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Analysis of Zero-Emission Scenarios of a Cruise Ship using a Modelica-based Digital Twin

Simulation Technologies, Digital Twins and Complex System Simulation

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ABSTRACT

Having to comply with zero-emission operation in the near future, the cruise ship sector is facing a substantial challenge. The paper deals with the energy-relevant systems on board a cruise ship and shows an application example in which the advantages of a modular Modelica-approach is utilised. Cruise ships in particular have high energy demands due to their hotel operations and their extensive infrastructure - comparable to that of a small town.

One of the first areas in which the zero-emission restrictions are to be fullfilled are those Norwegian fjords that are part of the World Heritage Site. An insight at the technical and operational conditions under which such a fjord passage can be passed in battery mode is provided. In battery operation, however, further measures must be taken, as the thermal energy supply from the waste heat of the main engines is no longer available. Thermal consumers like the HVAC (Heating, Ventilation and Air Conditioning) must be supplied by alternative sources. Instead, the HVAC could be turned down, which would have an impact on the room temperature and passenger comfort which must be taken into account. Based on detailed measurement data from a conventional fjord cruise with diesel-electric propulsion, the special challenges under the conditions of short-term zero-emission operation of future cruises are evaluated and solutions identified.

In order to be able to reliably assess those complex issues, an innovative simulation approach was developed, that simulates all energy-relevant systems on board in a modular structure. Typically, the focus of the modeling is on the main components of the energy conversion such as the main engines and the propulsion. Especially for passenger ships, however, it is essential to include in addition the coupled thermal subsystems like WHR (Waste Heat Recovery), HVAC and steam systems in a high level of detail. Particularly under the highest requirements, such as zero-emission operation, each individual subsystem is relevant. The paper provides a selection of such specific examples in which the Modelica-based digital twin is used to estimate the scale at which the new battery installed on the reference ship can make a decisive contribution to ultra-low-power operation. Besides, additional measures that are necessary for zero-emission operation are discussed.

Finally, these modules are combined to an entire system which can be used to analyze the energy flows with a high level of detail for any scenario as well as for different technologies for the digital twin "Cruise Ship".

1 INTRODUCTION

The cruise ship industry has witnessed substantial growth, driven by an increasing global demand for distinctive and immersive travel experiences that enable passengers to explore multiple destinations while maintaining high standards of comfort and convenience. The rising demand has resulted in the proliferation of large, energy demanding vessels, which collectively make substantial contributions to global greenhouse gas (GHG) emissions. Acknowledging this environmental impact, the International Maritime Organization (IMO) has instituted a series of stringent regulations aimed at reducing the carbon footprint of the shipping industry, aligning these measures with the United Nations' sustainable development goals. Furthermore, Norway has enacted some of the world's most rigorous emission regulations for cruise ships and ferries within its iconic fjords, specifically addressing UNESCO-listed fjords such as Geirangerfjord and Nærøyfjord. The Norwegian Maritime Authority (NMA) will require that only zero-emission vessels be permitted in these environmentally sensitive fjord areas effective from 2026 for ships under 10.000 gross tonnage [1]. For larger ships, the requirement will apply from January 1, 2032. To adhere to these stringent regulations, cruise operators are compelled to transition to advanced clean technologies. Potential solutions include fully electric propulsion systems and hybrid power sources.

2 METHODOLOGY

2.1 Reference vessel

The reference vessel has a gross tonnage (GT) exceeding 120.000. with the ability to accommodate over 3000 passengers. It is outfitted with numerous facilities designed to maintain a high level of passenger comfort. The vessel conducts operations across multiple maritime regions, encompassing the Baltic Sea, Western Europe, and the Mediterranean.

To address its substantial electrical power requirements, the vessel is outfitted with several diesel generators, collectively delivering a total rated power exceeding 45 MW. The majority of the electrical energy is utilized by the ship's propulsion and steering systems, as well as for hotel services. Additionally, electrical energy is employed by the ship's machinery to ensure smooth operations. The thermal energy requirement is met through the recovery of waste heat from the engines cooling circuits and exhaust gases, using economizer systems to generate hot water as well as high- and low-pressure steam. Moreover, the thermal energy provision can be enhanced by firing the two auxiliary boilers. Once all thermal demands are satisfied, the excess thermal energy is discharged into sea water through various heat exchangers.

2.2 Operational scenario

One of the first regions to enforce zero emission restrictions are the Norwegian fjords, classified as the World Heritage Site, including the Geirangerfjord area as shown in Figure 1, a popular destination for numerous cruise ships and ferries. The Geirangerfjord port has over 180 cruise ships visiting the port every year [2]. To adhere to these restrictions, the passage through the zero-emission zone can be achieved using battery systems, storage tanks and other zero-emission solutions. However, these systems must meet several criteria to ensure smooth operation during transit. In addition, numerous measures must be taken due to e.g. the unavailability of the waste heat from the engines, which requires that various thermal consumers be supplied by alternative sources or deactivated.

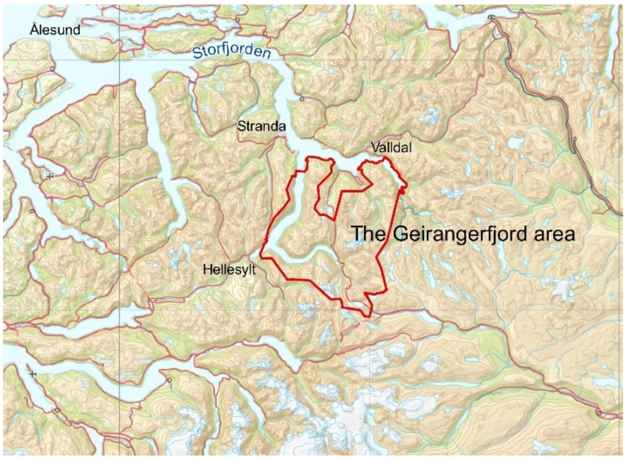

Figure 1. Boundary of the Geirangerfjord world heritage area [3]

In order to simulate the zero-emission passage, it is necessary to input various data into the simulation model, including instantaneous power demand. Measurement data specific to the reference vessel in the Geirangerfjord area were unavailable; hence, data from the Eidfjord were utilized. The travel distance through the zero-emission zone in the Geirangerfjord area is approximately 32.5 km, which can be assessed in the Eidfjord area, as depicted in Figure 2, to ascertain the start and end points of the simulation. Furthermore, upon reaching the port, the vessel is required to connect to the (assumed) shore power grid, given the absence of alternative power sources that comply with emission restrictions and to ensure battery recharging for the return journey. Consequently, an additional period of 45 minutes is incorporated into the simulation framework subsequent to the vessel's arrival at the port and prior to its departure, to accommodate the time required for the connection and disconnection of the shore power system [4].

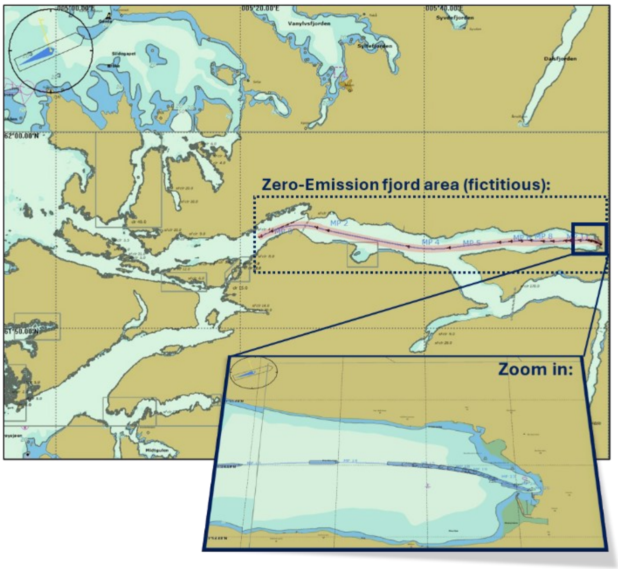

Figure 2. Equivalent of the zero-emission passage in the Eidfjord illustrated with the SAMMON Planning Software (by ISSIMS GmbH)

2.3 Data processing

To achieve a deeper comprehension of energy dynamics on the ship for the scenarios investigated, the measurement data were systematically processed and evaluated. The electrical energy consumed is determined by integrating the instantaneous electrical power output of the generators over the specified timeslot. The fuel mass consumed by the vessel's power generation plant is calculated using the specific fuel consumption rates of the four main engines as follows:

$$m_{fuel} = \sum_{i=1}^{4} \int_{t_{start}}^{t_{end}} \left(SFC_{ME_I} \,.\, P_{ME_i}\right) \cdot dt + \sum_{i=1}^{2} \int_{t_{start}}^{t_{end}} \left(\dot{m}_{Boiler_i}\right) \cdot dt \qquad (1)$$

The energy balance within the vessel can be represented as follow:

$$H_{fuel} = E_{elec} + Q_{recovered} + Q_{lost} \qquad (2)$$

Here H_{fuel} represents the enthalpy of the fuel engaged in the combustion process of the main engines and the auxiliary boiler. The right-hand side of the equation signifies the generated electrical energy E_{elec}, and the recovered heat from the exhaust gas economiser, the auxiliary boiler and the engine cooling circuits $Q_{recovered}$, as well as the dissipated heat released to the environment Q_{lost}. For the sake of simplification, the kinetic and potential energy contributions have been omitted in the computation of the energy flows pertaining to the material streams. The enthalpy of the burned fuel can be calculated using the lower heating value of fuel and its specific heat capacity according to the following equation:

$$H_{fuel} = m_{fuel} \cdot \left(LHV_{fuel} + c_{p_{fuel}} \cdot \left(T_{in} - T_{ref}\right)\right) \qquad (3)$$

The calculation was carried out using measurement data of the energy flows across the system. The energy balance then was set up by integrating the measurement data through the desired period.

2.4 Simulation

To simulate the battery-powered zero-emission passage, Modelica-based dynamic models were developed and implemented within the Dymola simulation environment. This approach enabled the detailed representation and analysis of the various systems operating onboard the vessel under the specified scenarios. The simulation utilized a combination of libraries, including the Modelica Standard Library (MSL) [5] and the Buildings Library [6], both of which provide a comprehensive collection of pre-configured and validated components. These libraries facilitated the modelling of key subsystems and aggregates of the vessel, such as energy storage, thermal management, and auxiliary systems, ensuring a robust and accurate simulation framework for assessing system performance and energy demands.

3 RESULTS

3.1 Preliminary analysis

In order to acquire a thorough understanding of the vessel's operational requirements throughout the zero-emission fjord passage, an analysis of the vessel's energy and power needs was conducted.

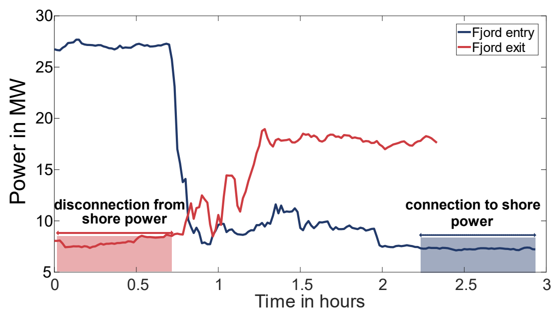

Figure 3. Ship’s electrical power demand during both fjord entry and exit

Figure 3 illustrates the electrical power demand of the vessel during its transit into and out of the Eidfjord. During the fjord entry, the vessel exhibits high power consumption due to elevated speed, which results in increased propulsion power demands. As the vessel approaches the harbour, its speed decreases, thereby reducing propulsion power demand and marking the onset of the manoeuvring phase. This phase is characterized by fluctuating peaks, reflecting variations in propulsion requirements and the activation of auxiliary systems. Following the proper positioning of the vessel at the berth, the power demand stabilizes at a moderate level. The fjord entry spans approximately two hours and eleven minutes, which is longer compared to the fjord exit duration of roughly one hour and thirty-five minutes. This discrepancy is attributed to the time-intensive process of accurately positioning the vessel at the berth during its entry. Furthermore, an additional 45 minutes is allocated to accommodate the time required for connecting to or disconnecting from shore power.

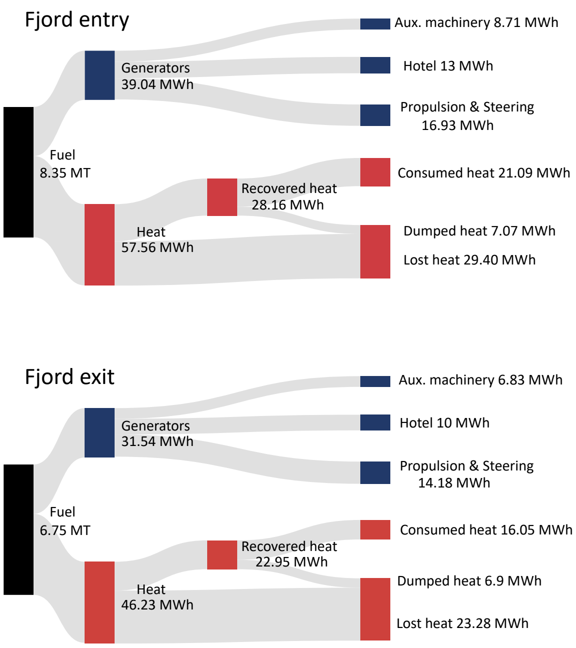

Figure 4. Fuel and energy demand of the ship

Figure 4 depict the different contributions to the energy demand associated with the primary consumers aboard the ship during entry into and exit from the zero-emission fjord. To fulfil the substantial demand for electrical energy, the vessel utilizes approximately 8.35 metric tonnes of fuel during fjord entry, as opposed to 6.75 metric tonnes during fjord exit. Approximately 40 % of the fuel's enthalpy is converted into electrical energy, while around 60 % is dissipated as heat. A portion of the dissipated heat is recovered using the exhaust gas economiser to generate high- and low-pressure steam, and through the cooling circuits of the main engines, which provide hot water for various shipboard consumers.

Once the thermal demand of the system is satisfied, the surplus heat is discharged into the seawater via different heat exchangers. The electrical energy generated is predominantly consumed by the ship's propulsion system, various hotel facilities, as well as the ship's machinery. Owing to the longer duration of the fjord entry compared to the exit, the ship consumes less fuel during the fjord exit and exhibits a decreased energy demand across all electrical and thermal consumers compared to fjord entry.

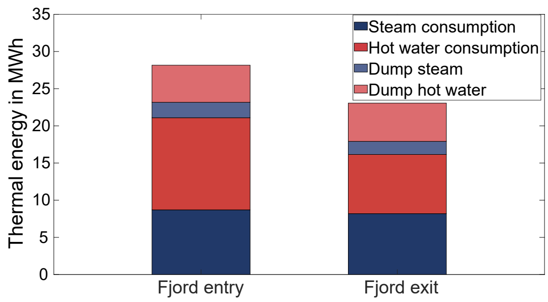

Figure 5. Thermal energy management during the fjord entry and exit under main engines operation

To achieve an efficient zero-emission passage through the fjord, it is essential to conduct an analysis of the thermal energy demand of the ship. Figure 5 illustrates the vessel's thermal energy management during both the entry and exit of the fjord while it operates under its four main engines. When travelling through the fjord, the ship consumes around 8.7 MWh of steam energy when entering and 8.1 MWh when leaving. The different steam consumers primarily include galleys, pools, and laundry services, as well as engine-relevant consumers such as fuel and lubricating oil heaters. In addition, the ship also uses a considerable amount of heat in the form of hot water, consuming about 12.39 MWh during fjord entry and 7.95 MWh during the fjord exit. To satisfy its electrical demand, the vessel operates multiple engines, resulting in a substantial amount of recoverable heat from exhaust gas economizers and engine cooling systems. This amount of energy frequently exceeds the thermal energy demand of the vessel, especially in seagoing mode. Consequently, the vessel discharges approximately 2.00 MWh of steam and 5.07 MWh of hot water into seawater during its fjord entry, and about 1.76 MWh of steam and 5.14 MWh of hot water during the fjord exit. The cooling load during the scenario is about 10 MWh for the entry and 8.6 MWh for the exit. The chillers mainly provide chilled water for the air conditioning system, where the fresh air is first cooled and dehumidified before being conditioned to the desired temperature.

3.2 Energy demand

The energy of the case study ship can be provided by various systems. The two main requirements are electrical and thermal energy. Given that the entry scenario is characterised by the higher energy demand, this scenario is selected as the reference point for the design of the battery system.

3.2.1 Thermal demand

The thermal energy requirement of the ship is divided into hot water, steam and a cooling load, as already mentioned in chapter 3.1.

3.2.1.1 Hot water

Hot water maintained at a supply temperature of 93 °C serves as the thermal medium for various purposes, such as supplying the absorption chiller units, providing potable water, heating components of the air conditioning system, and maintaining the jacket heaters of the engines. During the scenario under review, the thermal energy demand attributable to hot water amounts to 48.84 MWh. Approximately 12.39 MWh is consumed during the fjord entry, 28.5 MWh during the port stay, and 7.95 MWh during the fjord exit. The temporal progression of these segments is depicted in Figure 6, where vertical lines on the abscissa represent distinct phases of the scenario: the initial line marks the port call, and the subsequent line indicates the commencement of departure.

To determine the amount of the hot water that is used in the scenario, the volume flows traversing the heat exchangers of individual consumers were integrated over the designated time frame. For integrating any new system to provide hot water, it is necessary to be able to provide the required volume flow of each consumer. Each consumer exhibits a distinct return temperature of hot water following its heat transfer to the respective medium. Upon this integration of the volume flows, during the fjord entry and exit, the requisite hot water volume was determined to be 843 m³, distributed in 475 m³ for the fjord entry and 368 m³ for the exit scenario. This volume flow distribution results from the hot water consumption curve shown in Figure 6 (top).

The heat demand of the individual consumers supplied by the hot water system is also illustrated in Figure 6 (bottom). The significant heat demand primarily arises in the absorption chiller unit (ACU) and the heating units in the air conditioning system (ACH). The largest heat demand during the scenario is attributed to these heating units.

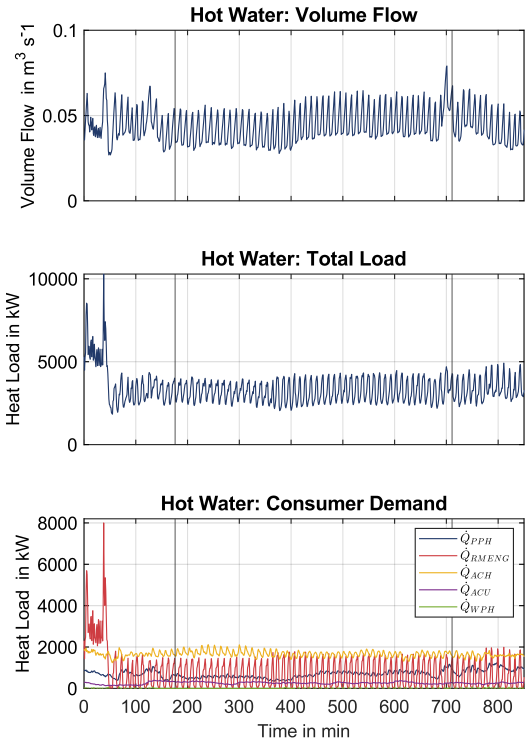

Figure 6. Hot Water volume flow and heat demand during the whole scenario

To ensure a seamless transition from zero-emission to normal operation, the engine room heater and the engine jacket heater are kept operational during the scenario.

The mean hot water return temperature is about 70 °C. In the simulation an electrically operated boiler is used to heat the water back up to 93 °C so that it can be fed back to the consumers. The following equation calculates the energy required:

$$Q = m \cdot \mathrm{c} \cdot \Delta\mathrm{T} \qquad (1)$$

The density of water is assumed to be 977 kg·m^{-3} at 70 °C, and the specific heat capacity is 4.18 kJ·kg^{-1}·K^{-1} [7]. An assumed efficiency of the boiler of 98 % leads to an additional electrical energy requirement of 12.65 MWh considering just the fjord entry and covering the original requirements.

3.2.1.2 Steam

A significant challenge to be addressed pertains to meeting the vessel's steam requirements, necessitating the provision of low-pressure steam at 4.6 bar and high-pressure steam at 9 bar. The primary consumers of low-pressure steam are the vessel's various galleys and pools, while high-pressure steam is mainly used by the laundry services, fuel oil and lubricating oil heaters, and the bio sludge dryer.

During the simulation of the zero-emission passage, only electrical energy is available for steam generation. Consequently, an electrical low-pressure steam boiler and an electrical high-pressure steam boiler are employed under these conditions. The simulation of the electrical boilers is based on an inlet water temperature of 20 °C, as no preheated water is available in the current scenario to offset the energy demand. This lack of preheated water results in the boilers having to heat the water entirely from ambient temperature, thereby increasing the overall electrical energy consumption required to achieve the desired output temperature. For the purpose of this analysis, an electrical efficiency of 98 % was assumed. Furthermore, it is imperative to analyse which steam consumers are critical for the vessel's operational efficacy. Figure 7 illustrates the energy consumption of the boilers corresponding to each steam consumer.

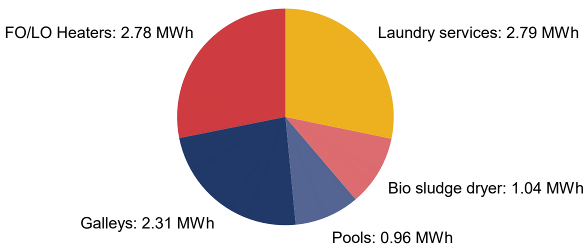

Figure 7. Energy demand of the electrical boilers for the different steam consumers

The fuel oil and lubricating oil heaters account for 2.78 MWh of the boilers' electrical energy demand and are essential for the operation of the main engines, particularly when transitioning from battery mode to engine operation. Therefore, maintaining these heaters at the appropriate temperature is imperative. Additionally, the pool heating demands approximately 0.96 MWh. The galleys consume around 2.31 MWh of thermal energy and require a constant steam supply for various tasks crucial to the passenger’s comfort. The bio sludge dryer consumes merely 0.96 MWh and the laundry 2.79 MWh.

3.2.1.3 Cooling

The cooling system provides chilled water for the air conditioning system and the potable cold water. It is provided by absorption and compression chiller units (ACU and CCU). Figure 8 shows the cooling load of both types of chiller units. Both units were used throughout the scenario, with the CCU having the highest energy load, while the ACU is lowered after a time.

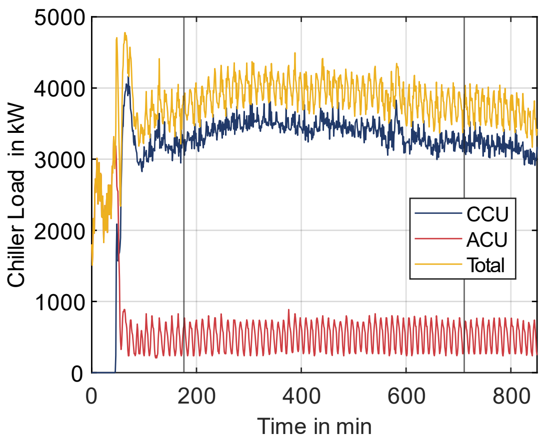

Figure 8. Cooling load of the chiller units

The entry scenario has a total cooling load of 10 MWh. The ACU has a total cooling load of 3.2 MWh and the CCU of 6.8 MWh. While for the fjord exit scenario a cooling load of 8.6 MWh is demanded (ACU: 1.2 MWh and CCU: 7.4 MWh).

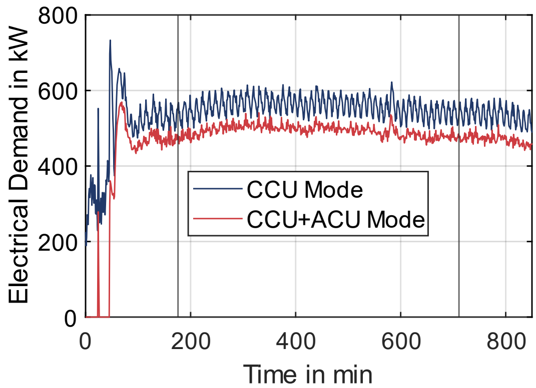

Figure 9. Electrical demand of the CCU

To get the electrical energy demand of the compression chiller unit, measurement for the CCU is provided and shown in Figure 9 (CCU+ACU Mode). The electrical energy requirements during the entry of the fjord for the CCU is 1 MWh. Due to the lack of waste heat from the engines during the zero-emission scenario, the ACU is inefficient and switched off. The CCU now takes over the entire cooling capacity from the fjord entrance. This is also shown in Figure 9 (CCU Mode). A COP for the CCU of 8 is assumed, based on the experience gained from measurement data and operating range in the characteristic map of the manufacturer's data. This results in an electrical energy demand of 1.4 MWh. This also means that the hot water demand for the ACU is eliminated and thus directly influences the required battery capacity. The electrical energy demand determined in the previous chapter is reduced by the amount required to provide the hot water for the ACU. This means that 3.78 MWh less electrical energy is required for the ACU and 0.4 MWh more for the CCU to a total of 1.4 MWh for the provision of chilled water. The electrical hot water boiler requires now 8.61 MWh for the provision of hot water in the entry scenario.

3.2.2 Electrical demand

The battery system employed in the simulation of the zero-emission scenario was designed to accommodate the electrical energy demands encountered during the operational phase of the fjord entry, which has been determined to require a higher energy input compared to fjord exit due to its prolonged duration and associated operational loads. The design specifications account for the total electrical energy consumption of 39.44 MWh during fjord entry, supplemented by additional demands including 8,61 MWh required for hot water production via the boiler system and 9.9 MWh for the generation of low-pressure and high-pressure steam through electrical boilers.

To meet these requirements while maintaining operational safety and efficiency, the total installed capacity of the battery system was set at 73 MWh. The operational strategy of the battery is governed by a battery management system (BMS), which enforces a maximum state of charge (SOC) of 90 % and a minimum SOC of 10 % [8]. This SOC window was established to ensure optimal thermal and electrochemical stability, thereby mitigating degradation mechanisms such as lithium plating and cathode deterioration, which are exacerbated at extreme charge states.

For electrical energy storage, a battery system is employed, operating within a voltage range of 1100 VDC max and 800 VDC min. The specifications of the battery system utilized in this scenario are detailed in Table 1.

Table 1. Specifications of the battery system

Type	Lithium Ion NMC
Voltage Range	800-1100 VDC
C-Rate- Continuous	3C
Capacity	73 MWh
Operating Temperature	15-20 °c

3.3 Optimization measures

In the following chapters, measures are presented that serve to manoeuvre the ship through the zero-emission scenario and reduce the load on the battery. This includes the consideration of switching off thermal consumers, using storage or utilising other, more efficient systems.

3.3.1 Switching off consumers

The battery can be relieved if unnecessary loads are switched off during zero emission operation. However, this option has an impact on the other machines and can be considered a safety risk. For example, the fuel may not be viscous enough to be pumped into the engines when switching from zero emission to fossil fuel operation. Or rooms or machines may cool down and then also have start-up problems during the changeover. It is therefore the responsibility of the captain to decide whether the systems should be switched off. Possible consumers that can be switched off or whose use is not mandatory during zero emission operation are analysed below.

The hot water system supplies energy for the potable water heater, the engine room heater, the main diesel jacket heater and the air conditioning heater. All of the above are necessary to ensure the comfort of the guests and the safety of the ship's operation or its conversion to fossil fuel operation. The following chapters assume that all active consumers from measurement data are turned on. Thermal suppliers are substituted by electrical suppliers.

Steam consumers include fuel oil heater, laundry services, galleys, bio sludge dryer and pool heater. Deactivating the pool heaters could cause the temperature of the pool to drop by around 3 °C during entry. This would result in a saving of 665 kWh LP Steam. The galleys are also used for passenger comfort and are therefore not regarded as consumers that can be switched off. The Bio sludge dryer is not critical for the vessel's operation or the passengers’ comfort and can be deactivated during zero-emission passages. The laundry service can shift its energy load to the port stay when shore power is available. This reduces the electrical energy requirement of the boilers and therefore the battery capacity. Switching off the bio sludge dryer and the laundry during the zero-emission entry leads to a potential saving of 3.75 MWh of electrical energy for the intended boiler.

The cooling load of the chilled water is mainly distributed between the air conditioning system, the cooling of switch boards and the provision of cold drinking water. These consumers have a direct impact on safety and passenger comfort and therefore cannot be switched off.

These considerations results in a possible reduction of the electrical energy requirement by only 3.75 MWh. Due to the safety risks mentioned above, it is assumed in the following scenarios that the energy requirements of all consumers must be met.

3.3.2 Thermal Storage

To supply the necessary thermal energy, storage options for hot water and the cooling load are being investigated. A system of storage tanks is being considered for the hot water and an ice storage system for the cooling load.

3.3.2.1 Hot Water

Based on the findings in chapter 3.2.1.3 it is more economical to have the CCU provide the cooling capacity, the ACU is not considered in the tank design. This means that the previously determined volume of the hot water of 475 m^3 is reduced to 318 m^3. Tanks up to 389 m^3 are already installed on the reference vessel and therefore it is not dimensioned any larger.

The storage system is designed with two tanks, each with a capacity of 323.5 m^3. These tanks are insulated to maintain the hot water at 93 °C for at least three hours. There is no return flow into the active storage tank; instead, the returning water from the consumers, with varying temperature levels, is collected in the second tank. Loading occurs during the voyage with excess hot water or if necessary, via shore power while in port. At the start of the scenario, the storage tank is assumed to be fully charged. Note that the integration of a second hot water storage tank may impact the ship's stability, a factor that was not further analysed in this study.

To estimate the charging time before the scenario begins, the dump hot water volume flow was determined and integrated. A constant hot water temperature of 93 °C and a constant seawater temperature of 14 °C were assumed.

Figure 10 shows the integrated total dump volume of the hot water stream. The gradient indicates the charging speed, with the highest speed occurring during the voyage to the fjord entry. During this period, there is a high demand for electrical energy (e.g. for propulsion), leading to increased thermal dump availability. As illustrated, the storage system can be fully charged within approximately 8.8 hours using 323.5 m^3 of hot water.

For the fjord entry simulation, a tank with 15 cm thick polyurethane foam insulation was modelled and placed in a room at 20 °C. A pump supplies the consumers with the required hot water mass flow, while an ideal heat exchanger extracts the necessary heat. The return water is collected in the second tank.

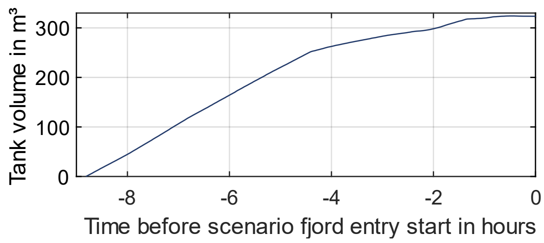

Figure 10. Loading the storage with dump hot water

Figure 11 (top) illustrates the charging process of the designated second storage tanks during the fjord entry scenario, with 323.5 m^3 of hot water supplied. This volume corresponds to the total thermal demand up to the port call. The temperature of the return water mass flow is shown in Figure 11 (middle). During periods of high load, the return water temperature is approximately 66 °C, while during low-load periods, it is around 74 °C. During the charging process, the temperature of the water in tank two increases to approximately 70 °C (Figure 11 (bottom)). The fjord exit scenario can be started with a storage tank charged with shore power. For a further entry into a zero-emission scenario, the storage tank can be recharged using the dumped hot water again.

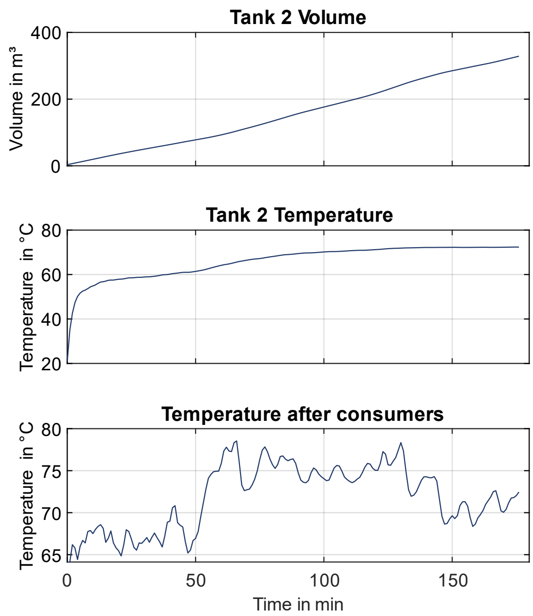

Figure 11. Water temperature after the consumers, which is then fed into the tank; water temperature and quantity in tank two

The study shows that a thermal storage unit can provide a bridge until the ship can again draw energy whose origin is permissible in a zero-emission area. Charging the storage unit with dump energy is considerably cheaper than heating it with shore power. This leads to the consideration of making the storage facility larger, that it can also bridge the time in the harbour. However, such a storage facility would have a very large volume for which is limited due to spatial constraints within the vessel.

3.3.2.2 Cooling

For the reference case, a cooling demand of approx. 10 MWh is required. If this cooling requirement is provided by a compression chiller unit (CCU) this means a consumption of approx. 1.4 MWh of electrical energy, as explained in previous chapters.

In order to reduce the size of the electric battery and still be able to meet the cooling requirement, it may be suitable to integrate an ice storage system as an additional thermal storage unit. Thus, in a zero-emission scenario, the ice storage can be used instead of the chillers. Using the enthalpy of fusion required for the phase change from ice to liquid water, a comparatively affordable and space-saving system is conceivable.

The saving potential in the case that the electrically operated CCUs can be switched off is 1.4 MWh, which would therefore not have to be provided by the battery.

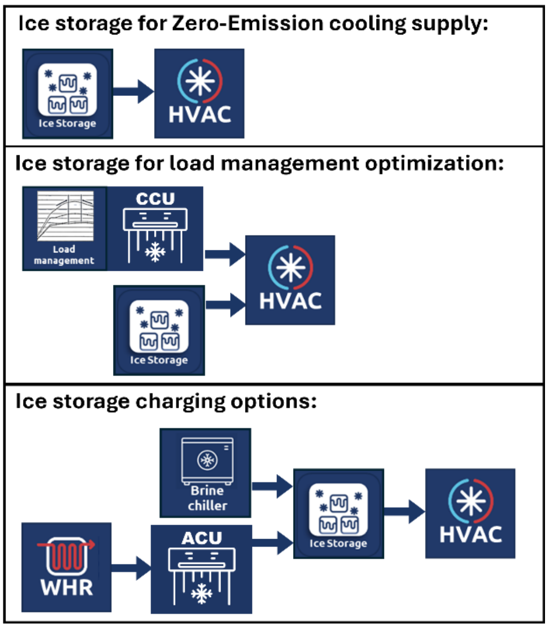

Figure 12: Options for using an ice storage system a) to reduce the battery capacity required in zero-emission scenarios (top), b) load management for more efficient operation of other chiller systems (middle) and c)possible loading of the ice storage system using brine chillers or absorption chiller units as waste heat recovery option (bottom)

The ice storage can be charged using brine chillers, which are already on-board cruise ships. It would also be possible to use an adequate absorption chiller unit (ACU) that can utilize waste heat recovery potential for this purpose. Ammonia would be a suitable medium for this temperature level.

However, an ice storage system can not only be used to save electrical energy during a zero-emission manoeuvre. Such a storage system also opens up the possibility of load shifting and load management for the chillers of the cooling system, which can be operated more often in the optimum operating range and therefore more efficiently.

3.3.3 Heat pump

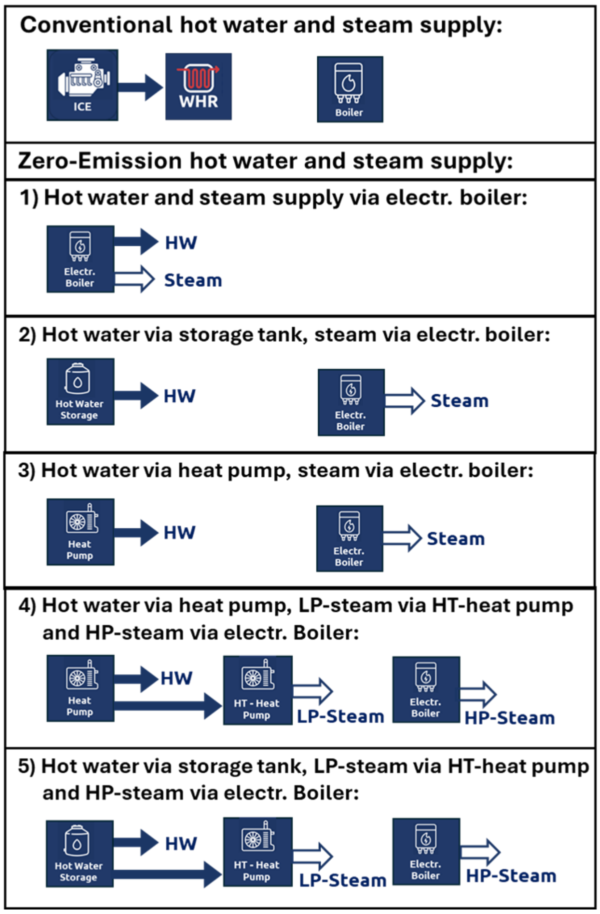

Figure 13. The analysed configurations for the electrical energy demand required for heat production during the fjord entry

In order to optimize the demand for electrical energy required for heat supply, the application of electrical boilers, heat pumps and storage tanks was examined across five additional distinct configurations as shown in Figure 13 during the fjord entry.

Employing configuration 1, the thermal requirements of the vessel are met via electrical boilers, which generate both hot water and LP and

HP steam. Conversely, configuration 2 incorporates the use of a storage tank to accumulate hot water prior to entry into the zero-emission zone, with the steam demand continuing to be fulfilled by the electric boilers. Configuration 3 employs a heat pump is to generate hot water for the various consumers, while steam production is facilitated through the use of electrical boilers. The heat pump utilizes return water from the hot water consumers, which maintains a high temperature of 70 °C, and raises it back to the set point temperature of 93 °C. The employed heat pump has a coefficient of performance (COP) that ranges from 2.4 to 3.5 [9], contingent upon the thermal load. Configuration 4 utilizes the same heat pump for hot water production. However, for low-pressure (LP) steam generation, a high-temperature heat pump is employed, and an electrical boiler is used for high-pressure (HP) steam generation. In this scenario, the high-temperature heat pump utilizes the return water from the hot water consumers as a heat source to generate LP steam. The high-temperature heat pump is designed with a constant COP of 3 [10]. Configuration 5 uses a thermal storage to store hot water before the vessel enters the zero-emission passage. This storage is used to supply hot water to the different consumers, and the return water line acts as a heat source for the high-temperature heat pump to generate LP steam, while HP steam is produced through the electrical boiler. It should be noted that all hot water and steam consumers were active during this analysis. Furthermore, the cooling requirements were satisfied utilizing the CCUs, whereas the ACUs remained inactive.

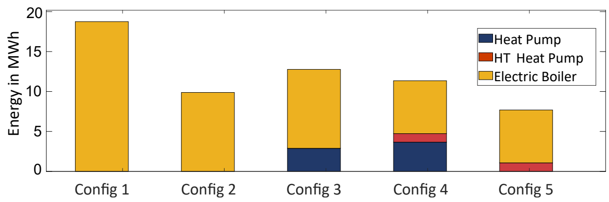

Figure 14. Electrical energy demand using the analysed configurations

Figure 14 illustrates the electrical energy requirements of the utilized aggregates. In configuration 1, both the hot water and steam boilers collectively consume 18.5 MWh of electrical energy during the fjord entry. By replacing the hot water boiler with a hot water storage tank, as depicted in configuration 2, results in a significant reduction in the demand for electrical energy. This change can be attributed to the requirement of only steam production, which consumes approximately 9.9 MWh. In configuration 3, the heat pump expends approximately 2.89 MWh to satisfy the thermal demands of the vessel with respect to hot water, while the energy demand of the electric boilers is similar to configuration 2. Conversely, configuration 4 witnesses the high-temperature heat pump utilizing approximately 1.07 MWh for the production of LP steam by employing the return line of the hot water consumer as a thermal source. This results in the further cooling of the return hot water line, thereby increasing the electrical energy demand of the hot water heat pump to 3.66 MWh, as it must reheat water from a lower temperature compared to configuration 3. Consequently, the boilers are required to produce only HP steam, which results in a decreased electrical energy consumption of the boilers amounting to 6.62 MWh. With configuration 5, hot water is readily available from the thermal storage tank. Thus, the use of a hot water heat pump is rendered unnecessary. Moreover, the high-temperature heat pumps and the boilers operate similarly to configuration 4, resulting in an equivalent electrical energy demand. The analysis indicates that configuration 5 exhibits the minimal electrical energy demand and could be adopted to decrease the overall energy consumption of the vessel, thereby facilitating a reduction in the capacity requirements of the onboard battery.

3.3.4 Slow steaming

Owing to the substantial electrical power requirements of the propulsion system, particularly during high-speed sailing, slow steaming emerges as a viable strategy to mitigate the propulsion's energy demand. Consequently, an analysis was undertaken to assess the impact of speed reduction on the vessel’s overall electrical energy demand during fjord entry. Two scenarios were considered. In scenario 1, the battery supplies the electrical and thermal energy needs of the vessel by utilizing electrical boilers for hot water production as well as for low-pressure (LP) and high-pressure (HP) steam generation (configuration 1). During this scenario, no optimization measures were implemented, and none of the thermal consumers were deactivated. However, the cooling demand was delivered by the CCU while the ACUs were deactivated. Figure 15 illustrates the variations in the vessel's overall electrical energy demand during the zero-emission passage under slow steaming conditions. Operating under normal conditions with no speed reduction results in the propulsion consuming approximately 17 MWh of electrical energy, while the hotel and services consume around 40.94 MWh, culminating in a total electrical energy consumption of 57.94 MWh that must be supplied by the battery.

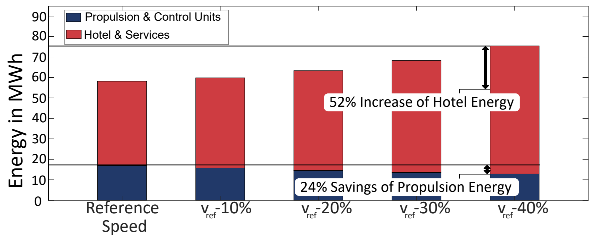

Figure 15. Electrical energy demand of the ship during scenario 1 (configuration 1) with slow steaming measures

Although reducing the ship's speed significantly decreases the propulsion's energy demand, this reduction leads to a longer duration of the zero-emission passage, thereby increasing the energy demand of the hotel and services. This increase surpasses the propulsion energy savings achieved through slow steaming measures, resulting in a continual rise in the vessel's total energy demand as its speed is reduced.

In Scenario 2, the vessel is managed utilizing all optimization strategies outlined in Section 3.3. The hot water requirements are fulfilled through a storage tank that is replenished prior to entering the zero-emission zone. Furthermore, low-pressure steam is produced via a high-temperature heat pump, while high-pressure steam is generated by an electric boiler (configuration 5). Additionally, the energy consumption of the laundry services and bio sludge dryer is deferred to the port stay, thus diminishing the electrical demand on the boiler.

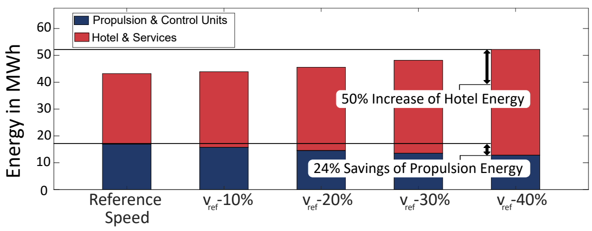

Figure 16. Electrical energy demand of the ship during scenario 2 (configuration 5) with slow steaming measures

Figure 16 illustrates the variation in the energy demand of vessels during scenario 2 under slow steaming conditions.

Operating the vessel without the implementation of slow steaming measures results in a total energy consumption of 43.26 MWh during the fjord entry. Analogous to scenario 1, a reduction in the vessel's speed leads to a continuous increase in the total energy demand due to the substantial energy requirements of the hotel and services, which must be maintained over extended periods.

Upon conducting this analysis, it is evident that slow steaming cannot be regarded as a viable option to optimize the vessel's energy demand in this instance, owing to the significant loads imposed by the hotel and services.

3.3.5 Premeasures: Steam turbine

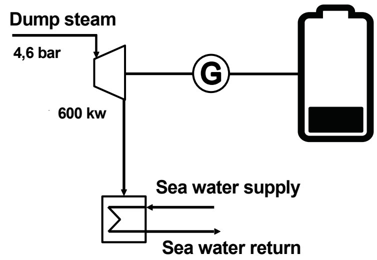

Figure 17. System to store the steam energy

To facilitate the storage of discarded thermal energy, a system has been devised and is illustrated in Figure 17. This system harnesses the available surplus steam flow which possesses an inlet pressure 4.6 bar and a specific enthalpy of around 2750 kJ·kg^{-1} [2] to drive a steam turbine, which is connected to a generator operating with an electrical efficiency of 90 %, subsequently recharging the battery. The steam is then condensed using the surplus steam condenser. This system is anticipated to substantially enhance the vessel's overall efficiency and yield significant cost savings on shore power that would otherwise be required for battery recharging. The system was then simulated utilizing measurement data for the mass flows of the discarded steam. The energy required for the battery cooling was neglected in this scenario. The power output of the generator as well as the state of charge of battery during the charging process is depicted in Figure 18.

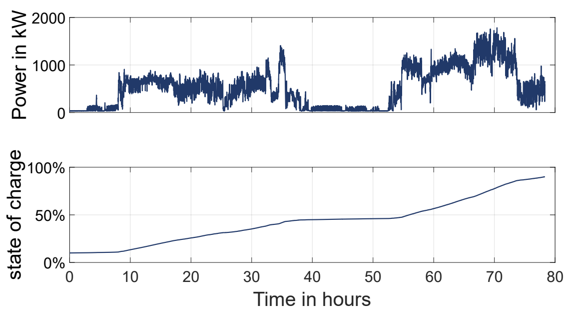

Figure 18. Generator power during battery charging

The fluctuations in the availability of surplus steam flow significantly influence the power output of the generator, which consequently influences the rate at which the battery system is charged. These variations in surplus steam mass flow are attributed to changes in electrical demand, which impact the operational load of the main generators as well as the changes in steam requirements of the various facilities aboard the vessel. Furthermore, during various intervals, the generator's power output is notably diminished due to the vessel's arrival at port. Such port stays are generally characterized by the dependence on a solitary diesel generator to fulfil the ship's electrical energy requirements, leading to insufficient steam production. Consequently, auxiliary boilers are utilized at targeted loads to enhance steam production and meet the vessel's thermal energy demands.

Charging the battery using this method can result in substantial cost savings by reducing reliance on shore power fees when charging before a zero-emission passage or minimizing fuel consumption when charging via diesel generators. It is important to note that the battery system was specifically designed to meet the electrical and thermal demands of the vessel exclusively during fjord entry. Consequently, the battery must be recharged using shore power upon arrival at the port. Further expanding the battery system’s capacity is not recommended due to spatial constraints within the vessel.

Following the charging process, the vessel is capable of transitioning to battery operation upon entering the zero-emission zone. Figure 19 illustrates the state of charge (SOC) of the battery system during both the entry and exit of the fjord. Initially, the battery system is charged to 90 %, which represents the maximum SOC permissible by the battery management system (BMS), equating to approximately 65.7 MWh of electrical energy storage. Nonetheless, the BMS permits a minimum SOC of 10 % to mitigate wear and prolong the system's lifespan, thereby making only 58.4 MWh of the stored energy available for use. Upon entering the zero-emission passage, the vessel switches to battery operation, initiating discharge at relatively high currents due to the significant electrical demand from the propulsion system. After approximately 45 minutes, the vessel experiences a notable reduction in speed as it shifts to manoeuvring mode, consequently diminishing the discharging current. As the electrical demand continues to decrease nearing the port, the SOC of the system persistently lowers, leading to a continuous decline in the battery voltage, maintaining a nearly constant discharge rate even though the actual discharging load is decreasing. Once the vessel is adequately positioned at the port, it remains on battery mode for an additional 45 minutes until the shore power connection is established. Subsequently, the vessel transitions to shore mode, operating in this mode for several hours while simultaneously recharging the battery for the fjord exit.

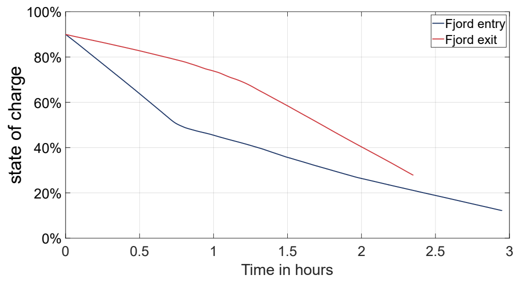

Figure 19. State of charge of the battery system during the discharging processes

Upon departure from the port, the vessel disconnects from the shore power supply and transitions to battery operation with an initial State of Charge of 90 %. The process of disconnection from shore power requires approximately 45 minutes. Subsequently, the vessel commences manoeuvring at low velocities, which induces a slight elevation in the electrical demand and therefore the discharge current of the battery system. Approximately 1 hour and 20 minutes into this period, the electrical demand of the vessel escalates significantly as it exits the manoeuvring mode and accelerates to higher speeds, thereby resulting in an increase in the discharge current that remains stable for the remainder of the zero-emission passage.

4 CONCLUSIONS

This study provides a comprehensive analysis of energy demand and optimization strategies for the reference vessel, aimed at enhancing operational efficiency and sustainability during zero-emission scenarios. The investigation of thermal and electrical demands highlighted key areas for improvement in energy usage. By employing optimization strategies such as switching off non-critical consumers, implementing thermal storage solutions, and integrating heat pump technology, significant efficiency gains were identified. Furthermore, the application of a steam turbine system underscored the potential for enhancing the overall efficiency of the vessel and mitigating its environmental impact, particularly in sea-going operations. However, further considerations of slow steaming measures were precluded by the high electrical load of the hotel facilities, which exceeds the propulsion energy conserved through slow steaming conditions.

The results underline the importance of adopting a holistic approach to energy management, combining innovative technologies with operational adjustments. These findings contribute to the broader efforts of minimizing energy demand and emissions in maritime operations. Future work should focus on validating these measures under real-world conditions and exploring their scalability across various vessel types.

5 DEFINTIONS, ACRONYMS, ABBREVIATIONS

ACH: Air conditioning heater

ACU: Absorption chiller unit

BMS: Battery management system

CCU: compression chiller unit

COP: Coefficient of performance

cp: Specific heat capacity

e.g.: for example

GHG: Greenhouse gas

HP: high-pressure

HW: Hot water

IMO: International Maritime Organization

LHV: Lower heating value

LP: low-pressure

NMA: Norwegian Maritime Authority

PME: Power Main Engine

PPH: Potable water heater

RMENG: Engine room heater

SFC: Specific fuel consumption

SOC: State of charge

WPH: Main Engine jacket heater

6 ACKNOWLEDGMENTS

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