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Technological and commercial assessment for Heat-Pump usage in Maritime Application

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Abstract

Ongoing developments in the market and from regulatory side as well as the rising costs for fuel and environtmental impact some of the many drivers towards a emission reduced and in future carbon neutral shipbuilding. Especially in the passenger based maritime field, the energy consumption for air conditioning and heating is on of the biggest factors and provides significant potential for a beneficial usage of environmental friendly heat-pump solutions.
The paper/presentations discusses challenges and technical solutions regarding the implementation of heat-pumps in maritime application, especially ocean and river cruise ships. Therefore, conceptual work, technological developments and industrial experiences are summarized. The survey considers the technical integration regarding operation profiles and scenarios with thermodynamic and electrical efficiency and evaluation of technologies and system integrations with respect to current and expected regulations and safety restrictions. From technical perspective different heat-pump technologies are evaluated together with the chilled water and heating water system compatibility. Supply/return conditions, storage concepts within the system are combined with load scenarios and simultaneous effects. Regarding the electrical compatibility with supply grids and automation, smart demand reply and DC technologies are subject of investigation. In parallel the paper targets Life Cycle impact and cost and total operation costs with maritime operation profiles for different heat pump applications, sizes and system designs. The findings are feeded with actual project data as well as R&D results from funded cooperation projects for efficient and sustainable cabin and accomodation areas on passenger vessels.

Keywords: Maritime Applications; District Heating & Cooling; Hotel Area; Emission reduction

1. Introduction

The heat pump usage is growing in the building sector in Europe since the economic and ecological advantages are obvious. Actual heat pumps are already using R290 (propane) as natural refrigerant.
Also, in the automobile sector with relation to electrical engines, heat pumps gain more importance, whereas CO_2 is widely used as refrigerant.
However, in the maritime industry on ships and offshore installations, heat pumps are not yet state of the art, although the pressure for sustainable end energy efficient heating and cooling solutions is increasing.
A target set by the International Maritime Organisation (IMO) foresees to reduce emissions by 50% by 2050 with a path for evaluation and penalties [1]. Although if a legal agreement in October 2025 was cancelled due to the resistance of the US Government, it is expected to be realized sooner or later. National and local regulations are already being reenforced, as e.g. in Norway where starting 2026, only zero-emission cruise ships will be allowed to operate in fjords featured on UNESCO's World Heritage Sites list.
In addition, ports have established common requirements on cruise ships' emissions during port stays [2].

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Furthermore, European Union is targeting zero-emission technology in EU ports from 2030 for Cruise ships [3]. Further regulation planning will also concern other ship types in the next years [4].
As the cruise ship industry is traditionally the technology leader in shipbuilding industry, technologically and economically approved technologies are likely to be implemented in the rest of the maritime market afterwards. Within this paper cruise ship applications are focused on.

2. Economic aspects

While technical challenges regarding implementation and operation make it less attractive to install heat pumps on ships there are economic aspects representing a high motivation potential for the technology.
The common operation scenario for cruise ships can be pointed out as follows:

- Mediterranean or tropical summer conditions: +35°C, 85% rel. hum.
- Average passenger count: 2.000
- 3/5 port stays vs. sea days
- Electricity generation onboard from main engine (Oil-Gas or LNG)
- Heat generation via waste heat and backup fossil boilers

The common cooling case is further discussed in section 3. Especially for older fleets and specialized excursion tours winter scenarios with sea and port days are gaining more relevance and represent an interesting case for heat pump usage.
For a simplified economic assessment, assumptions and average parameters are considered as summarized in table 1.

Table 1. Input values for heating consumption estimation

Parameter	**Value**	**Symbol**
Indoor temperature	+20 °C	T_i
heat pump engine efficiency	0,4	$\eta_{heat\text{-}pump}$
fossil heat efficiency	0,9	$\eta_{direct\text{-}heating}$
electrical generation efficiency (engine)	0,65	$\eta_{electrical}$
annual operation hours	7008	t_{year}
ambient temperature	… °C	T_a
average heat capacity humid air	1,5 kJ/(kg*K)	CP_a
average density of humid air	1,1 kg/m^3	ρ_a
condensation temperature	T_a+6K	T_C
energy efficiency ratio heating	$T_{condensation}/\Delta T_{effective}$	$EER_{heating}$

Operation hours will be significantly lower in reality due to simultaneous factors and low number of cold operation days, however for illustration purposes this worst case was chosen to highlight the general trend in a relevant scenario field.
As scaling factor for the scenario a fresh air flow of 250.000 m^3/h is used, which represents a larger public area on a cruise ship as e.g. a number of cabin decks, public restaurants or entertainment spaces.
In figure 1 the resulting heating consumption in kWh, the electrical consumption of the heat-pump and the respective EER for heating is shown for an ambient temperature range of -20°C to +20°C. Whereas the direct heating power is a linear function the power for heat-pump operation is sinking reversely proportional to the EER for rising ambient temperatures. As usual the indoor temperature on cruise ship are always held constant. Here, an air-to-air heat pump is considered, whereas ships usually use seawater as heat-sink or heat source as for practical and efficiency reasons as further discussed in section 3 [5].

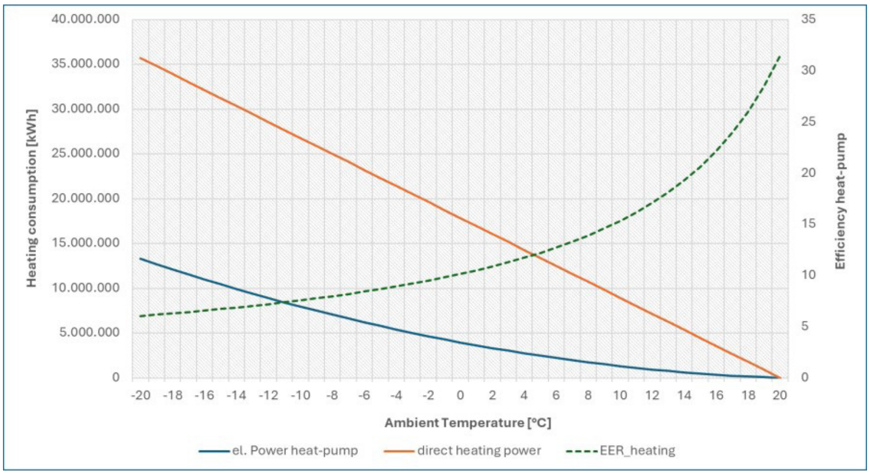

Figure 1. Heat and electrical consumption for EER for heating

2.1. Direct consumption scenarios

For economical comparison of conventional heating with fossil fuels and heat-pump usage some major consideration must be pointed out for cruise ship applications.
State of the art ships are operating with LNG engines and generating electricity with connected transformers. During operation of the engines the main heating demand is covered by waste heat of the engines while local heat demand is covered electrically. Backup heaters with Gas-oil are operating in case of engine stop e.g. in ports or when the waste heat is not sufficient.
Therefore, for comparing the heat-pump with conventional heating the LNG based consumption costs as well as gas-oil consumption and electrical generation costs are compared.
The two cased direct heating via fuel and heat-pump heating are compared by using the equations (1) and (2).

$$\frac{dm_{fuel,\ direct}}{dt}\left[\frac{t}{y}\right] = \frac{\frac{dQ_{heating}}{dt}[kW]*t_{year}\left[\frac{h}{y}\right]*\frac{1}{\eta_{direct\ heating}}}{CR_{heating}\left[\frac{kWh}{t}\right]} \tag{1}$$

Here the fuel consumption is considered in tons [t] based on the caloric heating value $CR_{heating}$ for the different fuels. In case of the heat-pump the required engine power is assumed to be produced by the LNG engine generator. The fuel consumption is corrected by the electrical efficiency.

$$\frac{dm_{fuel,\ heat\text{-}pump}}{dt}\left[\frac{t}{y}\right] = \frac{\frac{dQ_{heating}}{dt}[kW]*t_{year}\left[\frac{h}{y}\right]*\frac{1}{EER_{heating}}}{CR_{generator}\left[\frac{kWh}{t}\right]*\eta_{electrical}} \tag{2}$$

The scenario for the heat pump is therefore affected by two contrary effects. Due to the lower efficiency of electricity generation via LNG in comparison with direct heating (or waste heat usage) the scenario provides a disadvantage. On the other hand the heating efficiency is higher and fuel consumption sinks for high EER values.
A completely different scenario is the port operation when land-based electricity is used. Currently this is not the common case since not many ports are equipped with the required infrastructure as well as many cruise ships and electricity prices are not always compatible with fuel costs, especially when cheap oil-gas is used of heating on ships. However, the enforcement of emission reduction regulations for ships in ports will lead to a significant increase of relevance for this case and therefore the usage of heat-pump based heating in port operation.

2.2. Sanction based cost assumptions

Although usage of heat-pumps for heating on cruise ships is already beneficial from an economical perspective in certain scenarios, this advantage is strongly increased when expected emission regulations with respective penalties are considered [5].
Based on current and upcoming regulations and guidelines for emissions, the CO_2 and equivalent emissions shall be significantly decreased. Measures for reduction are supported by different legislative and regulatory changes, furthermore especially for the cruise ship sector emission reduction is also a key factor for the image and can have market impact, since passengers are considering the carbon footprint and local impact and operational options are increased as in Scandinavian and polar regions [6].
A possible scenario targeted by IMO could lead to penalties on CO_2 emission exceeding agreed limits which might add a major cost factor on all port based and close to shore operation periods.

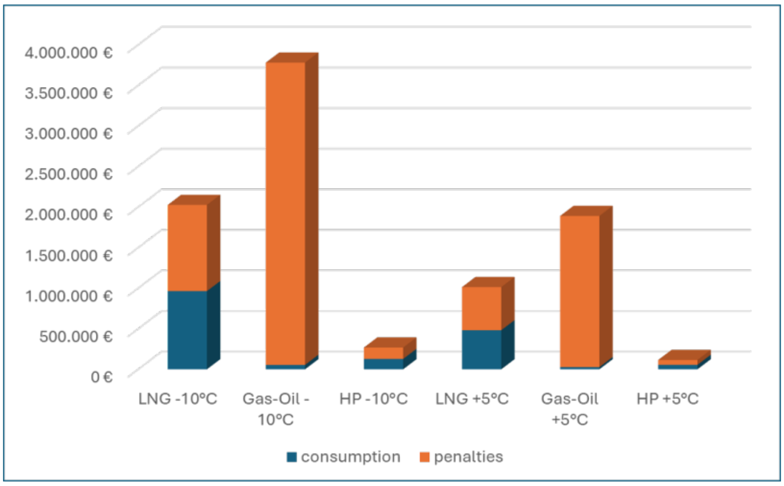

Figure 2. Penalty and consumption based annual heating cost for different scenarios

In figure 2 different scenarios are illustrated to compare LNG based, gas-oil based and heat-pump based heating. Therefore, the following additional assumptions are used [1], [9]:

- Overall fresh air demand: 1.500.000 m^3/h
- Seawater temperature (-10°C): 8 °C; Seawater temperature (+5°C): 11 °C
- Caloric energy LNG: 5.460 kWh/m^3; Caloric energy Gas-oil: 10.319 kWh/m^3
- CO_2 eq. emission per t fuel (LNG): 2,75; CO_2 eq. emission per t fuel (Gas-oil): 3,2
- LNG costs: 78 €/t; Gas-oil cost: 4€/t
- Average penalty costs per CO_2 emission: 86€/t

As clearly shown in the figure the penalty costs quickly exceed the direct fuel costs significantly. For lower ambient temperatures with higher heating demand the effect is increased. In the scenario LNG appears less expensive even if the direct fuel costs are significantly higher due to the reduced emissions.
It must be pointed out that the scenario shown is only a prognosis based on planned legislation changes, however the IMO even targets penalties of 100-400 USD depending on different emission corridors beyond the allowed level. Again, the usage of heat-pump is based on onboard produced electricity with LNG. Of course, land-based electricity usage would significantly improve the economic and ecological evaluation since penalties would become zero considered that grid electricity is produced renewable.

3. Technical constraints

For understanding the challenges for technical integration of heat-pumps on cruise ships this section summarizes the major constraints which are common before focusing on different potential scenarios.
The major case for Cruise-ships is high ambient temperature and humidity. For an optimal usage of spaces for passenger accommodation and entertainment technical spaces are minimized and located on the lower decks, while all areas must be air conditioned. Considered are ambient temperatures between -10°C and +35°C with rel. humidities of 55% – 90%, maximal seawater temperatures at sea +32°C and in port +35°C.

Usual simultaneous factor for HVAC are 55-90%. In addition, high comfort levels, enthalpy recovery demands and strict regulations regarding safety and fire protection (affecting flammable and toxic refrigerants) are relevant.
The economic relevance of the heating case has been illustrated in section 2. For a practical approach it is meaningful to distinguish between two major concepts: a large centralized system and smaller decentralized units. In a centralized system a heat-pump uses seawater as heat-source and is placed in the machinery deck, close to the main engines. As seawater temperatures are always over 0°C and slowly changing a high EER and constant operation points are reachable. Since the heat consumers are located all over the ship a widespread heating water system with hydraulic control function is installed. As during maneuvering of the ship waste heat from main engines is available, the dimensioning of the heat pump is based on port operation. For ships with electrical engines (zero emission operation) this could significantly change. Here, the current state of the art with LNG engine is considered only. A more relevant approach is decentral heat-pumps for accommodation spaces, further described in section 4.2.
Cooling scenario as previously mentioned is the common case on a cruise ship and therefore the major basis for system dimensioning. An average sized ship for around 2.000 passengers can easily exceed central installed cooling capacity of 20 MW. Of course, these require large units and a high energy efficiency since air conditioning is the major consumer of fuel after the main engines. The coefficient of performance (COP) is supposed to be minimum 5 for an actual chilled water unit, which is the benchmark for heat-pump systems.
The usual technology in use is turbo-core compressors with 4-5 separate units due to redundancy requirements. In addition, the currently valid regulations from classification societies limit the usability of natural refrigerants such as R290 (propane) or R717 (ammonia). With changing regulations regarding emissions and f-gases the usage of heat-pumps with natural refrigerants as in the building or mobility sector regarding trains and automobiles might become more relevant. An adequate system integration with thermal storage and predictive demand control will be key factors.

4. Actual developments and projects

As described, the usage of heat-pumps on ships is not yet the common case for several limiting factors such as technical integration, operation scenarios and missing regulation-based pressure. With respect to the prognosis of upcoming legislative changes, there are some ongoing developments and investigations for heat-pump integration worth mentioning.

4.1. Sustainable ship cabins ReCab

Within the funded project "ReCab" (BWME, FKZ: 03SX623E, 2024-2027) a sustainable ship cabin design considering a gradle-2-gradle design is being developed. The concept foresees the post or parallel usage of cruise ship cabins in land-based applications for living to avoid disposal and recycling impact. Therefore, the design respects both maritime and land-based regulations and system integration factors. Among the manufacturing approach, material and interface topics the air conditioning plays a major role in the design. Small decentral heat-pumps with natural refrigerant are investigated hereby as promising alternative. First presentable results are expected in 2026.

4.2. Decentral Heat Pumps

A promising approach which is currently being investigated from different perspectives is the usage of decentralized heat-pumps which are directly using fresh air from a nearby air inlet. Those shall replace actual Fan Coil units which are connected to the chilled water system and central Air Handling units and produce cold and heat independently. Among the potential of energy saving operation, usage of local heat-pump could also save weight and costs for ducting and piping systems from central units to the local consumers in accommodation areas. Investigated areas for this approach are especially spaces with high local heat loads and a general accessibility to outside spaces where air outlets and inlets could be placed, as sketched in figure 3.
While the thermodynamic evaluation and comparison with central system layouts is highly promising and indicates that such systems could provide major advantages, there are some barriers to overcome. Safety regulations for passenger ships, especially regarding usage of natural refrigerants as of the current validity represent a limitation and require holistic concepts for fire prevention and evacuation. Additional gas-warning systems and protective housings are cost drivers. Furthermore, the logic of passenger ships where a high demand for comfort is presents also regarding sound and smell and outside areas are valuable spaces, the

integration of required air inlets and outlets with high air flow amounts is a technical challenge. Ongoing research development efforts might lead to applicable solutions soon.

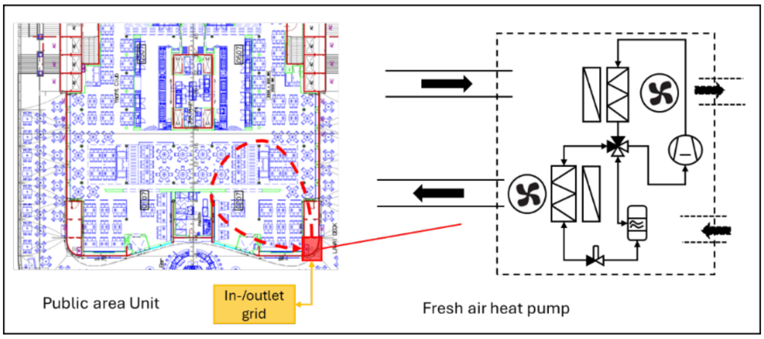

Figure 3. Conceptional sketch of decentral heat-pump units for public cruise ship areas

5. Conclusion and Outlook

Heat-pumps in maritime applications, especially on passenger ships, are not yet commonly used but a promising alternative which might become even more compatible when future regulations increase costs for CO_2 emissions. Ongoing research and development projects are working on technical solutions for efficient system integration and safe operation. Different operational and economic scenarios illustrated show a high cost saving potential among the ecological benefits, if a balance of technical and regulation constraints is agreed.

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