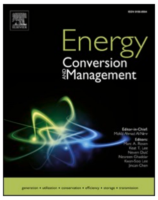
Energy Conversion and Management 288 (2023) 117121

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman



Energy use and energy efficiency in cruise ship hotel systems in a Nordic climate

August Brækken[a,*], Cecilia Gabrielii[a], Natasa Nord[b]

[a] SINTEF Energy Research, Postboks 4761 Torgarden, NO-7465 Trondheim, Norway
[b] Norwegian University of Science and Technology, Department of Energy and Process Engineering, NO-7491 Trondheim, Norway

ARTICLE INFO

Keywords:
Cruise ships
Passenger ships
Energy efficiency
Building energy simulation
Energy analysis

ABSTRACT

In light of climate change, the shipping industry is committed to reducing its greenhouse gas emissions. When transitioning from fossil fuels to low-carbon fuels, it is crucial to also reduce the ships' energy need. For cruise ships, the hotel system is a major energy consumer and the focus of this paper. This study aims to investigate the energy use of an existing fossil-fuelled cruise ship operating in a Nordic climate, and evaluate the effectiveness of various passive and active energy-saving measures. For this purpose, a dynamic energy model of the hotel system was developed in the building simulation tool IDA Indoor Climate and Energy (IDA ICE), including a customised weather file. Validation of the model was achieved through comparison with literature and some operational data from the actual cruise ship. Simulation results showed a total annual energy use of 55 MWh/passenger, with the hotel system accounting for 20%. The passive measures, such as increased insulation and improved windows, each resulted in less than a 1% reduction in the hotel's annual energy use. Larger energy savings were achieved by using heat pumps (38%), improved ventilation system (8–24%), and heating setback in port and during the night (5%). A hot water storage tank, charged with the engines' waste heat during sea operation, could reduce the use of auxiliary boilers, especially in port. A hot water tank of 600 m^3 could cover 97% of the heating demand in port, thereby minimising the use of fuel-fired boilers.

1. Introduction

The shipping sector, including cruise ships, contributes to large greenhouse gas emissions worldwide. Reducing emissions from ships is therefore necessary to limit the devastating effects of climate change. For cruise ships, the hotel system accounts for around 40% of the energy use on board, though this is rarely considered when it comes to evaluating emission reduction measures, as the focus is usually on the propulsion system [1]. In light of the International Maritime Organization's (IMO) decarbonisation targets, the last few years have witnessed an increase in studies focusing on alternative energy sources, regulatory frameworks and financial incentives [2–4], as well as novel waste heat recovery (WHR) technologies for producing electricity or cooling energy [5–7]. However, innovative technologies for reducing the thermal energy needs on board are rarely addressed. This includes passive designs, or innovative solutions for thermal energy supply, such as heat pumps and thermal energy storage (TES). Furthermore, as reviewed in [8], there are limited studies that consider the dynamic behaviour of cruise ships' thermal loads, i.e. the transient indoor and outdoor conditions, as well as passenger occupancy and behaviour. Most studies are instead based on the steady-state approach and design conditions specified in ISO 7547, leading to non-optimised thermal energy supply.

To achieve international and national emission targets, alternative fuels and propulsion systems are being introduced, which implies challenges related to large space requirements and reduced availability of waste heat. Therefore, reducing the hotel system's energy use is crucial, and the main motivation for this study.

1.1. Cruise ships' energy use

Even though many studies conclude that a cruise ship's hotel functions are a large contributor to the total energy use, studies focusing on estimating the hotel energy demand are scarce [9]. In [10], the power usage of 20 cruise ships visiting ports in Norwegian heritage fjords was estimated to be 1–4 MW for ships with 500–1000 passengers, and 5–10 MW for 2000–3000 passengers. Data on hotel energy use during port stays in Alaska were analysed for 11 cruise ships with 1900–3100 passengers [11]. The hotel power load ranged from 4.1 to 11.5 MW, corresponding to between 1.9 and 4.1 kW per passenger. It was evident that

---

[*] Corresponding author.
E-mail address: august.brakken@sintef.no (A. Brækken).

https://doi.org/10.1016/j.enconman.2023.117121
Received 2 January 2023; Received in revised form 26 April 2023; Accepted 27 April 2023

Nomenclature

Terms

Bulkhead	Vertical wall in a ship, separating rooms or compartments
Deck	Horizontal structure separating levels of the ship, or the level itself
Galley	Kitchen in a ship
HVAC auxiliary	Fans and pumps in the HVAC systems
Roll-on/roll-off	Vehicles driving onto/off the ship

Abbreviations

AC	Air conditioning
AHU	Air handling unit
BC	Base case
CAV	Constant air volume
CO_2eq	CO_2 equivalent
COP	Coefficient of performance
DCV	Demand-controlled ventilation
DHW	Domestic hot water
EGB	Exhaust gas boiler
FWG	Freshwater generation
HES	Heterogeneous energy storage
HFO	Heavy fuel oil
HT	High-temperature
HTHP	High temperature heat pump
HVAC	Heating, ventilation and air conditioning
IDA ICE	IDA Indoor Climate and Energy
IGU	Insulated glass unit
IWEC	International weather for energy calculation
LT	Low-temperature
MDO	Marine diesel oil
ORC	Organic Rankine cycle
PCM	Phase-change material
PV	Photovoltaic
Ro-Pax	Roll-on/roll-off passenger vessel
Ro-Ro	Roll-on/roll-off
RS	Reference ship
TES	Thermal energy storage
TRNSYS	Transient System Simulation Tool
VAV	Variable air volume
WHR	Waste heat recovery

Units

Met	metabolism, 1 met = 58 W/m^2 body surface

larger ships have a larger hotel load per passenger, probably explained by an increased number of "leisure facilities" in order to accommodate the passengers. The heat supplied from auxiliary boilers ranged between 1 and 7 MW, corresponding to 0.5–3.3 kW/passenger. However, the actual heating demand is larger, as waste heat from the auxiliary engines is also used for heating purposes. In [12], the energy analysis of a cruise ship operating in the Baltic Sea showed that 45% of the annual energy demand is related to propulsion, while the auxiliary electric power and heat demand represent equal shares of the remaining part. In port, the energy use for heating purposes constituted 34% of the total energy demand.

In [13], electrical and thermal demand curves were presented for a large cruise ship based on design documentation from the ship builder. Daily variation was only considered for the sanitary hot water demand, while the difference between port stay and sea passage was only considered for freshwater generation (FWG). The electrical load for hotel functions was assumed constant at 6 and 9 MW for winter and summer conditions, respectively. The heating demand (supplied by steam) was around 8 and 4.5 MW, respectively, but with a large daily variation in terms of the demand for sanitary hot water. There are also a few studies that aim to develop equations for estimating the power demand and fuel use for hotel services, e.g. for a fuel-cell driven expedition cruise vessel in [14], for cruise ships sailing in Norwegian waters in [15], and for cruise ships berthed in port in Barcelona in [16].

Based on the ships' fuel consumption, several studies focus on emissions from cruise ships, especially during port stays. In [17], detailed emission inventories in the port areas were shown to act as an important basis for designing emission reduction measures. However, as highlighted in [18], the fuel consumption of auxiliary boilers, used to supply steam and hot water, is often neglected in ports' emission statistics, which only include the engines' fuel use. When boiler fuel use was included in the statistics, the total annual emissions increased by 22% compared to the previous year, even though the engines' fuel use had decreased by 9%.

Establishing shore power supply in port, i.e. eliminating the need for running the engines to generate electricity, is a common measure to reduce local emissions in port. However, if the national electricity mix is not 100% renewable, these emissions should also be considered [19]. Only a few studies address the fact that onshore power supply increases the need for thermal energy supply. In [20], the electric power demand for 24 cruise ships was estimated to be between 1 and 12 MW, while the need for thermal energy was estimated to be 0.3–2.2 MW. It was emphasised that this thermal demand will increase when the ship is connected to shore power because waste heat from the diesel-electric generators is no longer available. A report evaluating measures for the realisation of a Norwegian zero-emissions port [18] concluded that, although some of the ships use shore power, a large portion of the emissions will persist due to a significant heating need, which must be met by boilers. For ships with 1000–5000 passengers visiting two major Norwegian ports, a heating demand between 1 and 5 MW is expected. If the ship is not connected to shore power, 1/3 of the thermal energy is assumed to be supplied by boilers, while 2/3 is from the waste heat available when the auxiliary engines are running.

For ships connected to shore power, there are essentially three alternatives for avoiding an increased use of fuel-fired auxiliary boilers in port: i) install electric boilers on board and increase the shore power capacity [18], ii) supply heat from shore, e.g. from a district heating network [21], or iii) install a TES that is charged with waste heat from combustion engines during sailing [22].

1.2. *Dynamic simulation of energy performance*

The impact of energy-saving concepts depends largely on how they are operated in relation to the ship's dynamic operational profile, with differing energy demands at sea or in port, and for different weather conditions. Therefore, dynamic simulations of typical cruise ship operations are necessary in order to compare their potential savings [23]. The development and validation of dynamic models representing the thermal energy system of a cruise ferry were presented in [24], which showed the significant benefits of using dynamic simulations when evaluating thermal energy-saving solutions, for both newbuilds and existing ships. In [25], the Transient System Simulation Tool (TRNSYS) was used to evaluate various WHR technologies for producing cooling energy, freshwater, and additional electricity. Both the ship envelope and the related plants were modelled in detail and simulated using dynamic profiles for occupancy, equipment load, ventilation load and ship orientation. The same approach was applied to a hypothetical cruise in Norwegian fjords, also including fuel cells and shore power supply [8].

In addition to TRNSYS, other building energy performance tools, such as EnergyPlus and IDA Indoor Climate and Energy (IDA ICE), are frequently used in the literature to simulate energy use and evaluate energy-saving solutions for land-based buildings, often with a focus on passive designs. Even though there are a few examples of studies using TRNSYS to simulate ships' thermal energy performance, none of them address passive measures. In [8] and [25], a 3D model of a large cruise ship was implemented in TRNSYS to optimise the WHR system when operating in Norwegian and Mediterranean waters, respectively. Indoor spaces with similar air temperature setpoints, internal gains, and heating, ventilation and air conditioning (HVAC) systems were grouped together in thermal zones, and a customised weather file was created based on hourly changes in geographical position and orientation.

1.3. Passive energy design

Research on passive energy-saving measures for maritime applications is still limited, despite a growing interest from ship owners and designers, and the potential savings shown in previous studies. For example, passive design measures such as advanced shading and natural lighting could potentially offer an annual CO_2 emission reduction of 10% for a cruise ship operating in the Mediterranean [26]. In [27], various passive, and active, energy-saving measures for passenger cabins were evaluated based on steady-state models and estimated user profiles. The most promising technologies were water recycling showers, waste-water heat recovery, LED lighting, lighting control using daylight sensors or presence sensors, variable air volume (VAV) ventilation, improved cabin windows, and active balcony door shading. Evaluation of passive designs for an offshore accommodation unit in the North Sea showed that extra insulation, local shading, and photovoltaic (PV) facade panels reduced the annual energy use by around 120 MWh, which corresponds to more than 10% of the total energy use [28].

There has been a significant increase in the use of large glass windows in cruise ship designs. Insulated glass units (IGUs) are applied to reduce heat loss, but do involve questions about structural issues. However, the insulating gas between glass panels might actually improve the structural performance, enabling a reduction in weight or an increase in window size [29].

1.4. Heat pumps and solar power

Heat pumps play an important role in the decarbonisation of industry and the building sector, but maritime applications are almost nonexistent. However, the electrification of the shipping sector, including shore power and battery operation, has resulted in an increased interest in heat pumps from ship owners and designers. Heat pumps could also be beneficial on conventional ships, as they enable the utilisation of the low-temperature (LT) engine cooling water, which is typically dumped in the sea. Yet, studies in literature are rare. In [23], heat pump concepts utilising LT water as a heat source were evaluated, either for preheating potable water or for simultaneously supplying chilled water for air conditioning (AC) and preheated potable water. Both concepts showed an increase in total energy efficiency, particularly if also combined with an organic Rankine cycle (ORC) to produce extra electricity. A high temperature heat pump (HTHP) that recovers engines' high-temperature (HT) cooling water to produce steam at 6 bar absolute pressure was proposed in [30]. The same authors also suggested a WHR configuration based on a reversing operation of an ORC/HTHP, which would enable electricity production at sea and steam generation in port, respectively. For several ship segments, the largest fuel savings were achieved with the combined HTHP/ORC, while for cruise ships the HTHP alone was most beneficial. In [31], a heat pump was suggested for recovering various waste heat sources on a military vessel in order to supply space heating and potable water heating, which are currently supplied using electricity. Another suggested application is the use of a hybrid heating system consisting of an air-source heat pump and an exhaust gas boiler (EGB) to heat a cruise ship's swimming pool [32].

Following the electrification of the shipping sector, several studies verify the possibilities of obtaining additional electricity from onboard PV panels. A theoretical evaluation of a solar array layout for a Ro-Ro (roll-on and roll-off) vessel in the Mediterranean showed an annual PV power production of 334 MWh, corresponding to a 7% reduction in fuel use [33]. When evaluating the benefit of PV panels, the performance prognosis must address short-term changes in solar irradiation and shading [34]. Partially shaded areas should also be considered for installation due to limited available space [35]. Seawater cooling of the panels has been suggested for improving the efficiency of a PV system for a Ro-Ro passenger (Ro-Pax) ferry operating in the Baltic Sea [36].

1.5. Thermal energy storage

TES enables the storage of the engines' waste heat for use when it is needed. This is especially relevant for cruise and passenger ships, where the maximum waste heat production is often at nighttime when sailing at high speed, while the peak demand is during the day. In 2012, a cruise ferry operating in the Baltic Sea was equipped with a TES that consisted of two hot water accumulator tanks with a total volume of 88 m^3, heated with excess steam from EGBs. The TES system was later evaluated using dynamic simulations, confirming that the TES size was appropriate for its current use, which is restricted to short port stays, and only for HVAC reheating purposes. To cover heat demands that require higher temperatures or steam, e.g. for galleys and laundry, a pressurised tank or steam accumulator is needed, the former being preferable due to space limitations [24]. With upcoming requirements for zero emissions in ports and other sensitive areas, a TES enables periods of zero-emission heat supply, as illustrated for a cruise ship operating in the Baltic Sea, where a TES could eliminate the use of auxiliary boilers during port stays [37]. TES installations are also relevant for other ship segments with large thermal energy needs in port, for example tanker ships, as exemplified in [38]. Here, a simple TES system, with thermal oil as the storage medium at a minimum storage temperature of 100 °C, was used to cover the heat demands of a product tanker during port stays, including accommodation, fuel tank heating and cargo tank cleaning. The results showed that a 1000 m^3 storage tank could reduce the boiler fuel use by 80%.

One challenge with using TES on board ships is the space limitations, which could be addressed by using a phase-change material (PCM) as the storage medium. Integrating PCM storage in space heating and domestic hot water (DHW) applications for buildings has been reviewed in [39] and demonstrated in [40], while a prototype for PCM-based steam storage was piloted in [41]. Studies addressing maritime applications are limited to a few studies on cruise ships. In [22], dynamic simulations were used to evaluate the suitability of a PCM-TES for covering the hot water demand during port stays on a 5000-passenger cruise ship. The results showed that a 143 m^3 TES water tank with embedded PCM resulted in a 40% lower peak boiler heating demand, compared to a storage tank without embedded PCM. With an intended use on board cruise ships, a lab-scale TES consisting of macro-capsules filled with PCM was developed and tested at typical operating conditions for a winter and summer cruise [42].

Studies on TES for maritime applications often propose integrating it with other WHR technologies, such as an ORC in order to supply zero-emission electric power in port when there is no access to shore power [43]. This solution could also include an absorption refrigeration system in order to enable cogeneration of electric power and cooling energy [44]. A heterogeneous energy storage (HES), including a battery and a thermal storage tank, was shown to reduce fuel use and improve quality of service by ensuring that the indoor temperature and hot water supply stay in the desired range [45]. In [13], an optimisation of the energy system for a large cruise ship was performed, including several potential technologies, such as an ORC, absorption refrigeration, PV panels, and solar thermal collectors, as well as a TES for hot water or steam. In the optimal energy system, no steam TES would be installed, but a hot water TES (90 °C) with a capacity of up to 50 MWh should be included, not only for heating purposes but also for cooling (absorption refrigeration) in summer and for electricity production using an ORC. Neither the PV panels nor the solar thermal collectors should be installed, due to the size penalty and the large availability of waste heat.

1.6. Aim of this study

Based on this literature review, there is a need for more studies that estimate the dynamic energy usage for ships' hotel systems and evaluate energy-saving measures that are not exclusively related to WHR. Therefore, the aim of this study was to assess how various innovative energy-saving solutions can decrease the annual energy use of a cruise ship's hotel system in a Nordic climate. To achieve that aim, a simulation model for the hotel system of an existing cruise ship was developed in the building simulation tool IDA ICE and validated with operational data from the ship. The model was then used to evaluate various energy-saving solutions, including passive design measures, TES and heat pumps. Finally, extensive analyses of the simulation results were performed to find the most energy-efficient solutions. The main novelty of this research lies in that, to the best of the authors' knowledge, it is the first study to use IDA ICE for ship applications and evaluate both passive and active energy-saving measures based on a cruise ship's actual operating conditions.

Section 2 outlines the methods of the study, mainly describing the development of the simulation model, while section 3 presents and discusses results from the energy simulations, including the results for the chosen efficiency scenarios. Finally, section 4 presents the conclusions of the study.

2. Methods

This work is based on a simulation model developed in the building simulation program IDA ICE. Fig. 1 illustrates the applied methods, where IDA ICE was used to model the hotel system, while MATLAB was used to consider the engine system in postprocessing. This chapter describes the case ship and reference ship, the development of a weather file for the case ship, as well as the modelling of the case ship, including ship construction, internal loads, the ship service systems, and the energy supply system. Finally, the energy efficiency scenarios considered in the analysis are described. More details can be found in [46].

2.1. Description of the case ship and reference ship

Color Line's cruise ship Color Fantasy was used as the case ship, which means that the available design data for this ship were used as a basis for the modelling and energy analysis. The cruise ship MS Birka Stockholm was used as a reference ship for comparing and calibrating the model. This reference ship was chosen because its size and operational climate zone are similar to the case ship. In addition, energy-use data for the reference ship have been published, allowing for this comparison. Table 1 contains key information about the case ship and reference ship.

Color Fantasy is the world's largest cruise ship with a car deck [47], i.e. a Ro-Pax ship. It sails between Oslo, Norway, and Kiel, Germany, and stays in port between 10 a.m. and 2p.m., alternating between Oslo and Kiel every other day [48]. The ship has several restaurants and shops, a casino, a show lounge, a spa and fitness centre, a conference centre, and the Aqualand water park [49]. The ship has four main engines and four auxiliary engines, all operating on marine diesel oil (MDO), which supply propulsion and electric power, respectively. The thermal needs are supplied through WHR from the main engines' EGBs, and from auxiliary boilers when needed, i.e. when the main engines are shut off or when the heat demand exceeds the recovered heat. It is important to note that when the main engines are running, all available waste heat is recovered through the EGBs. If this recovered heat is larger than the heat demand, the excess heat is heat exchanged with seawater, i.e. wasted.

The reference ship, MS Birka Stockholm, is a cruise ship without a vehicle deck, operating between Stockholm and Mariehamn, making one round-trip every day. The ship spends around 33% of its time in port or stopped for a night stay at sea. It has a similar energy supply system to the case ship, but also has EGBs installed on the auxiliary engines, and utilises heat recovery from the engines' HT cooling water [37].

2.2. Weather file for the case ship

To describe the weather conditions that the case ship experiences between Oslo and Kiel, IWEC (International Weather for Energy

Table 1
Key information about the case ship [47] and the reference ship [12].

	Case ship	Reference ship
Launched [year]	2004	2004
Passenger capacity	2400	1800
Passenger cabins	966	900
Car capacity	750	0
Length [m]	224	176.9
Width [m]	35	28.6
Shore power	Yes	No

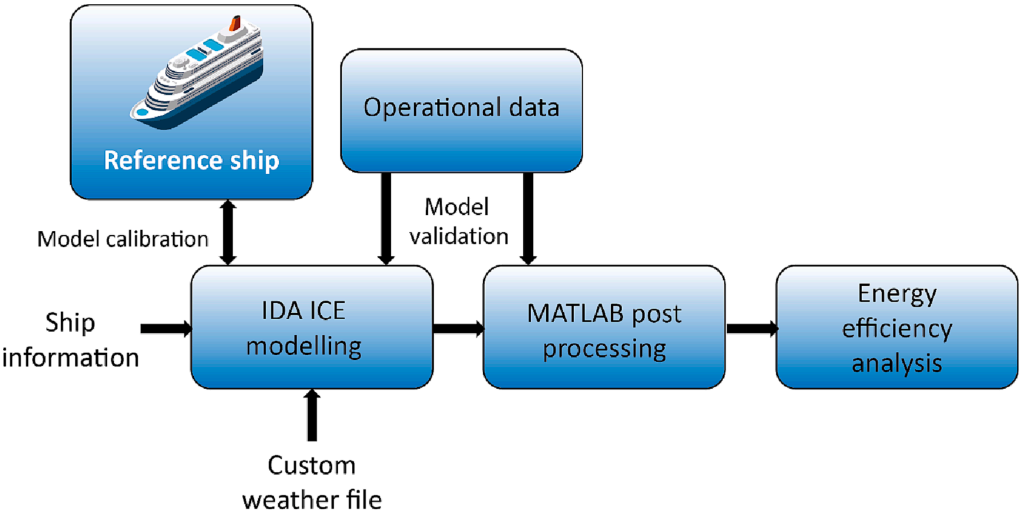


Fig. 1. Applied methods.

Calculation) files for several onshore locations near the ship's route were combined into one file. The files include hourly values for air temperature, wind speed, relative humidity, solar irradiation, and sky cover for one year. Previous work showed that including offshore wind data and the ship's speed did not significantly impact the simulated energy consumption [46], and therefore only onshore wind data were used here. Table 2 shows all the locations used, listed from north to south, as well as the estimated number of hours spent in each section on the 20-hour journey between Oslo and Kiel. Fig. 2 shows the locations marked on a map.

As a simplification, the front of the ship was assumed to be facing south on the way from Oslo to Kiel, and north from Kiel to Oslo. It is not possible to rotate the ship in IDA ICE during a simulation run. The ship's varying orientations were therefore taken into consideration by running simulations with the ship facing north and south, and combining these results with the ship facing north and south on alternating days.

2.3. Ship zone modelling

To reduce the modelling and simulation time, zones with a similar size, orientation and internal loads were represented by one zone using zone multipliers. This was especially useful for cabins, where the 966 cabins on board were represented using only 16 cabins. Officers' quarters, meeting rooms, galleys, and vehicle decks were also modelled using representative zones and zone multipliers.

For the larger areas of the ship with specific shapes and usage, each zone was modelled individually. This includes the restaurants, show lounge, promenade, and the spa and fitness centre. Zones with complex shapes were simplified, maintaining the correct total area. Fig. 3 shows the 3D model of the ship in IDA ICE, where the ship is facing towards the left. The front half of the ship is shown on top and the back half is shown on the bottom.

For walls with several windows, the windows were combined to simplify the model. Internal doors on the same wall were also combined. External doors were not included, as they were assumed to not significantly affect the thermal insulation of the ship envelope.

The height of cabin decks was set to 2.1 m. For decks with public areas, the height was set to 2.5 m, except deck 6, which was estimated to be 3 m [49]. The floor area of the vehicle decks was estimated based on the car capacity and the trailer lane metres. The heights of the car decks and trailer decks were estimated to be 3 m and 5 m, respectively.

Using the deck plan for the case ship [51], the gross internal area of the ship was estimated to be 62,271 m^2. Assuming 1% of this is internal walls, the required net internal area is 61,648 m^2. A general zone was created to reach this value. As most corridors in the ship had not been modelled, the zone was based on a large corridor with windows facing both sides of the ship. To achieve the desired total area, a zone multiplier of 57.7 was used for this zone. In total, 54 different zones were modelled on the ship. When zone multipliers are considered, this results in a total of 1323.7 zones.

2.4. Ship construction

The basic construction used for walls, ceilings, and floors consists of two 4 mm steel plates with insulation between. Vertical air gaps, wall panelling, and carpets were included where relevant. The insulation used in the ship construction has a thermal conductivity of 0.036 W/(m•K). Table 3 shows the thickness of insulation used in the constructions and the U-values achieved. U-values for the window glazing and window frames are also included. All thermal bridges were estimated to be "poor" in IDA ICE. Distribution system losses were set to "typical".

Table 2
Locations used to represent the ship route, and the estimated time spent in each region while cruising.

Location	Time [h]
Oslo, Fornebu	1
Sandefjord, Tjøme	4
Fredrikshavn, Skagen	5
Fornæs (cape)	4
Odense, Beldringe	4
Eckernförde, Holzdorf	2

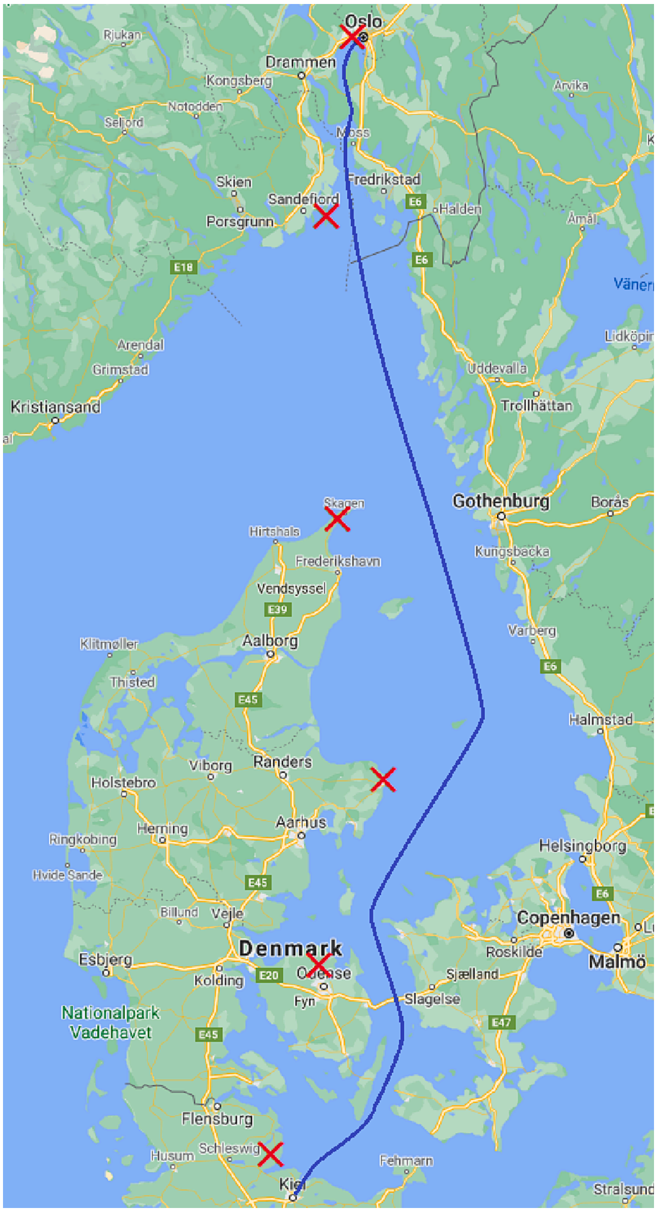


Fig. 2. The six locations used in the weather file, marked with red crosses. The ship's approximate route is marked in blue [50].

2.5. Internal loads

This section describes the internal loads, considering occupants, lighting, and electrical equipment.

Occupants on board release heat to the zones. The number of occupants in the cabins was set to the maximum number of adults who can sleep there [52]. The average activity level for occupants in cabins was assumed to be seated and relaxed, giving an internal heat production of 58 W/m^2 body surface, defined as 1 met [53]. The occupancy schedule used for cabins was based on a hotel schedule, with full occupancy in the evening and night, and no occupancy during the day [54].

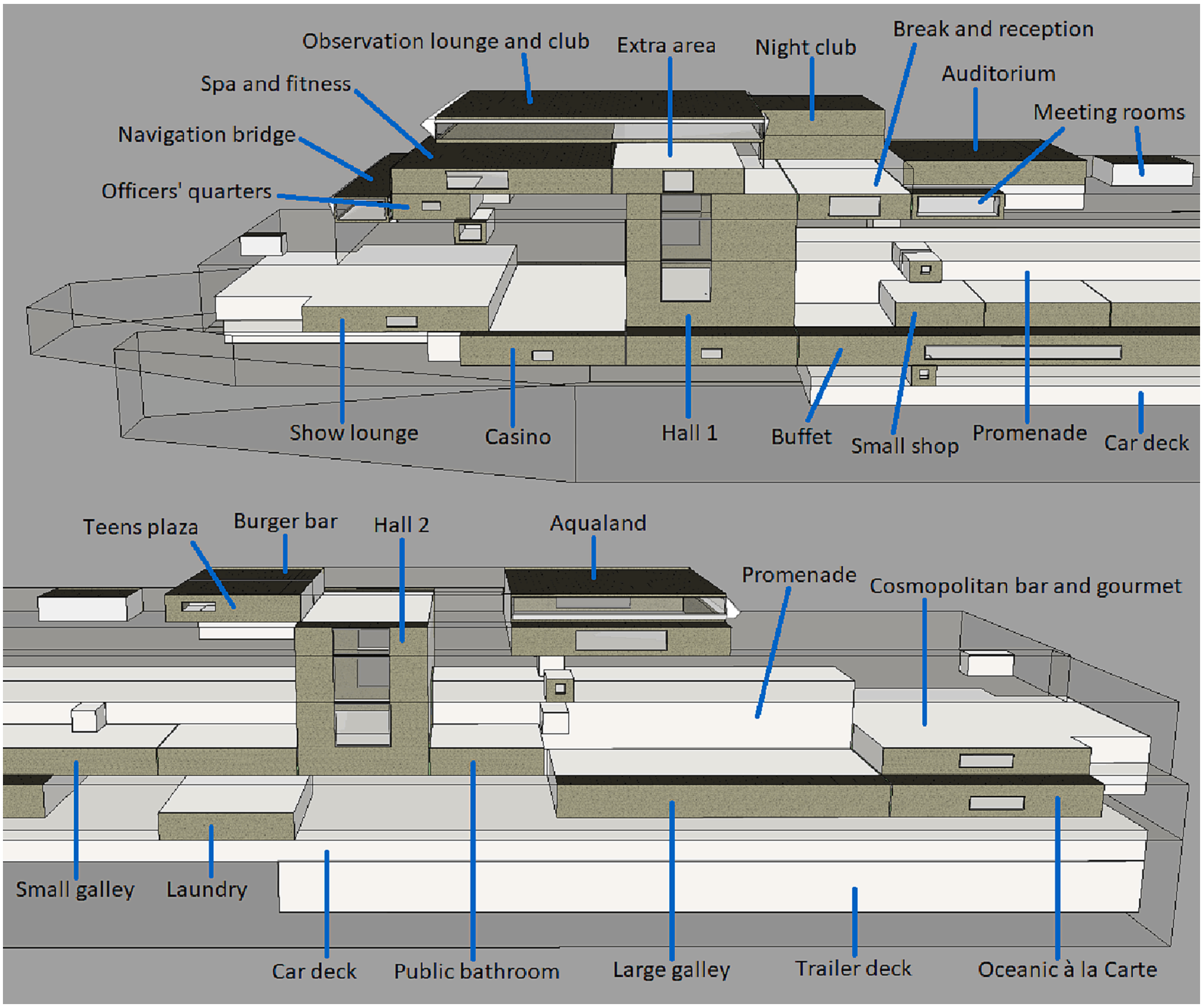


Fig. 3. Ship model in IDA ICE with several zones marked.

Table 3
Insulation thickness and U-value for ship constructions used in the model.

Construction	U-value [W/(m^2·K)]	Insulation thickness [mm]
External wall	0.2228	150
Roof	0.2306	150
Bulkhead	0.6542	40
Deck	0.7560	40
Window glazing	2.9	–
Window glazing (Aqualand)	1.9	–
Window frames	5.9	–

Use of the auditorium and the meeting rooms in the conference centre was assumed to be similar to the typical use of an office building, and therefore, schedules for an office were used [55]. For the public areas on the ship, the occupancy schedules were based on the opening hours of the restaurants [56] and other areas [57]. Occupancy schedules in the galleys were based on the occupancy in the connected restaurants. The maximum number of occupants in each zone was estimated based on the number of seats available or the area of the zone [49]. Table 4 shows the maximum number of occupants used for each zone, and the assumed activity levels.

For most zones, it was assumed that no passengers are present when the ship is in port between 10 a.m. and 2p.m. The occupancy was set to 10% to account for the ship crew. The occupancy schedules and maximum number of occupants were adjusted to achieve a total occupancy of around 2605, i.e. the maximum capacity of the case ship. Fig. 4 shows the total number of occupants on the ship throughout the day. Small reductions in the total occupancy during the daytime are considered realistic, as some passengers will go outside onto the deck.

Cruise ships usually use LED lights, which results in small internal heat gains. No lighting was included in the cabins, as the heat load from these lights was considered to be negligible. The lighting schedules in the rest of the ship were based on an efficient system using LED lighting [55]. In the conference centre, the lighting schedule for an office building was used in all zones, with a peak of 3.7 W/m^2. For all other zones, the schedule for a hotel was used, with a peak of 2.4 W/m^2. For areas with opening hours that differ significantly from the hotel schedule, the schedule was shifted to the correct hours.

The heat gain from refrigerators was assumed to be 0.3 W/l storage capacity, while heat gains from temporary electrical appliances were ignored [58]. The internal gain from electrical equipment was therefore set to a constant 18 W in all cabins, assuming minibars of 60 l. The equipment schedule for an office building, with a peak heat gain of 8.6 W/m^2, was used in all zones in the conference centre [55]. The other zones follow the hotel schedule, with a peak of 1.3 W/m^2. If occupancy differed significantly from the hotel schedule, the schedule was simplified and shifted to the correct hours.

Table 4
Maximum number of occupants and activity level for each zone.

Restaurants	Max occ.	Activity [met]	Promenade/ shops	Max occ.	Activity [met]
Oceanic à la Carte	180	1.2	Promenade	448	1.6
Cosmopolitan bar/gourmet	130	1.2	Halls	80	1.6
Private dining	8	1.2	Large corridors	48	1.6
Observation lounge/club	180	1.2	Public bathrooms	5	1.6
Grand buffet	500	1.2	Shops	10–30	1.6
Burger bar	25	1.2	Tax-free market	40	1.6
Conference centre			**Other public areas**		
Auditorium	272	1.2	Adventure planet	20	1.2
Meeting rooms	18	1.2	Aqualand	50	2.5
Break and reception area	272	1.2	Casino	80	1.2
Employee areas			Night club	140	2.5
Small galley	20	2.0	Show lounge	200	1.2
Large galley	40	2.0	Teens plaza	20	1.2
Laundry	20	2.0	Spa and fitness	60	3.0
Navigation bridge	2	1.2	Extra area	10	1.6
Officers' quarters (total)	4	1.0	Vehicle decks	0	–

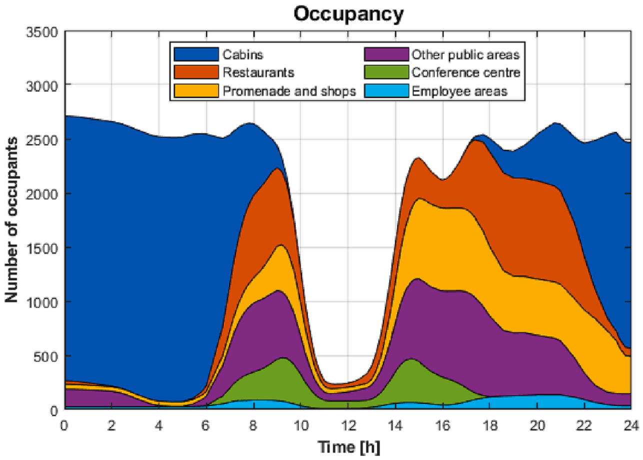


Fig. 4. Total number of occupants on the ship, divided into zone types.

2.6. Ship service systems

This section provides a brief description of the demand for steam, hot water, and HVAC on board the case ship.

Steam is used in the galleys for cooking purposes and dishwashing. The schedule for the steam demand in galleys, shown in Fig. 5, was based on the opening hours of the connected restaurants. With a total installed capacity of 650 kW, the peak demand was assumed to be 600 kW during dinner time. It was assumed that 100% of the heat would eventually be released to the zones.

The use of DHW was assumed to be similar to its use in hotels, which results in an annual energy use of 30.1 kWh/m^2 [55]. The "Ice rinks and pools" extension in IDA ICE was used to model swimming pools in the Aqualand. The pools were estimated to have a total surface area of 136.8 m^2 (25% of the floor area), an average depth of 1.2 m [49], and a setpoint temperature of 28 °C.

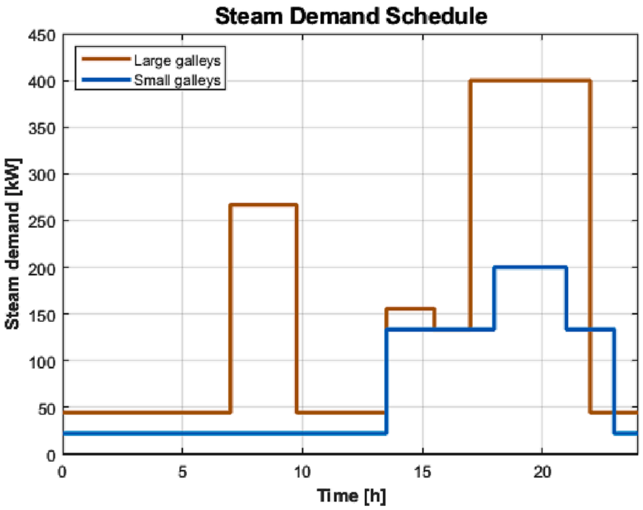


Fig. 5. Steam demand schedules for the galleys.

A total of eight air handling units (AHUs) were included, and zones were grouped together in the same AHU based on the supply air temperature chosen for the zone. All zones were set to have balanced ventilation with constant air volume (CAV). Apart from in the galleys, all AHUs have heat recovery. The heat recovery efficiency was assumed to be 50% based on the age of the ship. Vehicle decks were not given heat recovery, as they in reality have large fans for ventilation instead of AHUs. Table 5 shows the ventilation rates used in the different zones, as well as the temperature setpoints used by heating and cooling systems, modelled using fan coils in all zones.

2.7. Energy supply system

The ship's average speed on the open sea is 19.1 knots, while the daily average is 15.5 knots and the maximum speed is 24.5 knots. These values were used to calculate an annual propulsion demand of 102,000 MWh, which is covered by the main engines.

The case ship was originally designed to run on heavy fuel oil (HFO), which requires a large amount of fuel heating. As the ship today runs on MDO, the heating demand is significantly lower. Based on design data, it was estimated to be 2595 MWh/year.

The energy supply system in IDA ICE consists of a fuel boiler and an electric chiller, both modelled with unlimited capacity and an efficiency of 1 in order to estimate heating and cooling demands. At first, fan coils with unlimited heating and cooling were used in the model, meaning that the temperature setpoints can always be reached. Following the initial simulation, the DHW demand was calibrated based on the reference ship. After calibration, the fan coils were sized according to the maximum power reached during the one-year simulations with unlimited capacities.

Table 5
Ventilation rates and temperature setpoints used in the different zones.

Zone	Ventilation rate	Heating setpoint [°C]	Cooling setpoint [°C]
Aqualand	1.4 l/s per m^2 total area	30	32
Vehicle decks	10 h^{-1} (20 h^{-1} for roll on/off)	5	–
Laundry, public bathrooms	15 h^{-1}	21	24
Galleys	70 h^{-1}	21	24
Other zones	36 m^3/h per person	21	24

The propulsion power, electricity and heat produced by the ship's engines were not included in IDA ICE, and were instead considered in postprocessing using MATLAB. The cooling systems on board were assumed to have a coefficient of performance (COP) of 3. When the ship is at sea, the engines cover all electricity demands. In port, the engines were assumed to be off, and the electricity demand is covered by shore power. The waste heat recovered from the engines was assumed to be 15% of the propulsion demand, based on design data. The remaining heating demand was set to be covered by auxiliary boilers, also fuelled with MDO.

2.8. Energy efficiency scenarios

The ship model described in the above sections was established as the base case, representing the case ship as it is today. Several energy efficiency scenarios (Cases 1–11) were investigated in terms of annual energy savings for the ship's actual operating conditions in a Nordic climate. The chosen cases include several types of passive and active measures that are considered to be realistic to implement on a ship, either through retrofitting or in newbuilds. However, the evaluation of economic and operational feasibility is beyond the scope of this study, as is a quantitative analysis of emission reductions.

2.8.1. Passive measures

Case 1. *Increasing the amount of insulation in external constructions from* 150 *to* 300 *mm.*

Case 2. *Reducing the U-value of all windows and reducing the size of large windows. In Aqualand, the U-value was reduced from* 1.9 *to* 1.4 $W/(m^2\cdot K)$. *In all other windows, the U-value was reduced from* 2.9 *to* 1.9 $W/(m^2\cdot K)$. *The size of many large windows was reduced by* 50%.

Case 3. *Implementing a* 2 *cm thick PCM layer in all external and internal walls. The PCM melting temperature was set to* 24 °*C, i.e. the cooling setpoint, in order to reduce the cooling demand* [59]. *In Aqualand, the melting point was set to* 32 °*C.*

2.8.2. Active measures

Case 4. *Reducing the heating in port and at night (midnight to* 6 *a.m.) in the winter by reducing both the supply air temperature in the ventilation and the supply water temperature for zone heating to* 10 °*C. Aqualand was not included in this measure. Nighttime setback was not included in the cabins and the navigation bridge.*

Case 5. *Turning off heating on the vehicle decks in port.*

Case 6. *Increasing the efficiency of the ventilation heat recovery from* 50% *to* 80%.

Case 7. *Implementing VAV ventilation depending on needed airflow rates*:

- <100 m^3/h → CAV ventilation,
- 100–500 m^3/h → occupant-controlled ventilation with motion sensors,
- >500 m^3/h → demand-controlled ventilation (DCV) with temperature and CO_2 control.

For galleys, bathrooms and laundry, airflow rates were reduced to 10% outside the occupancy period. The ventilation was not changed in Aqualand or on vehicle decks.

Case 8. *Installing an air-to-water heat pump as base heating on the ship. For accommodation heating and DHW, the net thermal power demand for the base case was* 11.6 *MW, including all internal heat gains and solar radiation. The power coverage factor for the heat pump was set relatively low at* 27%, *resulting in a heating capacity of* 3.12 *MW. This gave an annual energy coverage factor of* 93%, *which was considered appropriate. Air-source heat pumps are likely not the best solution for cruise ships due to limited space on board, but can give an indication of the potential for heat pump solutions in general. Water from the engine cooling system is considered to be the most appropriate heat source, but this was not included in the IDA ICE model.*

Case 9. *Placing PV panels horizontally on the roof of the ship, covering* 50% *of the observation lounge, which is an area of* 450 m^2. *SunPower's* 360 *W PV panels, with an efficiency of* 22.2%, *were used as a reference* [60]. *It was assumed that the efficiency would be reduced due to harsh weather conditions at sea and salt deposition from saltwater, and an efficiency of* 15% *was therefore used.*

Case 10. *Including a* 200 m^3 *hot water storage tank to utilise more of the heat recovered from the engines. With a uniform temperature varying between* 50 *and* 80 °*C, and neglecting heat losses, the energy storage capacity is* 6.97 *MWh. The maximum rates for charging and discharging were set to* 2 *MW, which was high enough to not limit the energy savings.*

Case 11. *Increasing the size of the hot water storage tank to reduce the use of boilers in port. At sea in winter conditions, the boilers charge the tank until it is full. In summer conditions, the maximum storage capacity was set to* 75% *when charging with boilers, to enable the utilisation of unused recovered heat from the engines. In port, the tank is discharged to cover the heating demands. The maximum charging and discharging rates were set to* 2.5 *and* 12.3 *MW, respectively. Covering all the heating demands in port required a tank size of* 1105 m^3 *with a storage capacity of* 38.5 *MWh.*

3. Results and discussion

This chapter begins with presenting simulation results for the annual energy demand and supply for the base case, followed by a validation of the simulation model by comparing the results to real energy-use data. Finally, results for the energy efficiency scenarios are presented and discussed.

3.1. Annual energy use

Fig. 6 shows the annual energy use per passenger, excluding propulsion. The "initial model" refers to the case ship before calibration of the DHW demand, while the "base case" is after calibration and sizing of the fan coils. The sizing of the fan coils had a minimal impact on the energy use, as this was based on the heating and cooling demands in the initial model. Fig. 6 also includes the reported energy use for the reference ship (RS). Since 26% of the RS energy use is unspecified electricity use, the electricity related to the hotel system is unknown. Therefore, the energy use for the RS is presented as one low and one high

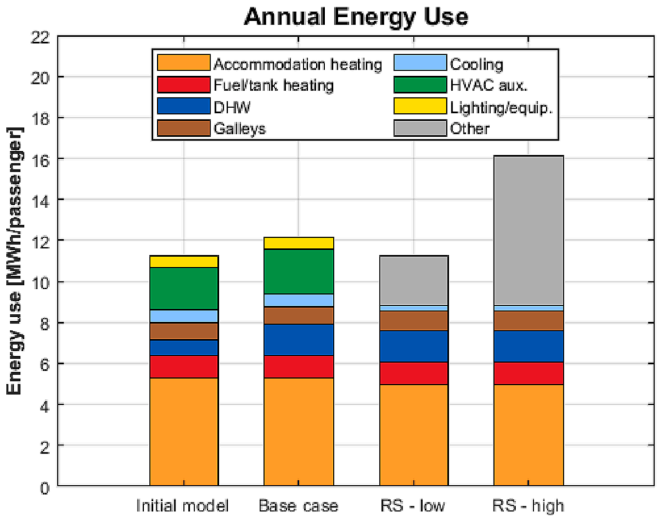


Fig. 6. Annual energy use (excl. propulsion) for the case ship before and after calibration, and for the reference ship.

estimate, including 30% and 90% of the unspecified electricity use, respectively [12].

As seen in Fig. 6, the demand for DHW in the case ship before calibration (“initial model”) was significantly lower than for the reference ship. One possible reason is that the schedule used in IDA ICE might not accurately represent the DHW use on cruise ships. Seeing as passengers stay on board most of the day, they might use more hot water than guests in land-based hotels. During calibration, the specific DHW demand was increased from 30.1 to 58.7 kWh/m^2, which gave an annual demand very close to that of the reference ship. After calibration, the annual energy demand for the case ship was 12.1 MWh/passenger, which is between the low and the high estimate for the reference ship’s energy use, and the model was therefore considered adequately calibrated. Including propulsion, the total annual energy demand for the case ship is 54.7 MWh/passenger.

As the two ships sail in similar climates, they were expected to have similar demands for accommodation heating and cooling. The difference in energy use for accommodation heating is only 6%, being higher for the case ship (orange bars in Fig. 6). Assuming a COP of 3.0, the electricity use for cooling on the case ship is 0.21 MWh/passenger, while it is 0.25 MWh/passenger for the reference ship. This difference could be caused by the assumed COP being too high.

Fig. 7 shows the accommodation heating demand throughout the year, including heating in AHUs, zone heating from fan coils, and pool water heating. The peak heating demand is 11.1 MW, while for a typical winter day it was estimated to be 7 MW, or 2.92 kW/passenger. This is somewhat higher than for the reference ship: 2.27 kW/passenger [46]. In the case ship, heating the vehicle decks significantly increases the heating demand, especially during roll on and roll off. The reference ship does not have a vehicle deck, which could account for this difference in peak heating demand.

Fig. 8 shows the total cooling demand throughout the year, including cooling in the AHUs and zone cooling from fan coils. Both the sensible and latent cooling loads are included. The cooling demand is naturally largest in the summer months, but there is also a smaller demand throughout the winter due to large heat gains in the galleys. The peak cooling demand is 2.89 MW, while for a typical summer day, it was estimated to be 2.2 MW, or 0.92 kW/passenger. This is significantly higher than for the reference ship, 0.67 kW/passenger [37], while the annual energy use for cooling is lower on the case ship. This could be caused by a more intermittent demand on the case ship, for example with occasional large solar heat gains, but with a lower demand for cooling in galleys.

The duration curves in Fig. 9 show a heating demand throughout the whole year, while the cooling demand occurs mainly during a small part of the year. This is typical for cold climates. In the combined weather file, the temperature frequently goes below 18 °C in the summer, which will require heating in most AHUs. In zones with low internal heat gains, space heating is also needed to bring the supply air temperature up to the zones’ setpoint temperature.

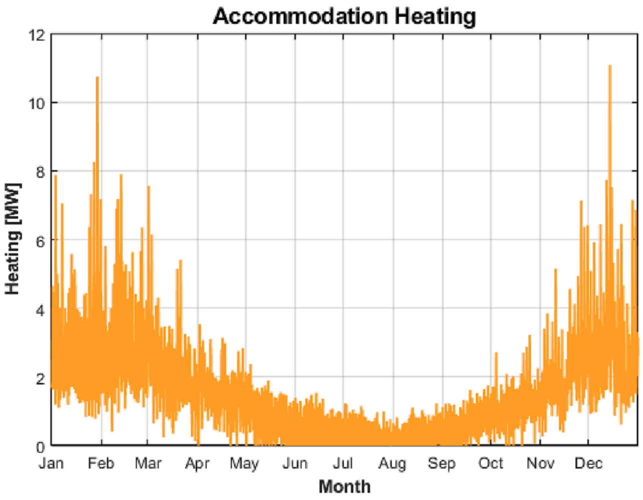


Fig. 7. Accommodation heating demand throughout the year, for the base case.

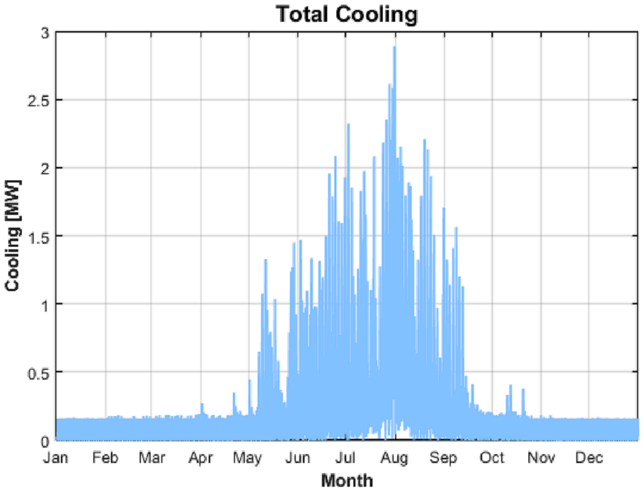


Fig. 8. Total cooling demand throughout the year, for the base case.

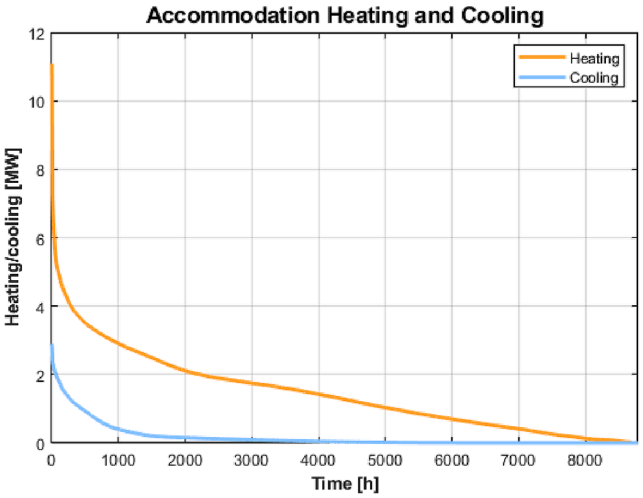


Fig. 9. Duration curves for accommodation heating and cooling demand.

In addition to AC chiller compressors and propulsion auxiliaries, the electricity use on board includes equipment and lighting, as well as HVAC auxiliaries. Fig. 10 shows the duration curve for the HVAC auxiliary, i.e. fans and pumps. The peak is caused by the ventilation rate on vehicle decks doubling for a total of one hour every day during roll on and roll off.

3.2. Energy supply system

Fig. 11 shows the heat supply from the engines’ waste heat and from auxiliary boilers, as well as the total heating demand and unutilised recovered heat (wasted heat), on a typical summer day. Due to low heating demands in the summer, more waste heat is available than is needed. Throughout the whole year, 2446 MWh of the recovered heat was wasted. In port, and connected to shore power, there is no waste heat available and the auxiliary boilers must cover all heating demands.

Fig. 12 shows a typical winter day, where the waste heat available from engines was always lower than the heating demand. The boilers therefore had to be used throughout the whole day, and no recovered

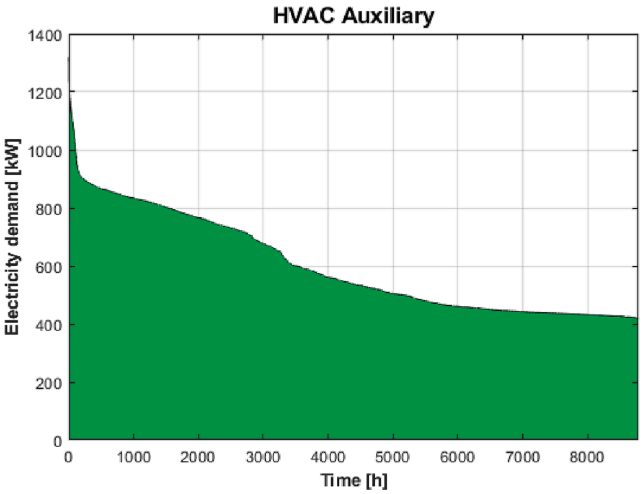


Fig. 10. Duration curve for the HVAC auxiliary electricity demand.

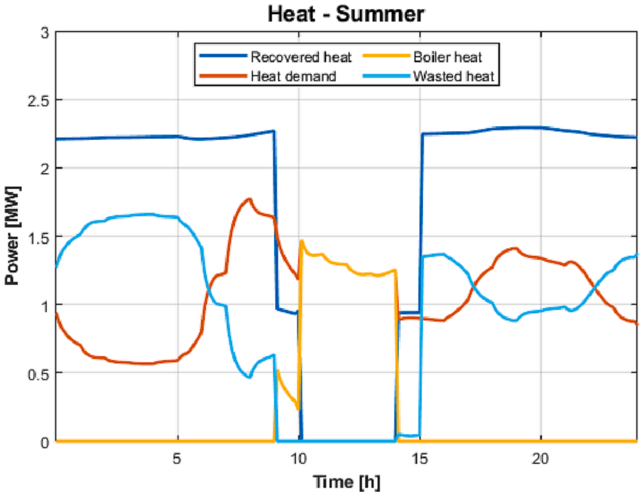


Fig. 11. Heat recovered from engines, heat delivered by boilers, total heat demand, and wasted heat for a typical summer day.

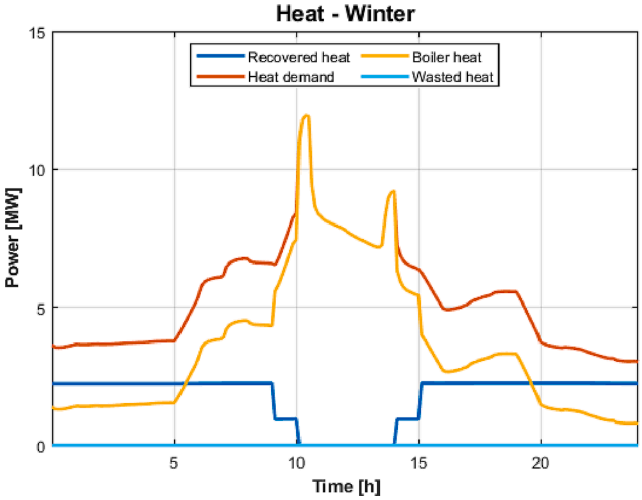


Fig. 12. Heat recovered from engines, heat delivered by boilers, total heat demand, and wasted heat for a typical winter day.

heat was wasted.

3.3. Validation of simulation model

Fig. 13 compares the annual propulsion demand to the real demand, which is based on fuel use data from Color Fantasy for Jan-Sep 2022, with the real demand being 16% higher than the model. The deviation could be explained by the use of average cruising speed in the model. The exponential relation between the speed and the propulsion power implies a larger total demand if the ship occasionally sails at the maximum speed, even if the average speed remains the same.

Fig. 14 compares the simulated annual heating demand with the real data for Color Fantasy. The "real" demand is based on the actual boiler fuel use (Jan-Sep 2022), combined with heat recovery estimated to 15% of the propulsion demand, as indicated in the ship's heat balance document. Since not all the heat recovered from the engines is actually utilised on board, the real heating demand might be overestimated. When operating at normal speed, recovered heat is also used for FWG, which was not included in the model.

Fig. 15 shows the total annual heat delivered by boilers and engines on the case ship, according to modelling results (left) and operational data on fuel use (right). Both bars include the maximum heat recovery from the engines, regardless of how much was actually utilised. For the model, about 35% of the heat is supplied from boilers, while this is only 23% according to the operational data. The larger share of boiler heat supply in the model could be explained by the lower propulsion demand (Fig. 13), leading to less heat recovered from the engines. For the case ship, which only has EGBs installed on the main engines, the ratio between the heat supplied from auxiliary boilers and from the engines depends on the relation between the propulsion and heating demands. For ships that also have EGBs on the auxiliary engines, as with the reference ship, the electricity demand also influences the heat supply. For such ships, waste heat is also available in port, as long as they are not connected to shore power. It should be noted that on several ships, the WHR systems also include the engines' HT cooling water, which reduces the share of heat supplied by boilers.

3.4. Energy efficiency analysis

This section presents results for the energy efficiency scenarios, as described in section 2.8. First, the cases are compared with each other, as regards the annual energy use, the annual heat delivered by engines and boilers, and the peak energy demands. In the following subsections,

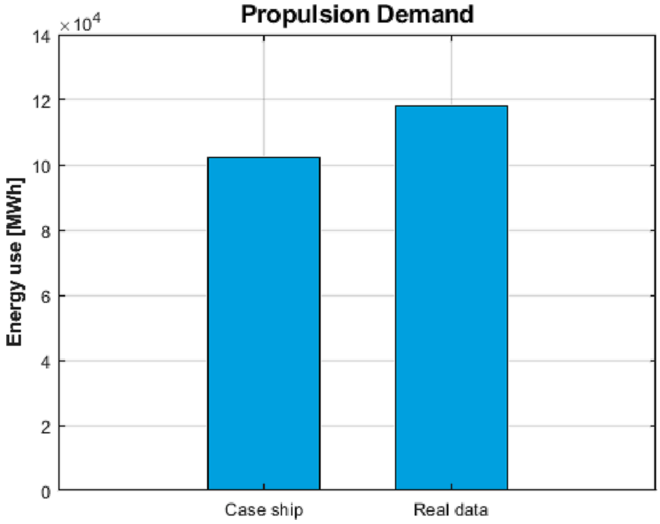


Fig. 13. Annual propulsion demand in the case ship compared to operational data.

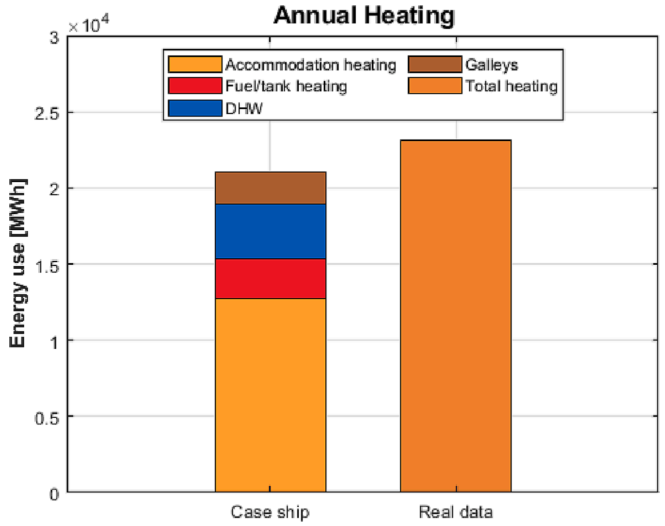


Fig. 14. Annual heating consumption in the case ship compared to operational data.

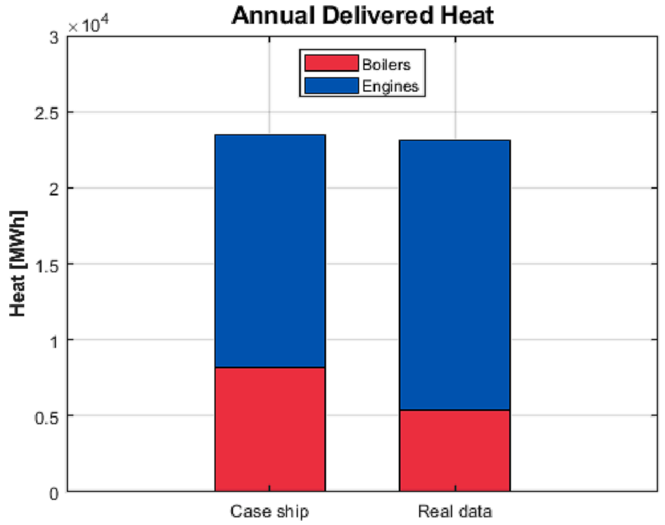


Fig. 15. Annual heat delivered by engines and boilers, including unused heat from engines, for the case ship and operational data.

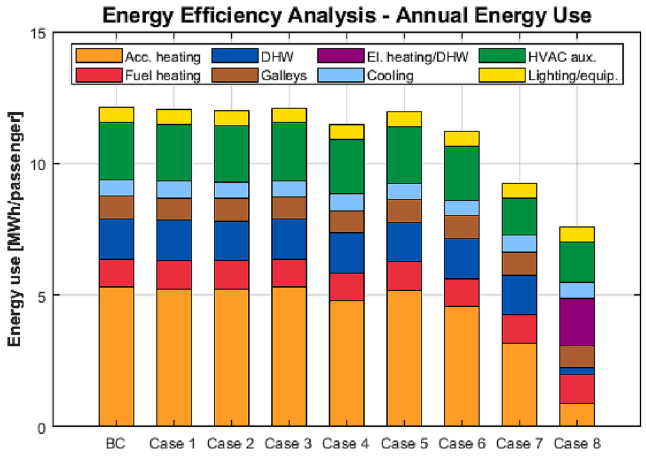


Fig. 16. Annual energy consumption for the energy-saving solutions.

the cases using heat pumps, PV panels and TES are investigated further.

3.4.1. Comparison of energy efficiency scenarios

Fig. 16 shows the case ship's annual energy use, excluding propulsion, for the energy efficiency cases that were simulated in IDA ICE (Cases 1–8), as well as the base case (BC). In the figure, "Acc. heating" refers to accommodation heating and vehicle deck heating supplied by auxiliary boilers and engine heat recovery, while "El. heating/DHW" refers to the electricity used by the heat pump. Cases 9–11 are not included in Fig. 16, as the annual energy use was not changed when implementing PV panels or hot storage tanks, and these cases were therefore identical to the base case at this stage.

The three passive measures evaluated, i.e. increased insulation (Case 1), improved windows (Case 2), and PCM layers (Case 3), resulted in reductions in annual energy use of less than 1%. Reduced U-values had limited influence on the heating demand, as much more heat is lost through the ventilation system than through the external facades. PCM layers in walls were ineffective, likely due to too small variations in indoor temperature during the summer.

Cases 4 and 5 with heating setback resulted in reductions in energy use of 5.3% and 1.4%, respectively, mainly achieved through reduced accommodation heating. For Case 4, with heating setback in port and at night, the energy savings could be increased by expanding the solution to include the summer months. In the summer, the supply air temperature should be adjusted based on the outdoor temperature to avoid unnecessary cooling. After the setback periods in Case 4, the heating setpoint was reached quickly in some zones and slowly in others. If this energy-saving measure is to be used, the heating capacity should be increased in some zones to reach the heating setpoint faster and provide a better thermal environment. However, this would require bigger fan coils, and would reduce the energy savings achieved. For Case 5, where vehicle deck heating was turned off in port, an alternative option could be to lower the setpoint temperature on the vehicle decks by 1–2 K at all times.

In Case 6, with improved heat recovery in the AHUs, the heating demand was reduced by 14%, the cooling demand by 2%, and the electricity use for HVAC fans and pumps was reduced by 8%. For Case 7 with VAV ventilation, the reduced ventilation led to a 40% reduction in heating demand, a 9% increase in cooling demand, and a 37% reduction in energy use for fans and pumps. Cases 6 and 7 were relatively effective due to the large amount of heat that is lost through the ship's ventilation system.

Case 8 with a heat pump showed the largest energy savings of all solutions and is the only case that resulted in reduced energy use for DHW. The total energy use for DHW and accommodation heating, including electricity for the heat pump, was reduced by 57% compared to the base case. Excluding electricity use, the energy use for accommodation heating was reduced by 83%. The electricity use for fans and pumps was reduced by 30%, while the total electricity demand was increased by 33%.

For each energy-saving solution (Cases 1–11), Fig. 17 shows the annual heat delivered by boilers and by engine heat recovery. It is clearly shown that the heat supply from auxiliary boilers has been reduced in many of the cases. It should be noted that, as the heat delivered from engines also includes unutilised heat, the actual reduction in energy use could be somewhat larger.

Case 9 with PV panels showed results very similar to the base case, likely due to a small PV panel area. Case 10 with a 200 m^3 hot water storage tank resulted in a 15% reduction in heat from boilers, as some of the unused heat from engines was saved and utilised.

Case 11 with a 1105 m^3 storage tank did not provide any larger energy savings than Case 10, as the use of the tank was optimised to reduce the use of boilers in port, which meant it had to be charged by boilers during sea passage. This solution could still be relevant in situations where it is crucial to reduce emissions in port. For ships with more unutilised recovered heat at sea, the increased tank size could result in

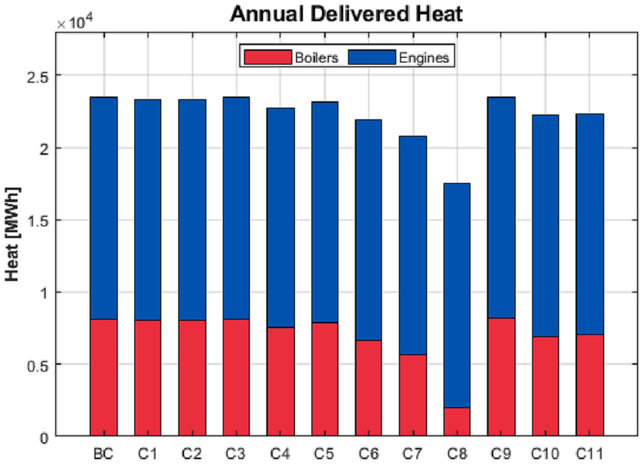


Fig. 17. Annual heat delivered from engines and boilers in each energy efficiency scenario.

large reductions in boiler use. Heat losses from the tank are not included in the model, and the losses would increase with increased tank size. The results for Cases 10 and 11 are discussed further in section 3.4.4.

Fig. 18 shows the peaks in accommodation heating and cooling, and hotel electricity, for Cases 1–8. As in Fig. 16, Cases 9–11 were identical to the base case and have therefore not been included. The peak in accommodation heating covered by boilers and waste heat is 11.1 MW in the base case. The lowest peak occurs in Case 8, with 5.2 MW, as the heat pump covers a large part of the heating demand. Case 5 with no vehicle deck heating in port and Case 7 with VAV ventilation also gave significant reductions in peak heating, with demands of 9.7 and 9.2 MW, respectively. There is a strong correlation between the peaks in cooling demand and electricity, as cooling is the electricity consumer with the highest peaks in all the cases. Therefore, the heat pump in Case 8 did not significantly increase the peak in electricity use.

Implementing energy-saving solutions that significantly lower the peak heating and cooling demands on an existing ship would lead to the fan coils, chillers, and boilers being oversized. The weight of the ship and the energy demand for propulsion could then be unnecessarily high. In the case of large reductions in peak demand, it should be investigated if it would be beneficial to downsize these components in order to reduce the weight of the ship.

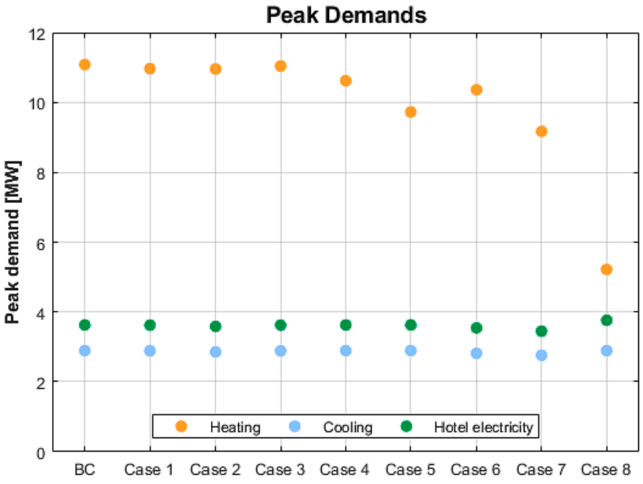


Fig. 18. Peak demands for heating, cooling and total hotel electricity in the different energy efficiency scenarios.

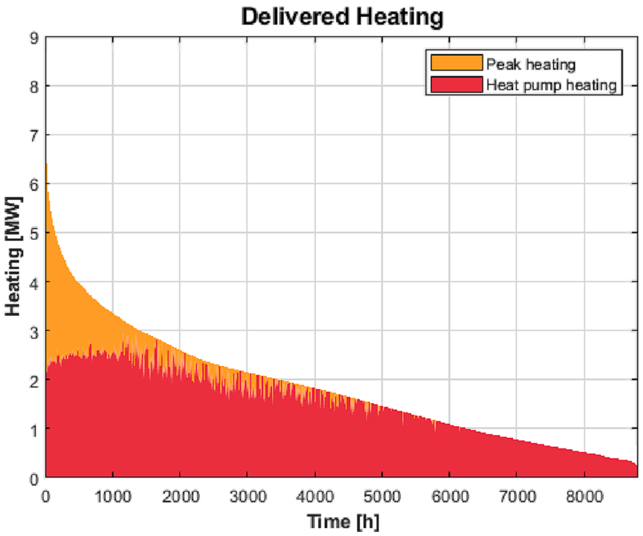


Fig. 19. Duration curve for heating delivered by the heat pump and by peak heating.

3.4.2. *Heat pump*

Fig. 19 shows a duration curve for the total heat delivered by the heat pump and the peak heating in Case 8. This includes accommodation heating and DHW heating. There is significant variation in the heat pump heating, which could be caused by variations in the outdoor temperature that do not match the total heating demand. When the heating demand is highest, the heat pump heating is reduced due to low outdoor temperatures, which reduce the heat pump's performance.

When unused recovered heat is available from the engines, it would be beneficial to use this instead of the heat pump. This would lead to somewhat larger energy savings for this case. However, as the recovered heat was calculated in postprocessing, this prioritisation could not be considered. Even though heat pumps are more energy-efficient than fuel-fired boilers, the use of them during sea passage might pose operational challenges, as more electricity has to be produced on board. In some cases, it could be more appropriate to only use heat pumps when the ship is in port and connected to shore power.

3.4.3. *Photovoltaic panels*

In Case 9, the peak electricity production from PV panels is 56.2 kW in July, while the electricity demand is always higher than this, meaning that no electricity will go to waste. The total annual production is 56.9 MWh, amounting to only 4% of the electricity used for lighting and equipment, or 0.8% of the total electricity use.

More PV panels could be added to the ship to increase the production. To maximise the production, the PV panels should be placed on a horizontal or slanted surface, such as on the front of the ship below the cabin windows. PV panels could also be installed between the cabin windows on the sides of the ship. On existing ships, it could be challenging to find appropriate locations for the PV panels, where they will not cause problems for passengers or operation of the ship, and where other constructions do not block the sun. In case of significantly increased PV electricity production, the electricity delivered from engines would be reduced. If the engines are equipped with EGBs, this would reduce the amount of waste heat available, and therefore more of the heat demand must be met by boilers.

3.4.4. *Hot water storage tanks*

The use of hot water storage tanks was investigated in postprocessing using MATLAB. Fig. 20 shows the results of including a 200 m^3 hot storage tank (Case 10) for a typical summer day (as shown in Fig. 11 for the base case), also considering the tank's charging and discharging rates. Fig. 21 shows the energy level of the tank throughout the day. The

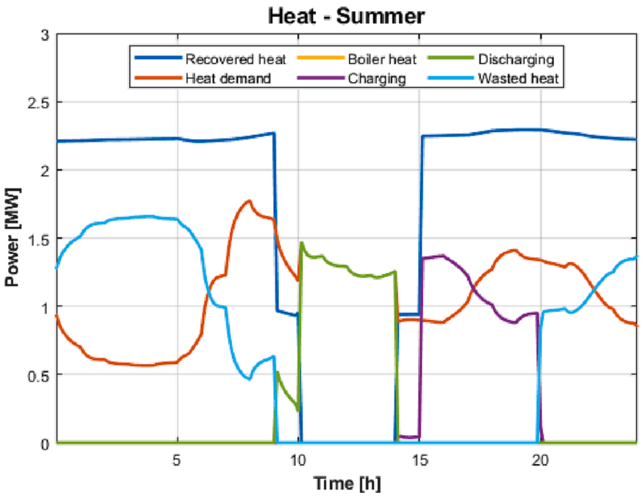


Fig. 20. Heat from engines, boilers, and storage tank, as well as total heat demand, charging rate and wasted heat for a typical summer day in Case 10.

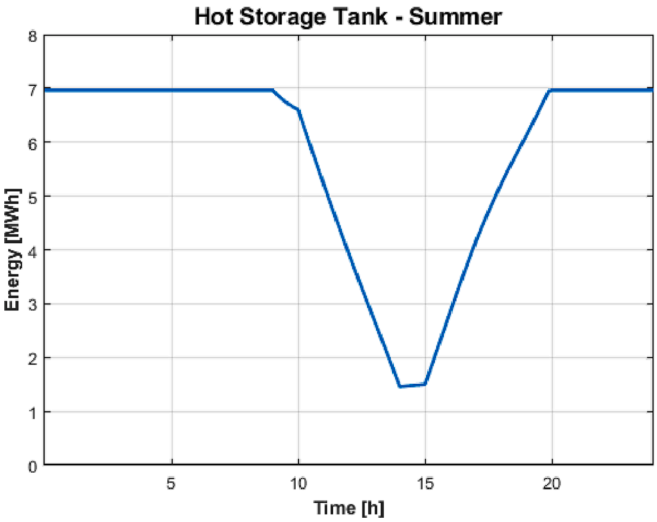


Fig. 21. Energy level of the hot storage tank on a typical summer day in Case 10.

tank is already fully charged at the beginning of the day, and the excess recovered heat is therefore wasted. In port, the heating demands are covered by discharging the tank instead of using boilers. After the port stay, the tank is charged again using excess recovered heat.

With a 200 m^3 tank, the annual energy savings were 1233 MWh, or 50% of the unused heat recovered from engines, which corresponds to 6% of the total heating demand. Fig. 22 shows the potential savings as a function of tank volume. A tank of 300 m^3 saves 1319 MWh (54%), while larger tanks provide very small additional energy savings, as the 300 m^3 tank utilised all waste heat in the winter. During summer, the heating demands are low, and it is therefore challenging to save additional energy.

Fig. 23 shows the results of including a 1105 m^3 tank (Case 11) to eliminate the use of boilers in port during the typical winter day (shown in Fig. 12 for the base case), while Fig. 24 shows the corresponding energy level in the tank. The fully charged tank is used to cover the entire heating demand in port. During sea passage, the tank is charged using the boiler, as no excess heat is available from the engines. The summer case was identical to Case 10 in Fig. 20, since both tanks were fully charged at the beginning of the day, with the only difference being the storage capacity of the tanks.

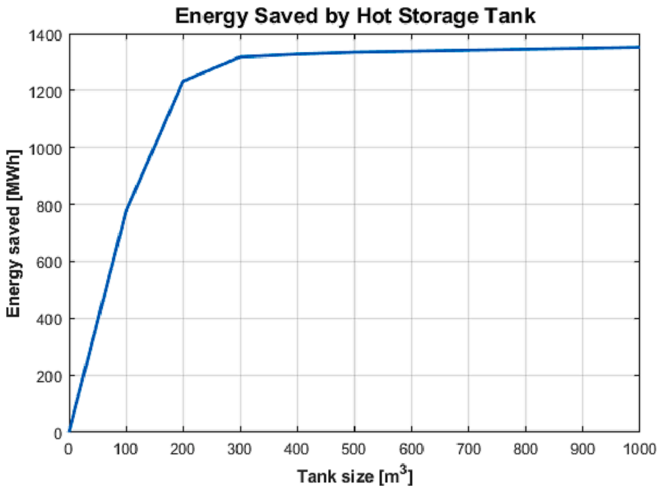


Fig. 22. Amount of energy saved by the hot storage tank, as a function of the tank size.

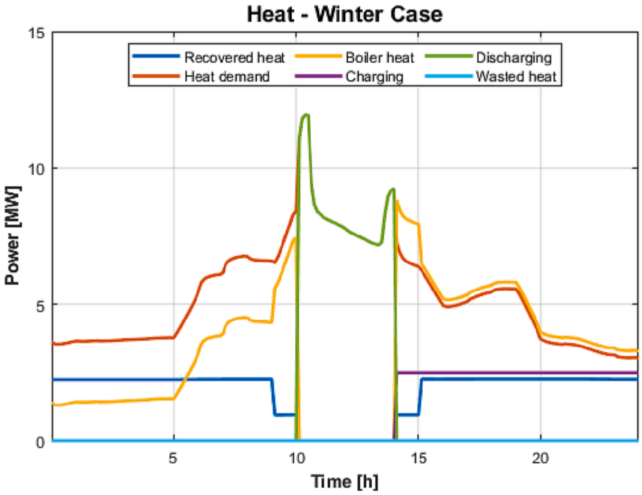


Fig. 23. Heat from engines, boilers and storage tank, as well as total heat demand, charging rate and wasted heat for a typical winter day in Case 11.

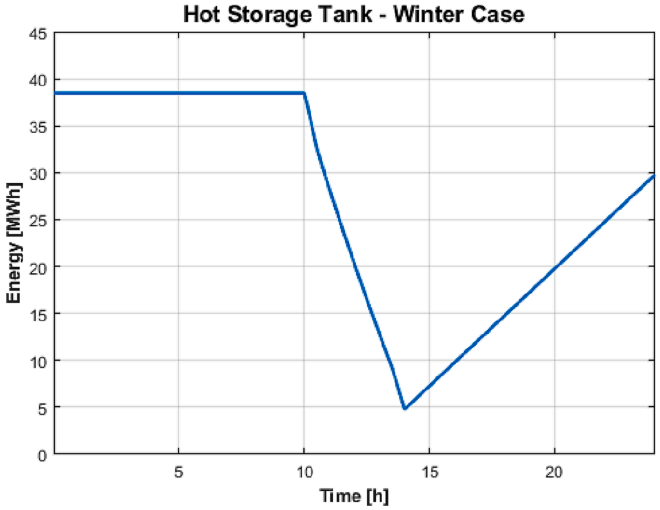


Fig. 24. Energy level of the hot storage tank on a typical winter day in Case 11.

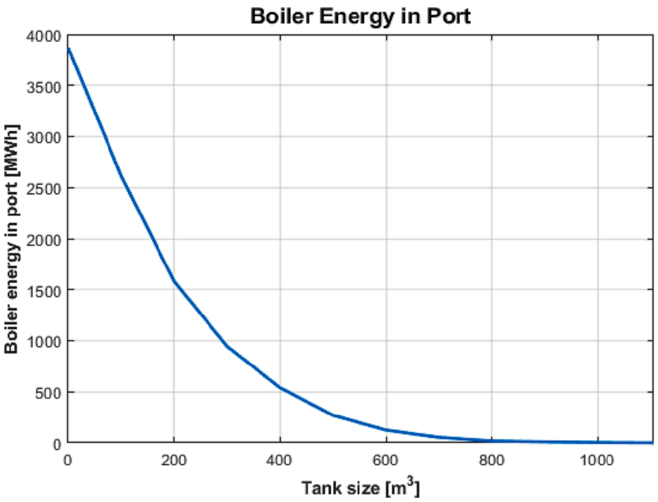


Fig. 25. Annual heat supplied by boilers in port as a function of the tank size.

A tank of 1105 m^3 is considered unreasonably large, especially for existing ships. Fig. 25 shows the annual heat supplied by boilers in port for tanks with sizes 0–1105 m^3. Tanks of 200 m^3 and 600 m^3 reduced the boilers' heat supply by 59% and 97%, respectively. Therefore, it would be more reasonable to use a smaller tank, unless it is crucial to ensure zero emissions in port. An electric boiler running on shore power could also be used in combination with a small tank in order to achieve zero emissions.

3.5. Further considerations and implications

The transition to future low- or zero-emission ships is characterised by fuel and propulsion systems that are more space-demanding and expensive, and provide less waste heat. Therefore, to realise large emission reductions, the ships' total energy usage must be minimised. The purpose of this study was to evaluate the energy savings of the efficiency measures and not their actual emission reductions. It should be noted that the percentage of energy savings cannot automatically be transferred to the same percentage of emission reductions. For example, since most of the case ship's heat supply comes from WHR during sea passage, a reduction in heating demand might imply no or minor emission savings. However, energy savings that reduce the auxiliary boiler operation result in about the same percentage of emission reductions. Reductions in electric power demand result in about the same percentage of emission reductions, given that the power is produced on board. When connected to shore power, the potential emission reductions depend on the carbon intensity of the national power grid, which is 30 g CO_2eq/kWh in Norway and 380 g/kWh in Germany, thereby resulting in larger emission reductions in Kiel [61].

The implementation of some of the energy efficiency measures could be limited by high investment costs, small reductions in energy use and consequent long pay-back times. This is especially prevalent for ships where most of the heat is supplied by WHR, as well as for retrofitting existing ships, where the additional costs related to implementation are much higher than in newbuilds. Another limiting factor for the implementation of energy-saving measures is weight and space requirements, both for retrofits and for newbuilds equipped with space-demanding, low-emission propulsion systems.

Since the energy consumption of ship hotel systems varies with the climatic conditions, the results obtained in this study are considered to be most relevant for other cruise ships sailing in a Nordic, or similar, climate zone. However, the simulation model can be used for similar cruise ships in other climate zones simply by replacing the weather file. For mega-cruise ships with more than 1500 passenger cabins and larger leisure facilities, and for ships with smaller hotel systems, such as ferries and offshore supply vessels, the model would need significant changes in order to properly represent the hotel system's energy use, though the same methods can be applied.

Using IDA ICE to simulate the hotel system of a ship implies some limitations since a cruise ship differs from a building in several ways, e.g. in terms of construction materials, the ship's movement through water, and a more complex energy supply system. In addition, the total occupancy used in the model is representative of a fully booked ship, which is likely not realistic due to seasonal variations in ship tourism. The data available for model validation consisted of the actual fuel use for the case ship's engines and auxiliary boilers. However, the collection of more disaggregated operational data is suggested for future research, to further improve the model validity.

4. Conclusions

The aim of this study was to investigate the energy use of an existing cruise ship operating in a Nordic climate and evaluate the effectiveness of various energy-saving solutions. To achieve this, a model of the case ship's hotel system was created in the building simulation tool IDA ICE, including a customised weather file. MATLAB was used to model the energy supply from the ship's engines, including WHR, and auxiliary boilers.

Simulations were performed for one year of operation, resulting in a total energy use of 54.7 MWh/passenger, with the hotel system accounting for 20%. The passive measures, i.e. increased insulation, improved windows, and PCM layers in walls, each resulted in less than a 1% reduction in hotel energy use. Heating setback in port and at night for the accommodation heating system, and turning off vehicle deck heating in port, achieved energy-use reductions of 5.3% and 1.4%, respectively. Measures for increasing the ventilation efficiency were more effective than the passive measures, due to a large amount of heat being lost through the ship's ventilation system. Improved ventilation heat recovery and VAV ventilation resulted in energy-use reductions of 8% and 24%, respectively. Implementing a heat pump resulted in the largest energy savings, with a reduction of 38%. All of these measures would reduce the use of auxiliary boilers and the reliance on waste heat from the engines, making them useful for future ships that are powered by batteries or fuel cells, with less or no waste heat available.

Implementing a hot water storage tank enables the ship to utilise unused recovered heat from the engines during sea operation, thereby reducing the use of auxiliary boilers. For the case ship, a 300 m^3 tank reduced the use of auxiliary boilers by 16%, corresponding to 6% of the total heating demand, while larger tanks gave small additional energy savings. A hot water storage tank of 1105 m^3 was required to eliminate the use of boilers and consequent emissions in port, while a 600 m^3 tank could cover 97% of the heating demands. Energy savings provided by a hot storage tank depend strongly on the actual WHR system. For future ships still relying on combustion engines or a hybrid solution with engines and batteries, a hot water storage tank could be beneficial for maximising the use of any available waste heat.

CRediT authorship contribution statement

August Brækken: Methodology, Validation, Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Cecilia Gabrielii:** Conceptualization, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Natasa Nord:** Conceptualization, Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The research work presented in this paper was conducted within the framework of the projects "LowPass – Future low-emission passenger ships" and "CruiZE – Cruising towards Zero Emissions". Both projects are funded by the Research Council of Norway, which is gratefully acknowledged. The authors of this paper would also like to thank the projects' industry partners – Fosen Design & Solutions, Color Line Marine, Ulmatec Pyro and Teknotherm Marine – for their financial support and knowledge contributions.

References

[1] Kizielewicz J. Eco-Trends in Energy Solutions on Cruise Ships. Energies 2021;14(13). https://doi.org/10.3390/en14133746. Art. no. 13.

[2] Mallouppas G, Yfantis EA. Decarbonization in Shipping Industry: A Review of Research, Technology Development, and Innovation Proposals. J Mar Sci Eng Apr. 2021;9(4). https://doi.org/10.3390/jmse9040415. Art. no. 4.

[3] Jimenez VJ, Kim H, Munim ZH. A review of ship energy efficiency research and directions towards emission reduction in the maritime industry. J Clean Prod Sep. 2022;366:132888. https://doi.org/10.1016/j.jclepro.2022.132888.

[4] Barreiro J, Zaragoza S, Diaz-Casas V. Review of ship energy efficiency. Ocean Eng Aug. 2022;257:111594. https://doi.org/10.1016/j.oceaneng.2022.111594.

[5] Guangrong Z, et al. Ship energy efficiency technologies - now and the future. VTT Technical Research Centre of Finland; 2017.

[6] Singh DV, Pedersen E. A review of waste heat recovery technologies for maritime applications. Energy Convers Manag 2016;111:315–28. https://doi.org/10.1016/j.enconman.2015.12.073.

[7] Lion S, Vlaskos I, Taccani R. A review of emissions reduction technologies for low and medium speed marine Diesel engines and their potential for waste heat recovery. Energy Convers Manag 2020;207:112553. https://doi.org/10.1016/j.enconman.2020.112553.

[8] Barone G, Buonomano A, Forzano C, Palombo A. Implementing the dynamic simulation approach for the design and optimization of ships energy systems: Methodology and applicability to modern cruise ships. Renew Sustain Energy Rev 2021;150:111488. https://doi.org/10.1016/j.rser.2021.111488.

[9] Baldi F, Ahlgren F, Melino F, Gabrielii C, Andersson K. Optimal load allocation of complex ship power plants. Energy Convers Manag 2016;124:344–56. https://doi.org/10.1016/j.enconman.2016.07.009.

[10] H. Weggeberg et al., 'Emissions to Air and Discharges to Sea from Ships in Fjord Areas with Heavy Cruise Traffic', Rambøll, May 2017.

[11] Simonsen M. CRUISE SHIP TOURISM - A LCA ANALYSIS. Western Norway Research Institution; 2014.

[12] Baldi F, Ahlgren F, Nguyen T-V, Thern M, Andersson K. Energy and Exergy Analysis of a Cruise Ship. Energies 2018;11(10):2508. https://doi.org/10.3390/en11102508.

[13] Gnes P, Pinamonti P, Reini M. Bi-Level Optimization of the Energy Recovery System from Internal Combustion Engines of a Cruise Ship. Appl Sci 2020;10(19):6917. https://doi.org/10.3390/app10196917.

[14] Boertz C. Energy demand of a fuel cell-driven cruise ship: Analysis and improved prediction method of the operational power variation under different loading and environmental conditions. Delft University of Technology; 2020. Master's thesis,.

[15] Simonsen M, Walnum H, Gössling S. Model for Estimation of Fuel Consumption of Cruise Ships. Energies 2018;11(5):1059. https://doi.org/10.3390/en11051059.

[16] Espinosa S, Casals-Torrens P, Castells M. Hoteling Cruise Ship's Power Requirements for High Voltage Shore Connection Installations. J Marit Res 2016:19–28.

[17] López-Aparicio S, Tønnesen D, Thanh TN, Neilson H. Shipping emissions in a Nordic port: Assessment of mitigation strategies. Transp Res Part Transp Environ Jun. 2017;53:205–16. https://doi.org/10.1016/j.trd.2017.04.021.

[18] Oslo kommune, 'Port of Oslo as a Zero-Emission Port', Jun. 2018.

[19] Stolz B, Held M, Georges G, Boulouchos K. The CO2 reduction potential of shore-side electricity in Europe. Appl Energy Mar. 2021;285:116425. https://doi.org/10.1016/j.apenergy.2020.116425.

[20] Starcrest Consulting Group, LLC, 'White Bay Cruise Terminal Shore Power Analysis', Apr. 2017.

[21] M. Aasen, 'Konseptevaluering: Fjernvarme på skip', DNV GL, 2018.

[22] Manzan M, et al. Potential of thermal storage for hot potable water distribution in cruise ships. Energy Procedia 2018;148:1105–12. https://doi.org/10.1016/j.egypro.2018.08.044.

[23] El Geneidy R, Otto K, Ahtila P, Kujala P, Sillanpää K, Mäki-Jouppila T. Increasing energy efficiency in passenger ships by novel energy conservation measures. J Mar Eng Technol 2017;17(2):85–98. https://doi.org/10.1080/20464177.2017.1317430.

[24] Lepistö V, Lappalainen J, Sillanpää K, Ahtila P. Dynamic process simulation promotes energy efficient ship design. Ocean Eng 2016;111:43–55. https://doi.org/10.1016/j.oceaneng.2015.10.043.

[25] Barone G, Buonomano A, Forzano C, Palombo A, Vicidomini M. Sustainable energy design of cruise ships through dynamic simulations: Multi-objective optimization for waste heat recovery. Energy Convers Manag 2020;221:113166. https://doi.org/10.1016/j.enconman.2020.113166.

[26] McCartan DS, Kvilums C. 'NEXT GENERATION ULTRA-LUXURY CRUISE SHIP: A PASSIVE DESIGN ECO-LUXURY CRUISE SHIP FOR THE MEDITERRANEAN', presented at the RINA Design & Operation of passenger ships, London. London 2013. https://doi.org/10.13140/2.1.3021.2487.

[27] M. Nurmi, 'Improving the energy efficiency of a cruise ship stateroom', Master's thesis, Aalto University, 2017.

[28] L. Hammer, 'Passive Offshore Accommodation: An Energy-Efficient Solution for the Façade Refurbishment of an Offshore Accommodation', Master's thesis, Delft University of Technology, 2016.

[29] J. Heiskari, 'On the design criteria of large insulating glass structures in cruise ships', Master's thesis, Aalto University, 2020.

[30] Kosmadakis G, Neofytou P. Reversible high-temperature heat pump/ORC for waste heat recovery in various ships: A techno-economic assessment. Energy Oct. 2022;256:124634. https://doi.org/10.1016/j.energy.2022.124634.

[31] Trzebiński S. Technical Aspects of Using the Heat Pump at the Ship. Sci J Pol Nav Acad 2019;217(2):5–15. https://doi.org/10.2478/sjpna-2019-0009.

[32] Xu Y, Guo Z, Yuan C. Feasibility study of an integrated air source heat pump water heater/chillers and exhaust gas boiler heating system for swimming pool on luxury cruise ship. Energy Rep Nov. 2022;8:1260–82. https://doi.org/10.1016/j.egyr.2021.12.037.

[33] Karatuğ Ç, Durmuşoğlu Y. Design of a solar photovoltaic system for a Ro-Ro ship and estimation of performance analysis: A case study. Sol Energy Sep. 2020;207:1259–68. https://doi.org/10.1016/j.solener.2020.07.037.

[34] Qiu Y, Yuan C, Tang J, Tang X. Techno-economic analysis of PV systems integrated into ship power grid: A case study. Energy Convers Manag Oct. 2019;198:111925. https://doi.org/10.1016/j.enconman.2019.111925.

[35] Schwager P, Gehrke K, Vehse M. Applicability of Standard Photovoltaic Modules for an Increased Share of Renewable Energies on Board Cruise Ships. In: in 2021 Sixteenth International Conference on Ecological Vehicles and Renewable Energies (EVER), May; 2021. p. 1–5. https://doi.org/10.1109/EVER52347.2021.9456658.

[36] Zapałowicz Z, Zeńczak W. The possibilities to improve ship's energy efficiency through the application of PV installation including cooled modules. Renew Sustain Energy Rev Jun. 2021;143:110964. https://doi.org/10.1016/j.rser.2021.110964.

[37] Ancona MA, et al. Efficiency improvement on a cruise ship: Load allocation optimization. Energy Convers Manag 2018;164:42–58. https://doi.org/10.1016/j.enconman.2018.02.080.

[38] Baldi F, Gabrielii C, Melino F, Bianchi M. A Preliminary Study on the Application of Thermal Storage to Merchant Ships. Energy Procedia Aug. 2015;75:2169–74. https://doi.org/10.1016/j.egypro.2015.07.364.

[39] Nair AM, Wilson C, Huang MJ, Griffiths P, Hewitt N. Phase change materials in building integrated space heating and domestic hot water applications: A review. J Energy Storage Oct. 2022;54:105227. https://doi.org/10.1016/j.est.2022.105227.

[40] Sevault A, Vullum-Bruer F, Tranås O. Active PCM-Based Thermal Energy Storage in Buildings. Reference Module in Earth Systems and Environmental Sciences 2020. https://doi.org/10.1016/B978-0-12-819723-3.00008-1.

[41] Garcia P, Largiller G. Performances and control aspects of steam storage systems with PCM: Key learnings from a pilot-scale prototype. Appl Energy Nov. 2022;325:119817. https://doi.org/10.1016/j.apenergy.2022.119817.

[42] Catapano F, et al. Development and experimental testing of an integrated prototype based on Stirling, ORC and a latent thermal energy storage system for waste heat recovery in naval application. Appl Energy Apr. 2022;311:118673. https://doi.org/10.1016/j.apenergy.2022.118673.

[43] Baldasso E, et al. Organic Rankine cycle-based waste heat recovery system combined with thermal energy storage for emission-free power generation on ships during harbor stays. J Clean Prod 2020;271:122394. https://doi.org/10.1016/j.jclepro.2020.122394.

[44] Ouyang T, Wang Z, Zhao Z, Lu J, Zhang M. An advanced marine engine waste heat utilization scheme: Electricity-cooling cogeneration system integrated with heat storage device. Energy Convers Manag May 2021;235:113955. https://doi.org/10.1016/j.enconman.2021.113955.

[45] Fang S, Fang Y, Wang H, Liu L. Optimal Heterogeneous Energy Storage Management for Multienergy Cruise Ships. IEEE Syst J 2020;14(4):4754–64. https://doi.org/10.1109/jsyst.2020.2966711.

[46] August Brækken, 'Energy Use and Energy Efficiency Potential on Passenger Ships', Master's thesis, Norwegian University of Science and Technology (NTNU), Trondheim, 2021. [Online]. Available: https://hdl.handle.net/11250/2787909.

[47] Color Line, 'Color Fantasy Facts'. https://www.colorline.com/kiel-oslo/facts-about-color-fantasy (accessed Jun. 19, 2020).

[48] Color Line, 'Rutetider'. https://www.colorline.no/rutetider (accessed Sep. 30, 2020).

[49] Color Line, 'Color Line Fantasy'. https://tourmkr.com/F1kVlcNnMa (accessed Jun. 19, 2020).

[50] Google, '[Google Maps image showing the area between Oslo and Kiel]'. https://goo.gl/maps/pN8XvWDgD5cLUAjY6 (accessed Sep. 30, 2020).

[51] CruiseMapper, 'Color Fantasy ferry deck plans'. https://www.cruisemapper.com/deckplans/Color-Fantasy-ferry-1884 (accessed Jun. 25, 2020).

[52] Color Line, ‘Lugarer Oslo-Kiel’. https://www.colorline.no/oslo-kiel/lugarer (accessed Jun. 25, 2020).

[53] Standard Norge, ‘NS-EN ISO 7730: Ergonomics of the thermal environment’, 2006.

[54] Norge S. ‘NS-EN 15232–1:2017: Energy Performance of Buildings - Part 1: Impact of Building Automation. Controls and Building Management’ 2017.

[55] Standard Norge, ‘SN-NSPEK 3031:2020: Energy performance of buildings - Calculation of energy needs and energy supply’; 2020.

[56] Color Line, ‘Restauranter og barer Oslo-Kiel’. https://www.colorline.no/oslo-kiel/restauranter-og-barer (accessed Jul. 02, 2020).

[57] Color Line, ‘Aktiviteter Oslo-Kiel’. https://www.colorline.no/oslo-kiel/aktiviteter (accessed Jul. 02, 2020).

[58] Standard Norge, ‘NS-EN ISO 7547: Ships and marine technology - Air-conditioning and ventilation of accommodation spaces - Design conditions and basis of calculations’; 2005.

[59] Saffari M, de Gracia A, Fernández C, Cabeza LF. Simulation-based optimization of PCM melting temperature to improve the energy performance in buildings. Appl Energy 2017;202:420–34. https://doi.org/10.1016/j.apenergy.2017.05.107.

[60] Solcellespesialisten, ‘SCCS Sunpower 360W X22’. https://solcellespesialisten.no/nettbutikk/solcellepanel/monokrystalinsk/sunpower-360w.html (accessed Jan. 22, 2021).

[61] Nowtricity, ‘Real time electricity production emissions by country’. https://www.nowtricity.com/ (accessed Mar. 20, 2023).