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Energy efficient and climate friendly refrigeration systems onboard fishing vessels

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ABSTRACT

Refrigeration systems onboard fishing vessels are necessary to keep the catch at a low temperature and to ensure long shelf life. Most refrigeration systems in the world fishing fleet still have R-22 as a working fluid, which has both ozone depleting potential and global warming potential. In this paper, key findings are presented from the CoolFish project, financed by The Research Council of Norway and industry partners. The primary objective has been to develop technology and increase knowledge for more energy-efficient and climate-friendly cooling, freezing, and heating systems onboard fishing vessels. Development and utilisation of natural refrigerants, especially R-744 and R-717, have been important to communicate. The main emissions come from engines, and the development within propulsion systems and fuels is described. Integration of cooling and heating is vital to reduce energy demand. The heat from the engine is commonly used onboard, but other integration possibilities are also explored.

Keywords: fishing vessel, energy efficiency, natural refrigerants, sustainability, greenhouse gas emission

1. INTRODUCTION

The fishing fleet of Norway consists of a range of vessel types, from small boats to large fish factories, in total 5593 (Directorate of Fisheries, 2023). All vessels have methods for keeping the fish cold to preserve fish quality and shelf life. There are mainly three different methods: Storing the fish on ice (which is brought from land or produced onboard), chilling in RSW (refrigerated sea water) tanks, and freezing in blocks in plate freezers. A few vessels also have quick freezers for single frozen fillets. Keeping the fish cold is necessary to avoid food degradation and losses, but refrigeration systems require electricity. The Norwegian land-based industry has, during the last decades, had an increasing focus on reducing energy consumption. It is necessary to extend this work to the fishing fleet to improve competitiveness in the world economy.

The Norwegian fishing fleet has a large potential of reducing its total energy consumption due to many vessels and a high average age (Directorate of Fisheries, 2023). The propulsion system is the main energy user, and there are several different actions for reducing its energy consumption. However, refrigeration systems also consume a great part of the electrical energy which is produced onboard. There is a complexity regarding the contribution to global warming of a refrigeration system since the greenhouse gas (GHG) emissions occur both from leakage of refrigerants with a high global warming potential (GWP), and from indirect emissions from electricity use. This electricity is produced onboard using diesel generators, thus contributing to large CO_2 emissions. Increasing the refrigeration system's energy efficiency or integrating it with other systems on board will reduce these emissions. It is also important to use natural refrigerants without GWP or toxic breakdown products such as HF (hydrogen fluoride) and TFA (trifluoroacetic acid), which are soon beeing restricted by ECHA[1].

Since seafood consumers are becoming more aware of the environmental consequences of fishing, the environmental impact of seafood products may influence the market share. For example, consumers require

[1] https://echa.europa.eu/documents/10162/f605d4b5-7c17-7414-8823-b49b9fd43aea

information about accumulated carbon footprint and traceability, i.e., where and how a product has been produced. There are legal requirements in place for temperature monitoring during transport.

The CoolFish project was started in 2019 with the objective of increasing knowledge for more energy-efficient and climate-friendly cooling, freezing and heating onboard fishing vessels. This paper summarises the main results and ideas from the project, divided into the sections shown in Figure 1.

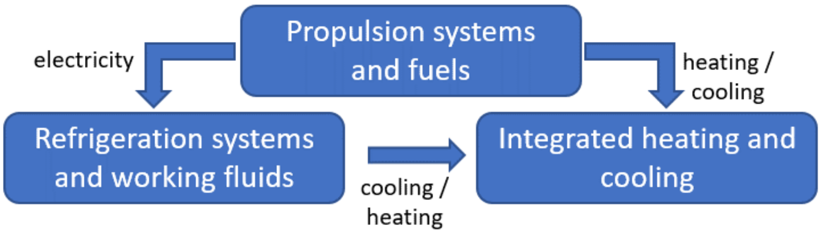

Figure 1. Illustration of energy flows between systems onboard fishing vessels.

A multidisciplinary research approach was applied with expertise from energy and process engineering, biotechnology, life cycle assessment, and traceability to propose different solutions for more integrated refrigeration systems on board fishing vessels.

2. REFRIGERATION SYSTEMS AND WORKING FLUIDS

During the IIR-ASHRAE-UNEP Conference on Sustainable Management of Refrigeration Technologies in Marine and Off-Shore Fisheries Sectors, several speakers stressed the challenges for these sectors to replace high-GWP refrigerants under the Montreal Protocol and the Kigali Amendment. Two types of refrigerants are widely used on fishing vessels: R-22 (about 70%) and R-717 (De Larminat et al., 2018). Since R-22 has both a high GWP and ozone depletion potential (ODP), it is being phased out in many countries. However, the usage of R-22 in the global fishing fleet must be addressed. Figure 2 shows the annual estimated loss of refrigerants from the fishing fleet. R-134a and R-404a are synthetic refrigerants with zero ODP but still with a substantial GWP. Therefore, they are also subject to a phasedown schedule, implying limited availability and higher costs. Low-GWP refrigerants are available (HFOs), but they come with the drawback of decomposing into toxic by-products[1]. However, natural refrigerants are long-term sustainable options, and several maritime applications are feasible for the phase-in of natural refrigerants (Hafner et al., 2019).

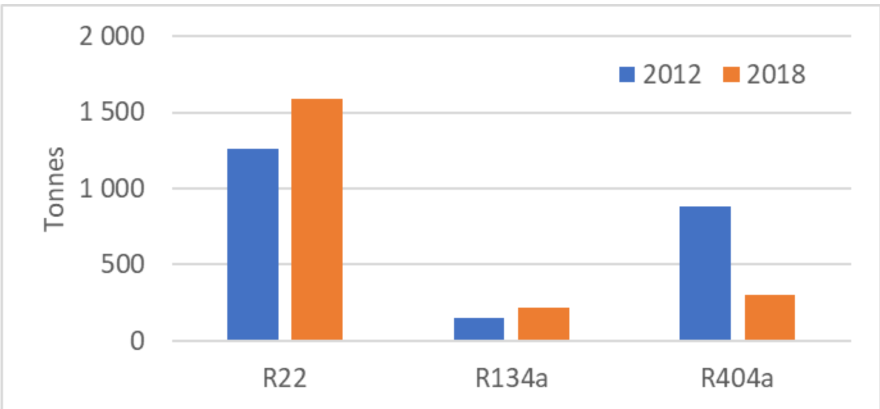

Figure 2. Annual estimated loss of refrigerants from the fishing fleet in metric tonnes *(IMO, 2021, 2014)*

In the Nordic region, the natural refrigerants R-717 and R-744 are today the primary choice of refrigerants for newly build systems onboard of fishing vessels (Widell et al., 2016). Those systems are efficient, compact and safe in operation when the right precautions are taken. Experiences from replacing the R-22-unit by installing an R-744 freezing system from the Norwegian company PTG include reduced deep-freezing times of 25-30%, more compact systems (20% less space), improved fish quality according to the customer, and easier maintenance. Experiences from RSW systems using R-744 are that they are space-saving and have worked as expected also with varying ambient temperatures and under harsh weather conditions. Verpe et al. (2019) did a numerical and experimental study on R-744 in plate freezers, showing an increased fish production capacity by 66% when using -50°C systems compared to -30°C systems.

Widell et al. (2021) described fishing vessels, fishing methods and equipment for fish handling, as well as different processing methods, such as slaughtering, refrigeration, and filleting. In addition, energy-saving methods were proposed, and sustainability issues were described. Gabrielii and Jafarzadeh (2020a), provided an overview of standards, methods, certification schemes, tools, and previous studies related to carbon footprint estimations of seafood, both in general but especially related to fishing vessels and refrigeration systems.

2.1. Availability and development of R-744 equipment

Söylemez et al. (2022) reviewed the status of R-744 refrigeration systems for fishing vessels, indicating a considerable interest in applying these systems. This interest is triggered by, firstly, the recent advances in system components; secondly, the successful implementation of energy-efficient solutions such as parallel compression, multi-ejectors, and internal heat exchangers; finally, heat recovery options (production of hot water for domestic needs and space heating, and integration with air-conditioning).

Compressor manufacturers have made key developments in R-744 compressors (Bitzer, 2022; Bock, 2022; Dorin, 2022; Javerschek and Yi, 2019), resulting in a wide range of commercially available units with high capacities and efficiency for different applications. Significant improvements have also been made in R-744 heat exchangers (evaporators, gas coolers, etc.). The development of high-capacity compressors enables more compact systems, as fewer compressors are needed for the same cooling capacity. However, R-744 compressors with higher cooling capacities and higher resistance to dynamic loads of seawater are still needed (Söylemez et al., 2022). Bodys et al. (2018) state that the implementation of parallel compression and multi-ejectors increase the energy efficiency, and applicability, of R-744 systems for fishing vessels operating in elevated seawater temperatures.

In 2003 the first large R-717/R-744 cascade system was installed onboard the Norwegian ship Kvannøy built on a Norwegian shipyard (Pachai, 2017). In the following years, several fleets were converted into this cascade system, among them the Dutch fleet of similar ships and, currently, the North American pacific market. When operating in cold waters (below 15 °C), one option, rarely used, is to condensate the R-744 at subcritical conditions. This can easily be done with a cascade system but might be more complicated with a system operating only on R-744.

2.2. Modelling of R-744 systems

One goal of the CoolFish project was to develop simulation models for R-744 cooling systems. Engineering Equation Solver (EES) was first applied, aiming at analysing system performance and energy efficiency for existing and future installations. Then, detailed mathematical models for each component of the system were developed using Modelica with TIL-library[2], an object-oriented programming language applied in the Dymola modelling environment. Different options to improve the cooling system's performance were tested:

a) an ejector as an expansion work recovering device,

b) multiple stages of throttling to maintain different temperature levels,

c) parallel compression

The simulation results clearly showed that using parallel compressors improved the performance of the configuration with double stages of throttling. Higher evaporation temperatures, as well as ejector implementation, further increased the cooling capacity and COP. It was also shown that proper control of

[2] TLK-Thermo GmbH: TIL Suite 3.11.0: Software package components

high side pressure and the design of the cooling system ensures efficient cooling, particularly for fishing vessels in warmer climates. (Semaev et al., 2021).

To further improve the system performance, flooded evaporators were investigated. A two-stage evaporator was designed by combining two plate heat exchangers side-by-side in one unit in a sandwiched fashion. The unique configuration, with a gravity-fed loop on one side of the plate heat exchanger and an ejector-fed evaporator on the other side, enables the production of chilled water with a large temperature gradient as the liquid side is internally connected within the heat exchanger. The simulation model was first validated with measurement data from a test rig and then used for further investigations. Simulation results showed that the flooded evaporator design improves the overall performance due to a better heat transfer rate. For the gravity-fed evaporator loop, the static height and tube diameter are critical parameters in terms of system performance. The two-stage evaporator improved overall performance as the cooling capacity was shared between the two stages, and the compressor suction pressure was elevated by utilising the ejector. (Hafner et al., 2022; Hazarika et al., 2022).

3. PROPULSION SYSTEMS AND FUELS

Globally, fishing ships are typically operated with conventional diesel-mechanical engines. Gabrielii and Jafarzadeh (2020b) provided an overview of alternative propulsion systems and fuels, with a focus on new-built or ordered Norwegian fishing vessels. There is a clear development towards diesel-electric or hybrid propulsion systems, often with hybrid power supply (e.g., batteries). Hybrid solutions enable several operating modes to match the speed and auxiliary requirements, such as refrigeration, resulting in a flexible and energy-efficient operation. However, it also poses challenges regarding the limited availability of waste that can be used for heating purposes (as further discussed in section 4.1). According to a study within the Green Shipping Programme[3], alternative fuels with high technical feasibility for the Norwegian fishing sector include liquefied natural gas (LNG) or biofuels for all fishing vessel types and hydrogen used in fuel cells for coastal fishing ships. Hybrid propulsion with battery implementations are considered relevant for the whole fishing sector. (Fiskebåt, 2020, 2018)

However, to enable both the national and global green transition, there is an urgent need for developing and coordinating regulatory frameworks, as well as dedicated support schemes for research and demonstration activities. Zero-emission technology is not yet readily available, specifically not for fishing vessels. LNG has been pointed out as a transition fuel towards carbon-free fuels, such as liquefied biogas (LBG) and ammonia. The Norwegian fishing vessel Selvåg Senior (Gabrielii et al., 2022), to be delivered in 2023, will be equipped with a hybrid propulsion system including an LNG-fuelled engine and a battery package. LNG is a cryogenic fuel which enables cold recovery from the fuel system that could supply parts of the cooling needs onboard (as discussed in section 4.3).

There is generally a considerable uncertainty related to future fuel choices in the shipping sector. Many different scenarios have been published trying to predict the maritime fuel mix in 2030 and 2050, as the one presented in Figure 3 (DNV-GL, 2019). Most of the ships designed for LNG or other alternative fuels are, and will most likely be, equipped with fuel-flexible machinery to tackle the large uncertainties in future fuel availability and cost. As an example, the recent sharp increase in LNG, partly due to the war in Ukraine, has led to several LNG-fuelled ships shifting back to diesel operation of their dual-fuel engines.

[3] Green Shipping Programme

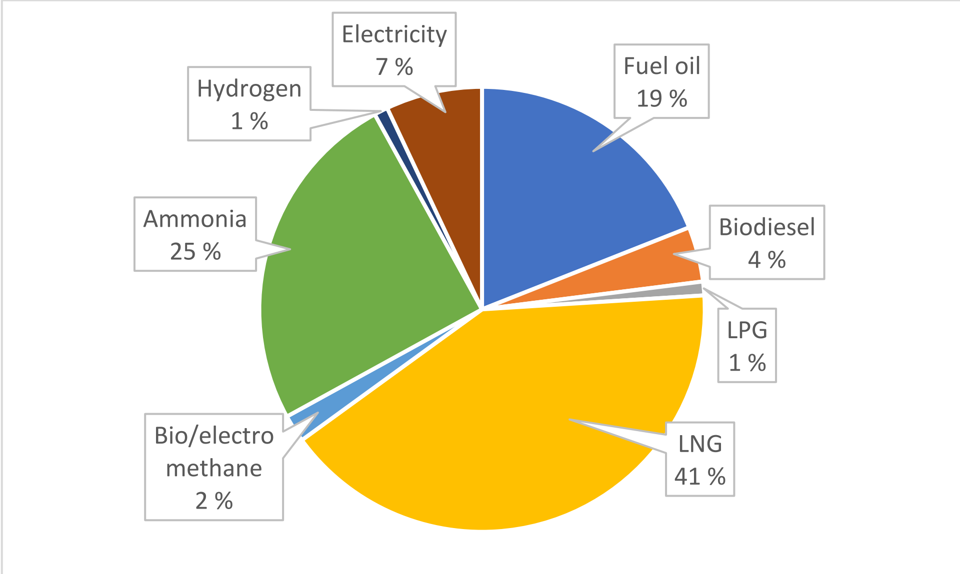

Figure 3: Example of fuel mix scenario in 2050. (DNV-GL, 2019)

4. INTEGRATED COOLING AND HEATING

The cooling, freezing and heating systems installed on most types of ships, including fishing vessels, are typically designed, operated and controlled as fully independent systems, neglecting considerable opportunities for energy saving by integrating them. For land-based systems, such as supermarkets, this opportunity of using integrated concepts for refrigeration, heating and AC systems have shown a 30% reduction in energy use (Hafner and Nekså, 2018). Furthermore, thermal storage concepts and heat pumps can play a crucial role in increasing energy efficiency by peak shaving systems or balancing any mismatch in energy supply and demand.

Since the change towards hybrid propulsion systems and alternative fuels influences the whole energy system onboard, a holistic approach is needed to minimise the ship's energy usage and emissions. Also, as the propulsion machinery and fuel system will be more space-demanding, energy-saving measures are crucial to still have enough cargo space. Thus, there is a strong need to develop heating and cooling concepts that are well integrated both with each other and with the existing propulsion system and operating conditions.

Saeed (2020) modelled innovative concepts, such as thermal energy storage and cold recovery from LNG, and waste heat recovery, to supply thermal energy to various consumers, including plate freezers, chilling tanks, fish oil production (hydrolysis process), and processing of rest raw material (RRM). The integration of water/ice and dry ice (R-744) energy storage and a two-phase ejector for R-744 thermal storage were also evaluated. Also, design modifications in chilling tanks for built-in and add-in thermal storage were investigated, as well as ice handling and generation for small and large fishing boats. (Saeed et al., 2020a)

4.1. Use of excess heat onboard fishing vessels

In combustion engines, around half of the energy supplied by fuel is converted into mechanical energy for driving the propeller(s) and/or electric generators. The remaining half is lost as heat in exhaust gases at 300-400°C and in cooling water at 40°C - 90°C. This waste heat can be used for space heating and domestic hot water needs, but also for refrigeration, power generation, de-icing, and freshwater production. (Palomba et al., 2019), as well as thermal processes for the utilisation of marine raw material, like enzymatic hydrolysis. However, waste heat recovery (WHR) on fishing vessels is almost limited to the heating of tap water, while space heating is supplied by electric heaters. For factory trawlers, their large steam/hot water demand is normally supplied by WHR boilers.

As more ships are being equipped with hybrid electric propulsion systems, such as combustion engines in combination with batteries, the waste becomes limited both in terms of temperature, amount, and time. Thus, innovative systems for thermal energy supply are needed. One option is to utilise surplus heat from the refrigeration system or from the battery cooling water. Since these heat sources is normally available at lower temperature levels, a heat pump might be needed. R-744 heat pumps, already used in land-based applications, are suitable due to their compactness and easily detectable refrigerant. However, the systems must be adjusted for fishing vessel applications, considering the large variation in operating conditions.

4.2. Processing of rest raw materials

Most catch are brought to land processing plants either as whole fish or gutted. When gutted, the rest raw material, such as viscera, must be handled in addition. These products deteriorate even faster than fish meat but, if properly treated, can be converted to high-value products used in the food and pharmaceutical sector (Wijayanti et al., 2016). Various thermal processes for this have been evaluated, including the energy requirement.

Fish protein hydrolysate (FPH) is produced from hydrolysation techniques which involve the breakdown of fish proteins and fats (Damodaran and Paraf, 2017). The reaction usually takes place in a controlled condition, and the most used techniques are enzymatic hydrolysis and chemical hydrolysis, the former being a more sustainable process (Šližyte et al., 2014). The hydrolysation process itself requires a maintenance temperature of 50 °C for a few hours with subsequent sterilisation (90 °C) and separation of bones and insoluble particles. Proper utilisation of the bones and insoluble parts (both rich in proteins) reduces the carbon footprint of the production process. Total energy requirement, with 1:1 ratio of water and enzymes using energy-efficient techniques, varies in the range between 606 and 3315 kWh/tonnes of RRM.

Since liquid FPH contains up to 95% moisture and is highly unstable, a drying process at high energy consumption is required (Petrova et al., 2018). Conventionally, spray dryers convert liquid FPH to final powder state, with an energy consumption of around 4500 and 11500 kJ/kg of moisture removed (Mujumdar, 2014)

Freeze concentration is a novel technology to maintain high quality and low environmental impact. The process utilises freezing point depression to transfer free moisture into the ice with its subsequent separation and cleaning, as schematically shown in Figure 4. The standard process, using the suspension method, can concentrate the hydrolysates to 30% solids. This can be increased further up to 60% by using two-stage freeze concentration techniques with an energy use of 900 kWh/tonnes of RRM. Khan (2022) and Leth-Olsen (2022) demonstrated how an R-744 system can be used to provide cold energy at -40 °C for freeze concentration and heat at 50 °C and 90 °C for enzymatic hydrolysation.

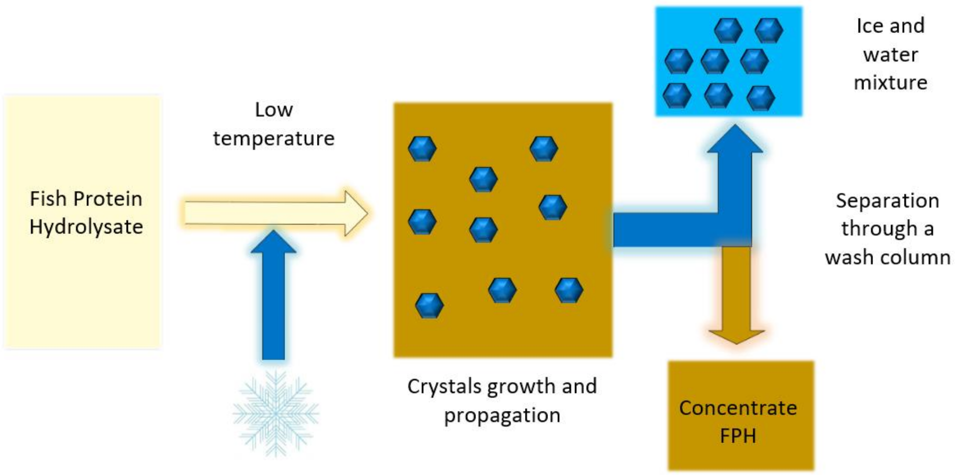

Figure 4. Principle scheme of freeze concentration process

4.3. Cold utilisation from fuel system

The cryogenic fuel LNG (or LBG) is stored on board at around -150 °C, and before entering the engine it is evaporated and heated to between 0 and 60°C. This enables cold recovery from the fuel system, i.e., utilising it for cooling purposes on board. Another fuel that enables cold recovery is liquefied hydrogen, being stored at around -250 °C. To use hydrogen in a combustion engine or fuel cell, it must be evaporated and heated up to around 0°C.

Current implementations of cold recovery in marine vessels are limited to LNG-fuelled passenger ships, where an intermediate water-glycol loop extracts the cold energy from the fuel system and delivers it to the air conditioning or air handling unit system (Baldasso et al., 2020). Selvåg Senior will be the first fishing vessel to utilise cold recovery. The potential for it is dynamic, depending on variations in ship speed and operation conditions (transit, fishing, port), especially for a ship with a hybrid propulsion system. Based on an onboard measurement campaign of a similar diesel-driven vessel (Svendsen et al., 2021), a possible fit between the cooling demand of the RSW system and the available surplus cold on the new Selvåg Senior was identified and explored through dynamic modelling.

Different concepts of integrating LNG cold recovery with chilling and freezing systems were evaluated by Saeed et al. (2020b). A coastal demersal trawler was used as a reference case for the dynamic simulations. The ship was assumed to be equipped with a 760 kW LNG-fuelled engine and an R-744 refrigeration system having an RSW load between 35 and 250 kW and a freezing load of 60 – 270 kW. Applying LNG cold recovery for sub-cooling of the refrigerant showed an increase in COP by 15 % for the RSW system, mainly explained by an increase in evaporation pressure and a reduced vapour fraction after the expansion valve. For the freezing process, the COP increased by around 6%. Thermal storage of dry ice for reduction of peak loads was also simulated.

Synergy effects of processing and refrigeration on board were evaluated by Widell et al (2020), providing an overview of refrigeration technologies and possibilities of utilising LNG cold recovery, as well as the use of cold thermal storage. Given the variety of fishing vessels and, thus onboard refrigeration/processing equipment, the report distinguished between the different processes (air conditioning, chilling, freezing).

5. CONCLUSIONS AND FURTHER WORK

The CoolFish project, a Norwegian initiative focused on knowledge-building, has reached its final phase and has made significant progress since its inception in 2019. The project results have been presented in reports, master theses, scientific papers and presentations, which can be downloaded from the CoolFish website. This paper has given an overview of the main findings within three topics:

- Refrigeration systems and working fluids
- Propulsion systems and fuels
- Integrated cooling and heating

Previous research activities at SINTEF and NTNU has contributed to the development of efficient and safe R-744 systems for various application, including RSW units, supermarkets and industrial heat pumps. A change to energy-efficient systems using natural refrigerants, on a global scale, would lead to a significant contribution to reducing the carbon footprint of the fishing sector. If, instead, the phase-out is done in the "easiest" way to HFCs, the carbon footprint will instead increase than decrease. It is, therefore, of utmost importance for knowledge transfer regarding the use of natural refrigerants. It has also been shown that most fishing vessels still use R-22, with both high ozone-depleting potential and global warming potential, or R134a, which has high GWP. It is essential to convert to working fluids without ODP and GWP but ensure that the alternatives have no other environmental issues.

There is a clear trend towards hybrid electric propulsion systems, for example, a combination of a combustion engine and a battery package. However, the use of alternative fuels is still limited to a few ships designed for LNG operation. Since hybrid propulsion and alternative fuel influence the whole energy system on board, in addition to being more space-demanding, it is of high importance to develop cooling and heating concepts that are well integrated.

The cooling, freezing and heating systems installed on most types of ships, including fishing vessels, are typically designed, operated and controlled as fully independent systems, neglecting considerable opportunities for energy saving by integrating them. Waste heat from the engine is often used for tap water and room heating. Still, there is also a potential for utilising surplus heat from the refrigeration system, especially if the propulsion systems become more electric. R-744 refrigeration systems can simultaneously meet both cooling demands at different temperature levels and heating demands for domestic hot water and space heating. It can also be easily integrated into air-conditioning systems to control the indoor temperatures of the spaces. The use of cryogenic fuels, such as LNG and hydrogen, opens up a cold recovery unit that can be integrated with refrigeration systems.

It is always necessary to focus on the products, the harvested seafood, that has to be brought to land while keeping the quality as high as possible. This is ensured by gentle handling and fast chilling or freezing after the catch is taken on board.

There are several possibilities for continuing this work with refrigeration systems on fishing vessels. There is a constant development of R-744 systems, and the potential of cold thermal energy storage should also be evaluated. Not all fishing vessels have cooling systems, but most can benefit from them, so there is a potential to develop small- and efficient refrigeration systems. Slurry ice systems are an alternative when there is insufficient space for RSW systems, but fast chilling is needed. Most new fishing vessels have a monitoring system, which can give information about fuel and energy demand, but there is a large potential for improving these systems when it comes to detailed monitoring of the refrigeration system.

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