due to activity in the fillet sections, which in turn increases demand for hot cleaning water, and that there is a higher brine/fish ratio in each cardboard box (i.e., higher total mass in each box).

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Whenever the monthly production exceeds 4000 tonnes, the SEC seems to approach the 200 kWh/tonnes-mark regardless of production composition.

The annual SEC values for 2017-2021 is presented in Figure 7, and it is important to keep in mind the relationship between production volume and SEC for better interpretation. No changes to the systems have been done during this period, and while the figure give the impression of a decreasing performance since 2017, it actually captures the effect on the SEC-production volume relationship. The 'worst years', 2019 and 2020, was also the years with most low-production months, i.e., volume below 4000 tonnes.

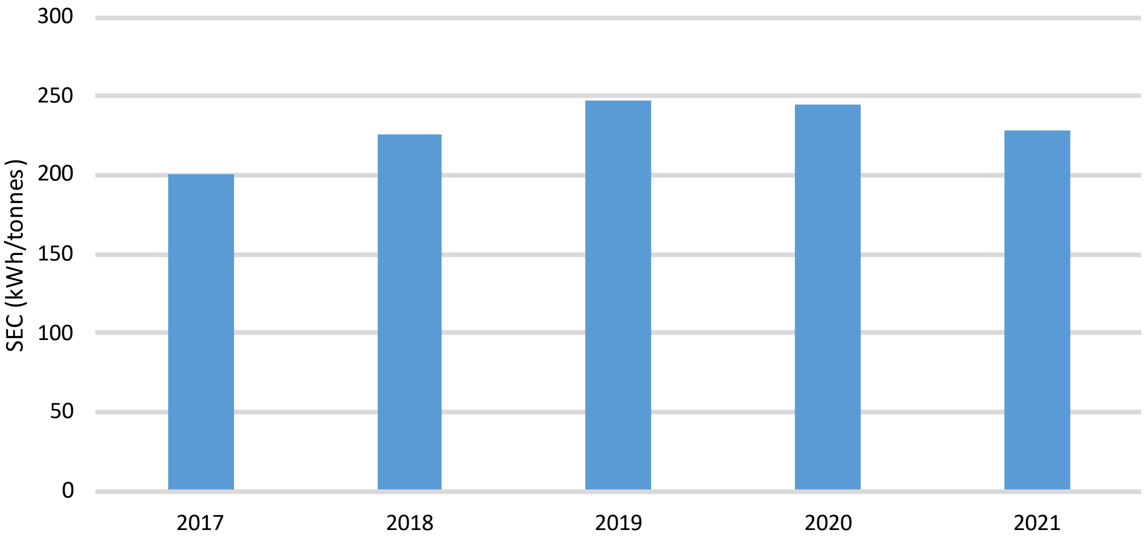

Figure 7: Annual SEC 2017-2021

For comparison, average SEC values reported by some pelagic plants in 2009-2012 were 197-271 kWh/tonnes (Widell and Stavset, 2014). The annual SEC of this fish processing plant is in within the range. In a series of papers, Pearson (Pearson, 2021, 2020, 2019a, 2019b) explored the energy efficiency of cold storage facilities and how to use the SEC as a continuous indicator on the performance of such facilities. As the papers are concerned with cold storage facilities in particular, the SEC is calculated on volumetric basis (storage volume) and is thus not directly related or cannot be compared to the study at hand. However, the principle of using SEC predictions to indicate energy use trends is of interest and the methodology could be adapted to processing plants as such in this study.

3.4. Heating

There is a demand for heating at the plant for several purposes and at different temperature levels. For processing, there is a need for hot cleaning water, heating of production areas and floor heating in frozen storages to prevent heaving. Besides processing there is a need for hot tap water and space heating in offices. This means that the heat demand is dependent on both production cycle and ambient temperature. All heat demands are covered by surplus heat from refrigeration system 1 and the electrical boiler. Surplus heat from the refrigeration system is recovered through a desuperheater and from the oil cooling heat exchangers, which provides water at approximately ~40 °C. The final temperature lift is accomplished by the electrical boiler towards 75 °C. Quantities of heat are not known, but it stands to reason that the amount of surplus heat from the refrigeration system is dependent on the load, i.e., production volume throughput. Furthermore, heat demand for space heating is dependent on ambient temperature, i.e., relatively higher during winter than summer. These dependencies together with the relative load of the electrical boiler (daily values) for 2021 is shown in Figure 8. Note that the relative production volume is given on a monthly basis.

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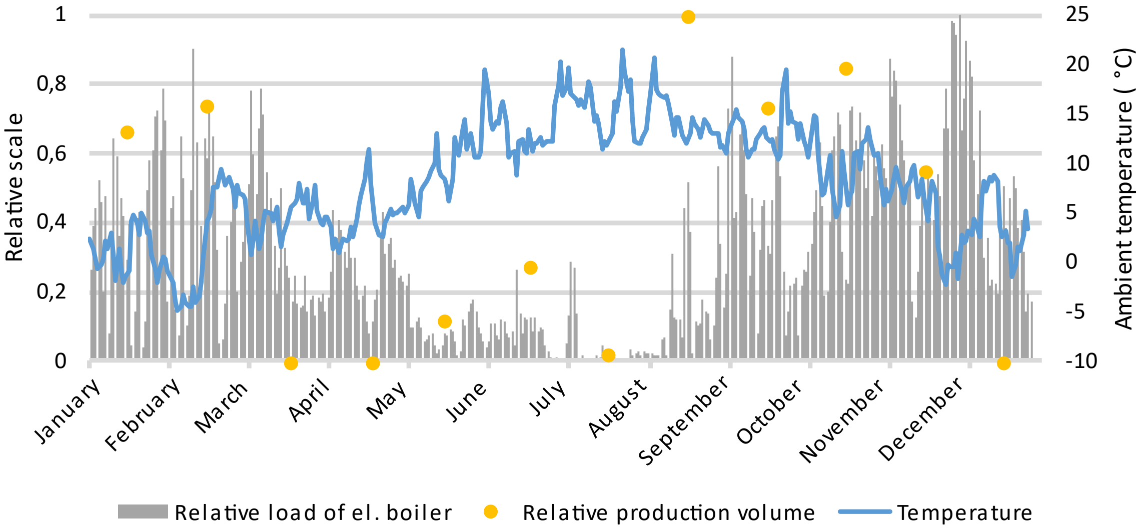

Figure 8: Relative load of electrical boiler and production volume (normalised against max value in period) and ambient temperature at the plant for 2021

The figure seems to show an inverse relationship between load of the electrical boiler and months with both low production and low temperature. The relationship between ambient temperature and electrical boiler is straightforward and easy to understand – less heat demand in warm periods. The relationship between production and electrical boiler is however a bit more complicated. Whenever there is production, load on the refrigeration systems increase and thus the amount of surplus heat which can be recovered increases, likely reducing load on the electrical boiler. However, the electrical boiler must still be used to supply hot cleaning water at high enough temperature. A more detailed look into this relationship can be seen in Figure 9. Whenever the refrigeration load peaks, load on the boiler decreases and vice versa. Further analysis require knowledge on quantities of available heat, heat demand, capacity of hot water buffer tanks and temporal mismatch between availability and demand.

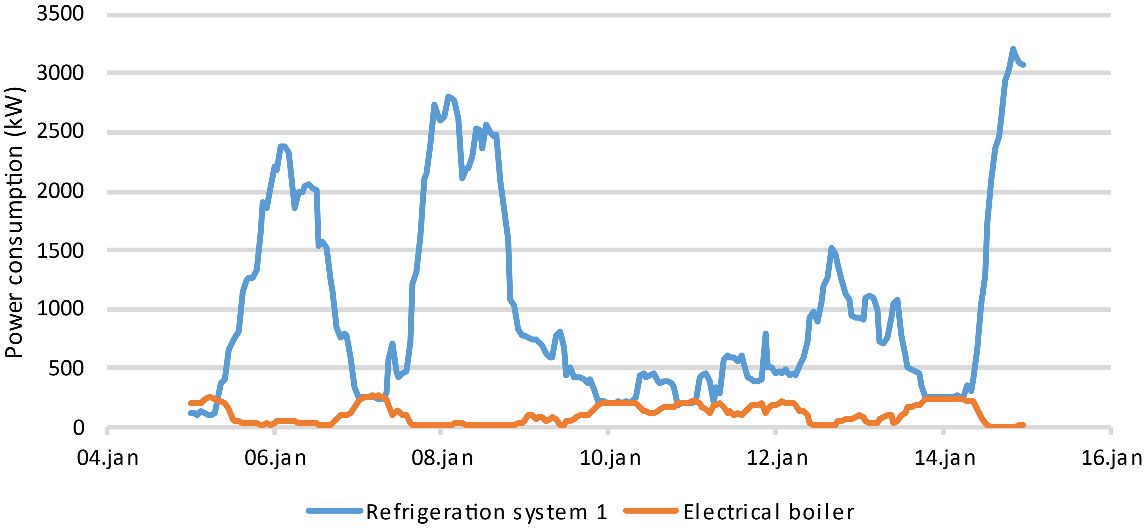

Figure 9: Power curves for refrigeration system 1 and electrical boiler during a period of production in January 2021

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4. POTENTIAL FOR COLD THERMAL ENERGY STORAGE

The processing plant has reported high energy costs, as well as high associated costs for peak power demands. Stopping the production at certain periods to cut the power peaks is not an option, since it could negatively affect the quality of the products. Another point is that fishing vessels could be waiting to unload their fish, which must be done both continuously and efficiently. A solution to the varying refrigeration load and high peak power costs can be to install a cold thermal energy storage (CTES) system with phase change material (PCM) as the storage medium. CTES systems with PCM utilise the latent heat of the material to store the thermal energy and have gained considerable interest in the recent years due to high compactness, resulting in an attractive area footprint for industrial applications (Sevault et al., 2020). It has been shown that implementing a CTES system with PCM into refrigeration systems can lead to reduced part-load operation and reduced energy demand (Selvnes et al., 2021c). Recent research has shown that a CTES combining phase change material (PCM) with a pillow-plate heat exchanger is especially well-suited for integration with pressurized refrigerants at large scale (Selvnes et al., 2021a, 2021b).

Considering the logged data from the presented processing plant, it is clear that the load varies both on a seasonal basis (Figure 5), as well as diurnal basis (Figure 9). For CTES systems with PCM, the most attractive strategy would be to cover the daily load variations. Actively using this type of CTES system with the refrigeration system will enable exploiting day/night electricity pricing by peak shifting of the electricity demand. The difference between the on-peak and off-peak electricity price in Norway can vary from 20-50 % during the summer months and up to 100 % during the winter months. The most suitable location of a CTES system in the process plant would be connected in parallel to the freezing tunnel, charging the CTES unit by supplying and throttling liquid refrigerant from the liquid separator. The peak shaving can be obtained by forcing the liquid/vapor mixture from the freezing tunnels through the CTES unit to condense the vapor, unloading the compressors in the plant. The phase change temperature of the PCM of the considered CTES system should be at least 10 K below the evaporation temperature of the tunnel freezers for efficient heat transfer. Reliable commercial PCMs with phase change temperature below -40 °C are currently scarce, but development is ongoing. A potentially attractive option in this temperature region is using solid CO2 (dry ice) as the storage material, a concept which was presented theoretically in the past (Hafner et al., 2011; Verpe et al., 2019). The operational data collected in this paper shows a potential for implementation of a CTES system into the refrigeration cycle. The detailed design and sizing of the CTES system, as well as the impact on operational costs and energy savings will be considered in further work.

In section 3.4 it was concluded that when the refrigeration system is in full operation, there is less need for the electrical boiler due to the heat recovery from the refrigeration plant. If a CTES system is installed, it will affect the schedule of the of the refrigeration system and hence also the surplus heat production. This can be solved by including a hot water storage to recover the condensation heat from the refrigeration plant. Depending on the temperature requirement of the process heat delivered from the boiler, implementing a high temperature heat pump could be an attractive option for reducing primary energy use at the plant.

5. CONCLUSIONS AND FURTHER WORK

There is an increasing effort to reduce energy demand in industry, mainly to reduce the total carbon footprint. The main objective of this paper was to describe and analyse data from a Norwegian fish processing plant which freezes Mackerel and Herring in air blast freezing tunnels. Results show that energy demand at the processing plant has a seasonal cycle which is linked to the availability of raw material. Peak seasons are January to February, and September to November, with peak power demands at around 5-5.5 MW. The peak power demand during non-production periods is less-than 1 MW. The two refrigeration systems account for most of the energy demand (approx. 75% of total).

Annual SEC numbers (200-247 kWh/tonnes) were found to be in line with other Norwegian pelagic plants. A strong dependency between SEC and volume throughput were also found, where months of low production resulted in high SEC values and vice versa. Knowledge about the processes indicates that a fillet production is more energy intensive compared to round production, due to more energy demand from the fillet sections, higher mass (fish and brine) in each box and higher requirement of hot water for cleaning.

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Heat demand at the plant can be divided into process related demands (hot water for cleaning, heating for production areas and floor heating in frozen storages) and other demands (hot tap water, space heating in offices). Thus, the heat demand is affected by both production cycle and ambient temperature. All heat demands are covered by surplus heat from the refrigeration system and the electrical boiler. While peaks in production demands more heat, more surplus heat is available from the refrigeration system to cover this, even though the electrical boiler is still required to increase heat quality. It was assessed that more knowledge and data on the heat demand and production was needed to conduct further analyses on this aspect.

There is a large potential for installing a CTES system at the plant. Several solutions have been presented, where the most promising alternative is installing a CTES system using PCM as the storage medium for diurnal cycles of charging and discharging. It is proposed to integrate the CTES system into the low temperature ammonia circuit supplying the freezing tunnels to realise the highest potential for peak shaving. Further advantages provided by the CTES system are increased flexibility for the use of power and providing backup cooling in case of compressor malfunction.

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DATA AVAILABILITY STATEMENT

The data supporting reported results can be found in a public repository under the DOI https://zenodo.org/record/6563580#.YodGHqBBxaQ

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