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Towards Optimized Maritime Energy: Focus on an Energy Analysis and Management to Replace Conventional Power Systems with Hydrogen Solutions

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Abstract. This work presents an initiative carried out within the framework of the EU co-founded sHYpS project (Sustainable HYdrogen powered Shipping), aiming to propose a solution to achieve decarbonization goals of the maritime sector. Focused on cruise navigation in Norwegian Fjords, zero-emission shipping was achieved by installing a hydrogen-fueled low-temperature fuel cell system. This required the redesign of the shipboard systems and the implementation of energy-saving strategies to reduce consumption.

Fuel cells integration significantly impacts the overall energy balance, as the high-temperature waste heat generated by internal combustion engines (which is currently used almost entirely for the heating, ventilation and air-conditioning systems) is no longer available. Instead, fuel cell power plants produce less waste heat at lower temperatures, thus presenting a critical challenge in reimagining the energy flows management to fully leverage the available waste heat from fuel cells, by minimizing fuel consumption.

The analysis was conducted on a cruise ship with a capacity of 998 guests, 465 crew members, 54,300 GT of gross tonnage, 239 meters long, and a conventional power installation of 23.5 MW. The fuel cell system was integrated alongside the traditional conventional power plant and an energy analysis and management has been carried out to minimize both thermal and electrical energy consumptions while maintaining adequate comfort levels, reducing the required electrical power, and limiting the amount of hydrogen storage needed.

Results show that achieving a zero-emission sailing day is feasible, though, certain energy-related limitations must be implemented. Additionally, the potential to leverage the ultra-low-temperature cold flow of liquid hydrogen to reduce power demand has been explored. Although the high costs of system development may present a significant barrier to its onboard implementation at these early stages of design, significant benefits might be achieved in the future.

Keywords. Zero emission navigation; hydrogen fuelled cruise ships; fuel cell system; energy analysis; energy optimization.

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Introduction

In response to the growing demands for environmental sustainability and energy efficiency in the maritime industry, hydrogen is increasingly gaining interest [1]. In this context, shipowners are increasingly making strategic decisions for the design of their new fleet of ships and for fuel selection leading to hydrogen-based hybrid solutions, including liquid hydrogen solutions [2], to combine traditional engines with cutting-edge technologies such as batteries and fuel cells.

With reference to cruise navigation in Norwegian Fjords and on the use of swappable Liquid Hydrogen tanks, the development and integration of alternative fuel systems became the primary objective of sHYpS, an EU co-funded project, encompassing an analysis of the existing conventional systems onboard and the development of an innovative hybrid solution to serve onboard users. As part of the project, the ship conventional operation, which takes about 7 days, has been analysed to collect the necessary data to preliminarily define the amount of hydrogen required to carry out the planned route: a typical fjord call scenario has been considered, lasting approximately 15 hours, which includes the following phases:

- *Navigation* (2.5 h of fjord entrance at constant speed)
- *Manoeuvring* (0.5 h high power requirement)
- *Harbour* (9 h sustaining only required auxiliaries and hotel loads)
- *Manoeuvring* (0.5 h high power requirement)
- *Navigation* (2.5 h of fjord exiting at constant speed)

By following this operational profile, the ship can achieve a full day of Zero Emission Mode (ZEM) navigation, supporting the Norwegian decarbonization target. During the navigation and port stationing phases, energy consumption remains almost constant, making these phases well-suited for optimal fuel cell operation. On the other hand, manoeuvring phases require high power peaks for the thrusters, a condition that necessitates the use of batteries, which can quickly respond to energy demands.

The zero-emission alternative power generation system consists of 16 PEM fuel cell modules, each capable of generating 375 kW of net power, allowing an available electric power of 6 MW from the entire Fuel Cell System (FCS), which is housed in two 40 feet containers. While 30 feet of each container are dedicated to the installation of the fuel cell modules, the remaining 10 feet are reserved for the DC/DC converters, power supplying the onboard electrical network. The system is divided into two separate rooms, each equipped with the necessary auxiliary systems, such as cooling, ventilation, inertization, and emergency venting to manage any potential failure. The integration of the new system required careful coordination with the existing conventional equipment, both from a technical perspective and in terms of the overall energy balance.

1. Energy analysis

1.1. Introduction

The on-board conventional electric generation plant has an installed capacity of 23.5 MW, able to cope with all possible sailing conditions and the necessary redundancy in case of emergency. For zero-emission shipping, on the other hand, the replacement of the complete conventional power generation with a FCS was not possible; being a novel technology, its cost per MW is still much higher than the well-mature diesel generators.

The installed FCS characterized by a capacity of 6 MW, was estimated sufficient to cope with most operational needs during fjord transit considering that a Battery Energy Storage System (BESS) will be available to cover the energy peaks characterizing some specific operation modes (as in example during *Manoeuvring*). This reduction was also made possible by the fact that the conventional electric generation system, during the ZEM is kept off at all times, but is ready to start if needed.

To meet comfort requirements without significantly altering the conventional system, it was essential to implement strategies aiming to minimize modifications of the starting plants. Given the nature of a cruise ship, changes to thermal availability for potable water, Heating, Ventilation and Air-Conditioning (HVAC) systems, galleys, and laundries are critical, as they directly impact passenger comfort.

When sailing with the conventional propulsion system, ship thermal demands are guaranteed by heat recovery from the engine cooling circuit (at about 90 °C), by economizers recovering heat from the exhaust gases by producing steam, and by 2x10 MW diesel boilers. Conversely, in ZEM all of these thermal sources are no longer available, and the only usable thermal source is constituted by the fuel cell cooling circuit (at about 60 °C). For this reason, it was necessary to implement strategies to reduce steam consumption and convert users to operate at a lower temperature.

1.2. Electrical consumptions

The main electrical consumer is represented by the propulsion system, which can demand up to 10 MW. However, during transit through the fjords, the vessel's speed is typically restricted to 10 knots, and the sea conditions are generally less severe compared to those encountered in open-water navigation. As a result, it is possible to maintain propulsion consumption within 6 MW while navigating the fjords, ensuring sufficient energy available to meet the needs of all other electrical systems. By side, the evaluation of electric consumption of the hotel and service users has been done with real data coming from on-board measurements carried out by the shipowner in the past few years on similar ships in terms of tonnage and installed power. Starting from the data measured on different ships and under different operating conditions, a benchmark electrical consumption value was identified, to be used as a reference both for winter and summer conditions. Afterwards, it was further reshaped by reducing the consumption through the energy efficiency strategy modifications implemented on the new ships design here discussed, and by identifying some users that may remain idle or with minimal consumption during the ZEM.

On the other hand, the consumption of the new users introduced by the installation of the fuel cell generators and the hydrogen storage system has been added, mainly consisting of recirculation pumps and ventilation systems.

To provide the minimum necessary amount of steam for those users that could not be converted to low temperature water as heat source, an electric boiler was foreseen. The installation of high-temperature heat pumps was also evaluated. Nonetheless, this option was not considered due to their still limited application within the maritime sector, and in order to avoid further increase of both plant complexity and footprint issues, with respect to the consequent energy benefits (also by considering that steam requirements in ZEM are limited).

1.3. Thermal consumptions

Table 1 lists the main thermal users on board the ship and the strategy implemented during ZEM. Figure 1 summarizes with a simplified schematic the integrated thermal system, both the low-temperature water heat recovery circuit (W60) resulting from FCS and the steam circuit supplied by the electric boiler. The water circuit is also used to heat up the FCS during its start-up.

Table 1. Main Thermal Users and Strategy During ZEM.

Thermal users	**Strategy implemented during ZEM**
Tank heating	Steam powered, reduced power by 80%
Engine room	Steam powered, reduced power by 80%
Galley	Steam powered
Fresh potable water generator	Switched off, activity rescheduled
Laundries	Switched off, activity rescheduled
Swimming pools	Switched off, due to plant complexity
Hot potable water	Switched to W60 with steam boost
HVAC	Switched to W60 with possible steam integration
FC Process air heating (NEW)	Supplied by W60
LH2 vaporizers (NEW)	Supplied by W60

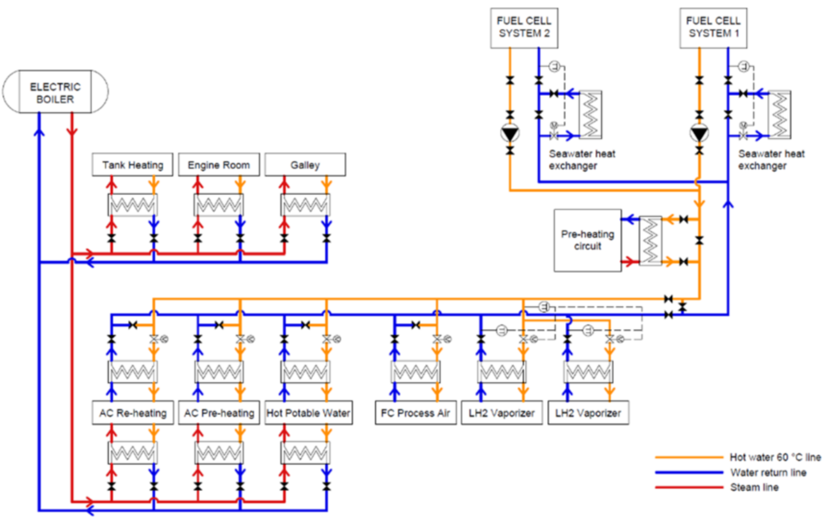

Figure 1. Integrated Thermal System.

All the pre-existing users are normally steam-powered, and since in ZEM steam is produced with electric boilers, it is firstly imperative to implement strategies to reduce their consumption as much as possible. Some users have even been switched off during ZEM after a revision of the scheduling of routine activities before entering and after exiting the fjord; others have been switched off due to large modifications and plant complexity that would have entailed bringing hot water piping in different locations. Users reconverted to low-temperature circuit feed have also a steam supply in case the heat from the FCS is not sufficient. Lastly, new thermal users have been designed specifically to be compatible with the low-temperature circuit.

2. Energy analysis results

For each electrical and thermal user, distinct consumption values were determined for all the operating modes considered: *Navigation, Manoeuvring and Harbour*, for both Winter and Summer seasons. Each operating mode has been analysed by means of a mathematical model specifically developed to process the energy consumption values fed as input to simulate the operation of the heat recovery system from the FCS, while also accounting for the possible contribution of the electric boiler, when required. It is important to emphasize the interdependence between thermal and electrical production sources: the amount of low-temperature heat available depends on the FCS's operating point, which in turn depends on the steam demand through the electric boiler. Additionally, the steam demand is directly tied to the low-temperature heat demand from the thermal users supplied by both sources.

The energy analysis confirms that, under the proposed integration of the new hydrogen-powered energy system, both the electrical and thermal energy balances are achieved across all operating modes. With careful management, the heat generated by the FCS is sufficient to meet the demand of all the identified thermal consumers, while the BESS is primarily employed to cover peak loads and rapid changes in electrical energy demand.

The thermal demand is primarily driven by the HVAC system, which is much lower during Summer than during Winter. As a result, a substantial portion of the low-temperature heat produced by the FCS during Summer must be dissipated into seawater. Conversely, the primary distinction between *Harbor* and *Navigation* consists in the electrical demand, which is much higher during *Navigation* due to propulsion requirements. From the combination of these two energy demands requirements, the most critical operating mode identified in the *Harbor* one, during Winter, when the FCS operates at a lower operating point compared to *Navigation*, and resulting in reduced availability of low-temperature heat, when instead seasonal conditions impose higher thermal demands, and implying that all of the available low-temperature heat is recovered and used during this operating mode.

When thermal demand exceeds available low-temperature heat from the FCS, such as during unfavourable conditions, the steam production must be increased to provide additional heat primarily to the HVAC and Hot Potable Water users. Consequently, a higher electrical need from the electrical boiler is requested, prompting the FCS to produce more energy, both electrical and thermal.

In short, with the proposed configuration of the hydrogen-fuelled energy system and the outlined management strategies, it is expected that the reduced energy demands of the entire cruise ship can be met without relying on continuous BESS usage. Except for peak shaving (mainly occurring in *Manoeuvring* and emergency situations), which is requiring significant battery power usage, the state of charge of BESS is expected to remain high. In case major hydrogen savings would be desired (e.g. in relation to cost scenarios and considerations), BESS could also be used during *Navigation*.

Additional optimization strategies could be explored and implemented to enhance energy recovery and reduce fuel consumption further. Notably, leveraging cold energy from liquid hydrogen evaporation offers significant potential for reducing the overall power demands.

3. Future optimization

3.1. Further exploiting the thermal gradient

As hydrogen is stored as a liquid at about -253 °C, a high quality (i.e. very low temperature) cold flow is available at the hydrogen evaporator. The on-board utilization of this flow could provide additional means to reduce the overall fuel consumption, as the cold energy recovered from hydrogen evaporation could be: (i) directly used to reduce the power load of HVAC or cold room chillers, or (ii) used for electricity generation by means of an electric power cycle using liquid hydrogen as cold sink and the water flowing in the fuel cell cooling circuit as the hot sink. These two possible approaches are here introduced.

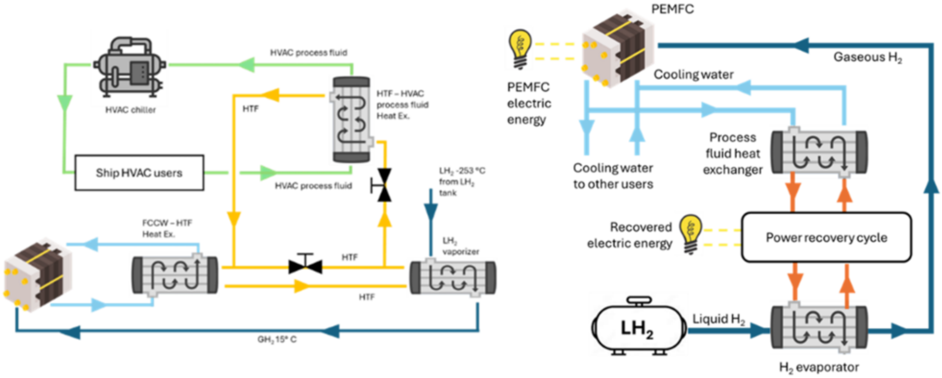

Figure 2. Possible approaches for cold energy utilization: (left) simplified scheme of a cold heat recovery system for direct use of cold energy. (right) Simplified schematic of a recovery system for indirect use of cold energy for electricity generation through an electric power cycle.

3.2. Direct use of cold energy for reducing the load of Heating, Ventilation, and Air Conditioning (HVAC) or cold room chillers

When the PEMFC system operates at its peak power of 6 MW, approximately 500 kW of low-temperature cold flow can ideally be recovered. To directly exploit this cold energy, a simplified scheme of a potential low-temperature heat recovering plant configuration is proposed as shown in Figure 2 (left). Here, the Heat Transfer Fluid (HTF) exiting the liquid hydrogen vaporizer is flown across a second heat exchanger, where low-temperature heat is transferred to the HVAC process fluid. Analogously, the HTF exiting the liquid hydrogen vaporizer could also flow towards cold rooms, for transferring heat to the chiller process fluid. Nonetheless, due to the great temperature difference between the heating medium and liquid hydrogen, the risk of HTF freezing inside the vaporizer is not negligible, leading to an interruption of the energy recovery process. At present, there are no commercially available applications for liquid hydrogen cold recovery. Nonetheless, some research studies confirm their feasibility, showcasing systems with a TRL ranging between 3 and 4.

In the example, it was demonstrated as a properly designed Heat Exchanger Network (HEN) allows for effective cold energy recovery by preventing freezing [3] via of a freezing-free heat transfer process. Authors indicate that the recovered efficiency of the developed prototype can reach up to 90% within a 7.5% error range.

For the ship considered in this work, calculations indicate that the low-temperature recovery system could provide measurable electricity savings for HVAC chillers. Moreover, during *Navigation*, it was estimated that more than 1.5% of hydrogen fuel could be saved. More effective fuel savings are expected if all the cold flow were used to reduce the load on cold room chillers, which typically have a lower Coefficient of Performance (COP) compared to HVAC chillers.

To justify the integration of this recovery system onboard, an economic assessment was conducted to evaluate the conditions necessary for ensuring the system's financial viability. This involved determining the maximum allowable investment cost that would allow the cold energy recovery system to achieve a reasonable payback period. The cost of liquid hydrogen and the number of voyages undertaken by the ship were important factors, as the amount of fuel saved was converted into fuel-saving costs, also known as the annual profit. Results indicated that, when considering the expected annual number of voyages, the development costs of the recovery system, and the added complexity to the overall system, its effective onboard implementation is currently constrained.

3.3. Use of cold energy for electricity generation through an electric power cycle

In this case, the cold energy released during hydrogen evaporation could be used in a thermodynamic cycle to produce work, in the form of electrical energy. Here, liquid hydrogen could be used as a cold sink and the water circulating in the FCS could be used as the hot source (see Figure 2, right). The recovered energy could thus be used to increase the overall system conversion efficiency, reduce fuel consumption, and supply electricity to various users. In literature, different power recovery cycles, with increasing system complexity, have been studied especially for on-land applications [4]. When relating to on board applications, proposed systems concentrated especially on Organic Rankine and Brayton power recovery cycles [5].

Thus, a computational analysis comparing different plant models across four potential configurations was conducted, with the aim of highlighting their cold energy recovery capabilities. The considered systems were: (i) Organic Rankine Cycle (ORC), (ii) Double Stage ORC (DS-ORC), Bryton Cycle (BC) and Regenerative Bryton Cycle (RBC). These four configurations were compared according to their capabilities of cold recovery, which was expressed in terms of (i) produced electric power, (ii) electrical efficiency (calculated with respect to the amount of absorbed heat), and (iii) overall power gain (that is the power increment with respect to the maximum power delivered by the FCS). Results show that the regenerative Brayton cycle exhibits the highest conversion efficiency, leading to the greatest electricity production. Furthermore, due to its high efficiency, a significant amount of cold flow is still available at the cycle's exit. This cold flow could be directly used to reduce HVAC or cold room chiller consumption, further lowering fuel consumption.

Conclusions and future developments

This study provides a comprehensive analysis of the integration of an innovative energy system required to facilitate zero-emission navigation for cruise ships, specifically focusing on operations in the Norwegian Fjords. By implementing a hydrogen-fuelled PEM FCS, the research establishes a foundational framework that supports the dimensioning of the energy system for cruise vessels aiming to meet stringent decarbonization targets.

The findings underscore that achieving a full day of ZEM navigation is feasible, contingent upon careful energy management and system design. The integration of the hybrid energy system, which combines fuel cells with traditional power sources, not only addresses the immediate operational needs but also highlights the importance of rethinking thermal and electrical consumption strategies. The study emphasizes that significant modifications to existing shipboard systems are necessary to optimize energy flows and minimize hydrogen consumption.

Moreover, the analysis reveals that while the installed capacity of the FCS is sufficient for most operational demands, strategic measures must be adopted to manage peak loads effectively. The research identifies critical challenges in adapting thermal users to operate efficiently under new conditions, particularly in maintaining passenger comfort without compromising energy efficiency and environmental impact.

As the maritime industry continues to evolve towards greener technologies, the experience described by this work serves as a reference point for future endeavours in maritime decarbonization initiatives laying the groundwork for further exploration and optimization of hydrogen-based energy systems in shipping. It illustrates how state-of-the-art energy solutions can be dimensioned and implemented paving the way for sustainable practices in cruise ship operations, and explores the potential to leverage the ultra-low-temperature cold flow of liquid hydrogen to reduce power demand.

Acknowledgements

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