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Report

CruiZE project– results report

Cruising towards Zero Emissions - Development of innovative and integrated cooling and heating concepts onboard cruise ships

Author:

Cecilia Gabrielii

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Client:

Research Council of Norway, Project 308779

SINTEF Energy Research
Postal address:
Postboks 4761 Torgarden
7465 Trondheim, Norway
Switchboard: +47 45456000
energy.research@sintef.no

Enterprise /VAT No:
NO 939 350 675 MVA

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AUTHOR(S)
Cecilia Gabrielii

CLIENT(S)
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PREPARED BY
Cecilia Gabrielii

SIGNATURE
Cecilia Gabrielii
Cecilia Gabrielii (Dec 19, 2023 12:28 GMT+1)

CHECKED BY
Mette Bugge

SIGNATURE
Mette Bugge
Mette Bugge (Dec 19, 2023 12:29 GMT+1)

APPROVED BY
Petter Egil Røkke

SIGNATURE
Petter E. Røkke
Petter E. Røkke (Dec 19, 2023 13:43 GMT+1)

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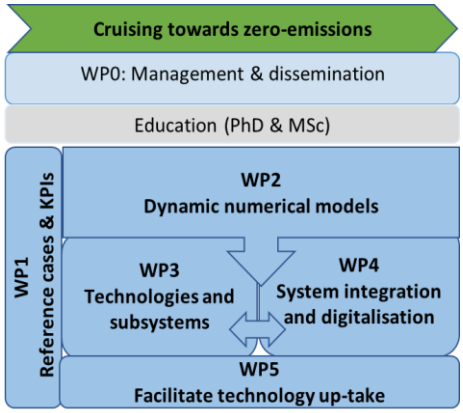
1 Background and objectives

For cruise ships, the energy use of the hotel facilities, such as heating, ventilation, air conditioning and provision refrigeration (HVAC&R) constitute on average 40% of the ships' total energy use. This makes cruise ships significantly different from many other ship segments, where propulsion is by far the largest energy user. Traditionally, a cruise ship's energy demand is supplied by burning fossil fuels, but the cruise industry is facing ever more stringent regulations on emissions, both internationally, regionally and nationally. Today, the heat demand is primarily met through waste heat recovery (WHR) from engines, complemented with an oil-fuelled boiler when there is not enough waste heat. For ships operating in warm climates, the electric power for air conditioning (AC) is a major consumer, and is mostly produced with fossil fuels. Current systems for AC and provision refrigeration use synthetic refrigerants that are harmful to environment and humans.

Many efforts are dedicated towards developing energy-efficient propulsion/power generation systems, including batteries, fuel cells, and combustion engines using "greener" fuels. However, to realise zero-/low-emission operation in a cost- and energy efficient way, it is of key importance to also reduce energy usage of hotel facilities. Also, the change towards "greener" ships influences the total energy system onboard, implying challenges for the hotel's energy supply, such as a more limited availability of waste heat. CruiZE addresses these challenges, aiming to turn them into opportunities, by developing innovative concepts that are well integrated and adapted for the ships' propulsion system and varying operating conditions.

1.1 Objectives

The aim is to develop energy-efficient and environment-friendly concepts for the heating and cooling supply on board cruise ships, aiming at zero-emissions in ports, minimised emissions at sea, and 10-20% reduction in total energy use. The project is divided in five research WPs, representing the five secondary objectives.



WP1: Define industry-relevant reference cases and KPIs, to be used for evaluating innovative technologies and integrated concepts.
WP2: Develop dynamic numerical models, supported by industrial experience, to be used for analysing energy performance and operational strategies of innovative technologies and concepts.
WP3: Suggest design criteria for HVAC&R systems using natural refrigerants, innovative waste heat/cold recovery technologies, and integration with compact thermal energy storage.
WP4: Suggest concepts of preferred combinations of technologies for different propulsion systems and operating conditions.
WP5 (and WP0): Facilitate the technology uptake by addressing barriers, and disseminating knowledge and project results.

2 Research activities and results

2.1 WP1 Reference cases

A set of reference ships and cases was defined, having different characteristics as shown below. The choice of them was primarily based on input from industry partners, complemented with information in literature.

No. of passengers, year of built:	150→5000 passengers, year: 2012-2019
Operational area, season, pattern:	Norway, Baltic, Mediterranean. Winter, summer. Up to 35% of time in port.
Energy supply in ports:	Power: Diesel engines or shore supply. Heat: Waste heat and/or oil boiler
Existing propulsion, fuels:	Combustion engine operating on fuel oil or liquefied natural gas (LNG)
Future propulsion, fuels:	Hydrogen fuel cell and battery. Ammonia combustion engine.

For each case, the ships' heating and cooling loads were estimated based on a combination of operational and design data provided by industry, data available in literature, and through energy balance calculations. A general lack of operational data on the energy use of ship hotel systems was confirmed, making such

estimations challenging. For one ship (3500 passengers), some data were made available, representing a seven-day cruise in the Mediterranean. This ship is further referred to as the main case. A comparative analysis of operational data and design data, at various operating conditions, showed significant deviations.

2.2 WP2: Dynamic models

Models were mostly developed in the Modelica/Dymola environment, enabling detailed physical modelling of technologies and concepts, and analysis of their dynamic energy performance. Based on continuous discussion with industry partners, a set-up of such models was developed. Examples of key models include:

- HVAC&R systems using the natural refrigerant CO_2, including innovative components / configurations.
- Waste heat recovery technologies such as heat-to-power cycles (e.g., Organic Rankine Cycle).
- Compact thermal energy storage (both hot and cold) based on phase change materials (PCM).
- Control systems of innovative waste heat recovery system including thermal energy storage.

Due to lack of operational data, and complexity in technology choice for a specific ship, some complementary models were developed, resulting in a step-wise methodology that is now applied in other projects.

1) IDA-ICE model (building simulation tool) to estimate the ship's heating and cooling needs.
2) Excel model for choice and preliminary dimensioning of technologies, for given thermal needs.
3) Dynamic models in Modelica for analysing performance, design modifications and control strategies.

2.3 WP3 and WP4: Innovative technologies and integrated concepts

The models developed in WP2 enabled evaluation of several concepts, and suggestions on their integration. Since the results of implementing the concepts, e.g., in terms of energy savings, are highly dependent on the ship characteristics, the quantitative results from the project mainly serve as showing the potential.

Innovative HVAC&R systems using the natural refrigerant CO_2. The results show a clear potential for CO_2 as refrigerant, enabling a more compact, flexible and energy efficient system. Depending on the ship's needs, the supply of cooling and/or heating could be achieved at several temperature levels. For example, on ships with limited waste heat (e.g., partly operating on batteries or on low-temperature fuel cells), a CO_2 heat pump could supply the heating needs with less than one third of the energy use compared to a boiler, and at the same time supply some of the cooling needs. For ships operating on LNG or hydrogen (H_2), integrating the AC&R system with cold recovery enables more than 50% reduction in power usage. If these ships also partly rely on battery operation, further improvement can be achieved with a cold energy storage.

WHR technologies such as heat-to-power (H2P). The on-going electrification of ships has increased the interest in H2P solutions. In general, the priority use of WHR should be for heat supply, but any additional high-temperature waste heat could be used for other purposes, such as power production. Results for the main case ship indicates that 5% of the hotel power need can be supplied by H2P, but if combined with a thermal energy storage, the operational and energy performance can be further improved. The H2P potential was also evaluated for a cruise ferry operating in the Baltic Sea, hypothetically with NH_3 as fuel. After having covered all heating needs with WHR, a H2P unit could supply 6% of the ship's electrical need.

Compact thermal energy storage based on phase change materials. The results clearly show that thermal energy storge can play an important role towards zero emission operation, for example when the ship is connected to shore power or operating on batteries, implying that there is no waste heat/cold available. For the main case-ship, the connection to shore power means a four times higher energy use for the oil boiler. Replacing it with an electric boiler would increase the peak shore power need with 50%. A PCM storage tank of 265 m^3, or a water tank of 850 m^3, could cover all hot water demands in port, while supplying the steam needs (for galley, laundry) is not feasible. For the same ship, integrating a CO_2 provision refrigeration system with LNG cold recovery and a PCM storage of 16 m^3, enables a reduction of the power need with 100% for freezing and 70% for cooling. If connected to shore power, the reduction is 80% and 60%, respectively.

Control systems of innovative WHR systems including thermal energy storage. With the more complex and integrated systems, sophisticated control strategies are needed. Using Modelica/Dymola models to evaluate

control strategies was shown useful for this purpose. For example, a model was developed for the engine's WHR system that supplies heat consumers with their varying demands. The dynamic model was applied for evaluating the control of pumps and valves, and for dimensioning a thermal energy storage to maximize heat recovery. The model was further developed in a direct project with one of the industry partners.

The following experimental activities have been performed to support the modelling activities:

- **A full-scale test-rig for a CO2 HVAC&R unit**, developed by SINTEF/NTNU for supermarkets, was adapted to an innovative AC cooling unit for small cruise ships, showing high energy efficiency potential.
- **A pressure exchanger device**, a novel component, was implemented into a CO_2 test rig. Extensive tests were done in the PhD project, confirming the proof of concept and evaluating the energy efficiency.
- **Characterisation of Phase Change Materials** through calorimetric measurements, was performed to confirm suitable properties for use in a thermal storage at temperatures relevant for cruise ships.

2.4 WP5: Facilitation of technology uptake

In addition to dissemination activities (see section 4), two main activities were dedicated for this purpose:

Review of environmental indices, including compulsory regulatory indices issued by IMO, voluntarily indices offered by classification societies, ports etc., which all could serve as incitements for implementing new technologies. However, the critical review clearly showed that heating/cooling systems are either limited, or improperly addressed, implying a need to adapt these indices. Stakeholder discussions were initiated.

Regulations for implementing natural refrigerants are, to some extent, included in rules and regulations issued by classification societies. Based on a thorough review of documents by DNV and LR, several issues were identified, such as "unnecessary" barriers related to CO_2. A dialogue with DNV and LR was initiated, to facilitate the uptake of CruiZE concepts, and will continue in other projects together with industry partners.

2.5 Implementation and use of resources

The CruiZE start-up coincided with Covid-19 outbreak. Since the cruise industry was one of the segments most impacted, the project was also affected. This forced the contracts with industry partners to be issued on a year-to-year basis, and resulted in a total budget reduction of almost 40%. However, collaboration with 3 of 5 industry partners continues in other projects (see below). CruiZE has involved over 20 researchers at SINTEF Energy Research, most of them contributing with expertise from land-based industry, and has educated one PhD candidate and 6 MSc students at NTNU. The PhD student will be employed by one of the industry partners. One MSc student now works at SINTEF, and has a central role in CruiZE spin-off projects.

3 Impact of results

General awareness: Several stakeholders have increased their awareness and knowledge on the importance of ships HVAC&R systems, especially about realising zero-emission operation. The industry's initiation of spin-off projects shows that this is valid not only for cruise ships but also for other segments. This awareness has also led to collaborations with new researchers and industries having their focus on propulsion systems, and also with cruise ports and authorities. The need for operational data on ship hotel systems was confirmed crucial for the uptake of energy saving concepts, and is now addressed in other projects.

Industry: The CruiZE partners have strengthened their role in Norwegian maritime industry, especially by the gained knowledge on natural refrigerants and thermal storage, as well as insights on how dynamic modelling and onboard measurements can help to optimise their systems. The spin-off projects (shown in tables below) will contribute to secure Norway's maritime industry still being in the front. Even though not ship-specific, the quantitative results for the case-ships, together with new competence, will facilitate knowledge-based decision-making, for ship designers, technology suppliers and ship owners. For ship owners, the CruiZE concepts also enables long-term regulation compliance, fuel savings and market advantages (zero-emission).

Spin-off projects from CruiZE

Type of project	CruiZE partner	Research topic	Ship type	Project period
Spin-off projects, initiated by CruiZE industry partners, continuing the collaboration with SINTEF Energy Research				
IPN	Vard Design	Integrated heating & cooling	Offshore supply vessel	2023-2025
RFF	Ulmatec Pyro	Heat-to-power concept	Cargo ships	2023-2024
Forsker-til-låns	Ulmatec Pyro	Control of for WHR system	Explorer cruise ship	2021
Spin-off projects, where CruiZE enabled to include hotel system, and SINTEF Energy Research, in the project				
Industry	-	Pre-study	Hurtigruten coastal ship	2022
Green Platform	Teknotherm, Vard	Zero-emission passenger ship	Hurtigruten coastal ship	2023-2025
FME application	Ulmatec Pyro	Maritime energy transition	Cargo, offshore, fishing	

Collaboration with, or knowledge transfer to, other projects.

Project	Collaboration activities, and/or contribution with CruiZE knowledge	Project period
KPN CoolFish	Joint development of the Maritime Refrigeration Technology Hub (webpage)	2019-2023
KSP Interport	Knowledge on cruise/passengers ships' energy demands during port stays	2020-2024
IPN LowPass	Experience of dynamic modelling, and technology evaluations	2020-2025
KSP PCM Store	Common arrangements on two industry workshops on Thermal Energy Storage	2021-2022

Research field: CruiZE contributes to fill the gap of maritime research on WHR for zero-emission operation, implementation on natural refrigerant, and holistic evaluations of ships' energy system. The models and experiments, especially for CO2 HVAC&R units, add valuable knowledge also for land-based research fields.

Society: CruiZE's overall goal of developing concepts for reducing the hotel systems' energy use with at least 30% during sea passage and of realising zero-emission operation during port stays or in sensitive areas, was confirmed. Since most concepts are also relevant for other ship types, and operational regions, their implementation can contribute to both Norway's, EU's and IMO's climate goals. Especially the concepts to support zero-emission operation is of high importance for Norway's cruise tourism and value creation.

4 Dissemination

CruiZE's target audience includes ship operators, technology suppliers, cruise ports, maritime authorities and organisations, and the maritime research community. Examples of targeted dissemination activities are:

- Attendance at several seminars organised by cruise ship destinations and owners (e.g., Trondheim Havn, AIDA Cruises, Cruise Norway, Vestlandet Fylkeskommuner), to present and discuss CruiZE topics with different stakeholder, e.g., local politicians, maritime administrations, ship and port owners.
- Publishing in popular science channels (e.g., several blogs and a TU article) to highlight challenges and opportunities with zero-emission cruise ships. This has resulted in several requests for presentations.
- Arranging annual CruiZE seminars for knowledge transfer between researchers and industry partners.
- Presentation at seminar arranged by SINTEF's research centres (e.g., SFI Smart Maritime, and FME HighEff) reaching out to a broader industry (other shipping sector and industry segments).
- Co-organize industry workshops on thermal energy storage involving researchers from various fields.
- Presentations at scientific conferences focused on natural refrigerants in land-based systems. This, to contribute with knowledge transfer between research fields, and extend the conferences' scope.
- The maritimereftechhub.no, issued by CruiZE and KSP CoolFish, provides open information on maritime refrigeration, including briefs of project publications. Webpage updates continue after the projects.
- The spin-off projects ensure utilisation of CruiZE results, both for cruise ships and other ship segments.

5 After the project

The PhD thesis will be submitted Q1-24 and defended in Q2. One scientific journal paper is under review in Thermal Science and Engineering Progress, and one will be submitted to Int. J. of Refrigeration in Jan -24.