Improving the Energy Efficiency of Ships: Modelling, Simulation, and Optimization of Cost-effective Technologies

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Abstract

This paper includes a part of the findings of an international research project, called HEMOS, funded by the EU through the Horizon Europe program, with the aim of decarbonizing the maritime sector. This study focuses on the use of dynamic simulation and optimization to identify policies and technologies for reducing carbon emissions and enhancing the energy efficiency of cruise ships. The primary findings of the study, which sought to identify the ideal ship plant topology, are presented with a particular emphasis on the optimization of the thermal and energy behaviour of a case study cruise ship. By exploiting the developed simulation model and the optimization procedure applied to the Allure of the Seas of the Royal Caribbean Group, potential efficiency measures were identified to enhance the overall efficiency of energy utilization. Several scenarios, including diverse energy efficient user technologies, were analysed and optimized with the aim of providing guidelines for the design of future ships. According to the obtained numerical results, the application of thermal devices for the utilization of on-board waste heat and the implementation of a fuel cell powered by bio-LNG can result in significant primary energy savings of up to approximately 17%, demonstrating that workable solutions to improve the energy efficiency of ships are already available.

Keywords: Ship energy efficiency, dynamic simulation, energy optimization, waste heat recovery, green fuels.

1. INTRODUCTION

With the goal of reducing greenhouse gas (GHG) emissions in international shipping, the IMO Marine Environment Protection Committee (MEPC 80) recently established new goals and policies [1]. The transition to cleaner energy sources requires considerable reductions in GHG emissions from ships to be achieved through the implementation of technologies, fuels, and energy sources with low or zero GHG emissions. The updated IMO GHG Strategy, FuelEU maritime initiative, and recent international agreements comprise ambitious goals to achieve net-zero GHG emissions from international shipping by 2050, including a commitment to secure the use of alternative fuels with zero or nearly zero GHG emissions by 2030, and suggested checkpoints for 2030 and 2040 [2], [3].

According to international institutions and governments [1], [2], large ships such as cruise ships are thus required to gradually reduce GHG emissions and air pollutants, use a fuel mix that includes renewable fuels, and consider on-shore power supply when in ports [4]. Despite the technologies and measures that can be implemented to enhance the energy efficiency of cruise ships, particularly in the context of cooling and overall energy management, a holistic approach that combines several strategies will likely yield the best results. From this point of view, the use of sophisticated energy analysis techniques allows for a thorough understanding of the energy behaviour of ships, facilitating the identification of energy-saving opportunities and the implementation of effective design modifications [5].

In the context of cruise ships, *dynamic simulation* can be used to model the ship's energy consumption, heat flows, and cooling requirements under various conditions [6]. The application of dynamic analysis in ship design or refurbishment is crucial for achieving these objectives. Simultaneously, in the context of cruise ship energy efficiency, *optimization techniques* can be applied to maximize energy savings and minimize energy consumption [7].

Dynamic analysis enables the evaluation of the variable behaviour of a ship's energy system, its interaction with the weather, and the variability of its electrical and thermal requirements. The energy efficiency and viability of on-board production systems, including diesel engines and oil-fired boilers, are significantly affected by load variability, particularly the electrical demand

DOI: https://doi.org/10.59490/ moses.2023.665

related to propulsion. Therefore, to properly *model and simulate the ship energy system*, it is vital to thoroughly understand these load behaviours. At the same time, optimization is necessary to investigate several potential layouts while specifying the optimal design parameters and operating conditions for the complete ship system [8]. The exploitation of waste heat from the main engines to power thermally activated technologies and the optimization of the energy management of heat are now becoming the standard for shipowners [9].

Several studies are available in the literature on the sustainability of ship energy systems, taking into account various approaches (such as model based design [10], dynamic simulation [11], optimization [12], analytical analysis [13], multiple techniques [14], life cycle assessment, and experiments [15]), and highlighting the solutions more frequently implemented (evaluation of different propulsion systems, implementation of heat recovery, thermal boilers, electric auxiliary systems, or emission abatement) [16], [17].

Promising results have been obtained by implementing the *dynamic simulation* to achieve a holistic approach to find the most effective and energy efficient technologies and their mix (e.g. absorption chiller, steam turbine, Organic Rankine Cycle machine, fuel cells), the best control logics to be implemented on-board [6, 18], and to provide more knowledge on advanced fuels and relative crucial issues for ship applications [7]. The analysis of the literature highlights that most of the proposed energy efficiency measures for ship applications include the exploitation of the thermal energy produced from the on-board engine system; different level temperature energies are, in fact, available on board to be properly exploited to satisfy users' needs (e.g. domestic hot water, air conditioning, etc.) or to produce energy from thermally activated technologies. Among the technologies that can be used for waste heat recovery, there are Rankine cycle machine [19] also based on organic fluids [20], supercritical Rankine cycle, Kalina cycle [21], exhaust gas turbine systems, absorption chillers, etc.. Obviously, the optimal configuration depends on several aspects (such as the initial configuration, actual energy requirements, and boundary conditions), suggesting that a unique solution cannot be achieved [22]. Moreover, the optimal solution for a specific ship must be properly assessed by using dynamic simulation and optimization [23]. This strategy not only improves energy efficiency, but also reduces the risks associated with operating adjustments and shipowner expenditures in new technologies.

1.1 Aim of the work

The research activity described in this paper is centred in this framework. The study is part of the HEMOS research project on the development of a dynamic simulation tool for the optimization of the on-board waste heat and of the energy efficiency of large cruise ships. The tool is finally used to identify suitable technologies to be implemented on-board an existing ship, the Allure of the Seas, an Oasis class ship of the Royal Caribbean Group (RCG). To this aim, several simulation environments (Revit, EnergyPlus, TRNSYS and MATLAB) were used to model the ship envelope and its energy systems. The developed holistic approach enables the investigation of diverse optimal solutions that can guarantee energy savings and support the on-board implementation. A comprehensive assessment of ship energy performance has been recently published [24], and the optimization procedure and its main findings are described in this paper. The entire procedure enables the evaluation of the proposed solutions and of the set of operating parameters that improve the selected objective functions (minimum fuel consumption) while satisfying some constraints (e.g. comfort levels, fresh water production, ship speed). Multiple configurations were considered to find the most energy efficient and effective layouts and the mix of technologies to be implemented on-board the Allure of the Seas. The ultimate goal of this study is to provide answers to various research concerns regarding how to use current and cutting-edge technologies and fuels to ensure compliance with changing environmental requirements and standards [25]. Some questions can be formulated as follows:

- *What strategies and technologies can enhance fuel efficiency, reduce emissions, and ensure compliance with the evolving environmental regulations and targets?*
- *How can waste heat recovery systems be improved to capture and reuse energy effectively?*
- *What and how can emerging technologies be combined and implemented on ships to improve their energy efficiency?*
- *Which alternative fuels can feasibly support the maritime environmental transition?*

2. MATERIAL AND METHOD

2.1 Modelling and simulation of ship

The ship under investigation was the Oasis class ship Allure of the Seas of Royal Caribbean (RCG). Schematic drawings and data used to develop the ship model were provided by the shipowner and retrieved from public repositories [26], as shown in Figure 1. The energy analysis of the ship, conducted in previous studies [24], [27], was used as the starting point for the optimization analysis here described.

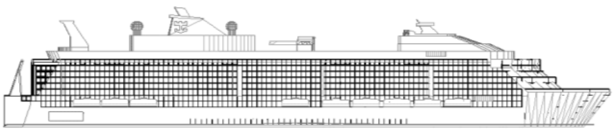

Figure 1. 3D model of the Allure of the Seas.

Dynamic simulations were conducted to assess the energy performance of a ship system by considering the interaction between its envelope, which is seen as a moving building, and its integrated systems. Details about the case study ship envelope are reported in reference [24], whereas key information regarding its energy systems is reported hereinafter. The main geometrical features of the ship, information on the dimensions and capacity, and power systems are summarized in Table 1.

The modelling of the ship was carried out by considering the ship geometry with the aim of assessing the real thermal behaviour of the Allure of the Seas. Several simplifications and assumptions were considered to perform dynamic simulations of a complex ship system, as detailed in reference [24] regarding the ship envelope.

Table 1. Info about the Allure of the Seas.

Built	STX Europe Turku Shipyard, Finland. Delivered on October 28th, 2010. Classification society DNV
Sister ships	Oasis of the Seas (2009), Harmony of the Seas (2016), Symphony of the Seas (2018), Wonder of the Seas (2022), Utopia of the Seas (planned 2024)
Length,	361.82 m
Beam	47 m at waterline (max 65.47 m)
Height	72 m above waterline
Draught	9.15 m (max 9.3 m)
Gross tonnage	225282 GT
Decks	16 passenger decks, 18 decks in total
Capacity	5492 passengers, 2200 crew
Installed power	Diesel-electric type power plant 3×13860 kW (Wärtsilä 12V46D) 3×18480 kW (Wärtsilä 16V46D)
Propulsion	3×20 MW ABB Azipods 4×5500 kW bow thrusters

Autodesk Revit was used for the 3D modelling of the case study ship envelope (to assess its thermal behaviour), whereas *TRNSYS* and *MATLAB* were used to model the heat energy system of the ship. Figure 2 shows the prospects of the Allure of the Seas merged with its Revit model, which was created by zoning the ship considering thermo-hygrometric conditions and usage.

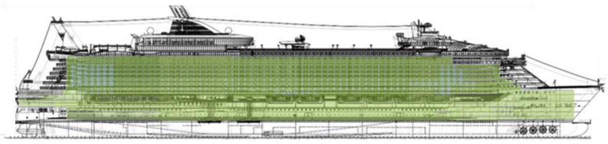

Figure 2. Merge of ship prospect and Revit model.

The existing on-board heat energy system is illustrated in Figure 3, and its main equipment is:

- 3 Wärtsilä 16V46D-CR (DG 1 - 3);
- 3 Wärtsilä 12V46D-CR (DG 4 - 6);
- 3 plate Heat exchangers by Alfa Laval (HEX 1 - 3);
- 3 plate Heat exchangers by Alfa Laval (HEX 4 - 6);
- 3 Exhaust Gas Boiler Unex G-622 (EGB 1 - 3);
- 3 Exhaust Gas Boiler Unex G-533 (EGB 4 - 6);
- 2 Oil Fired Boiler Aalborg MISSION (OFB 1 - 2);
- 4 Multi Stage Flash Evaporators Hamworthy;
- 5 electrical chillers;
- 2 Reverse Osmosis unit by Triton Water;
- Several heat exchangers are used to feed thermal users (e.g. Air Conditioning, Domestic Hot Water).

A simulation model of the ship, which is necessary to assess the heating and cooling demands, was developed and implemented in *Autodesk Revit*, *OpenStudio* and *EnergyPlus*. The obtained electricity, heating and cooling load profiles were processed to simulate the behaviour of the *waste heat recovery system* coupled with *ship engines* and the *heat integration of boilers*, which is necessary to assess the energy performance of the existing energy system, namely the reference layout (RL).

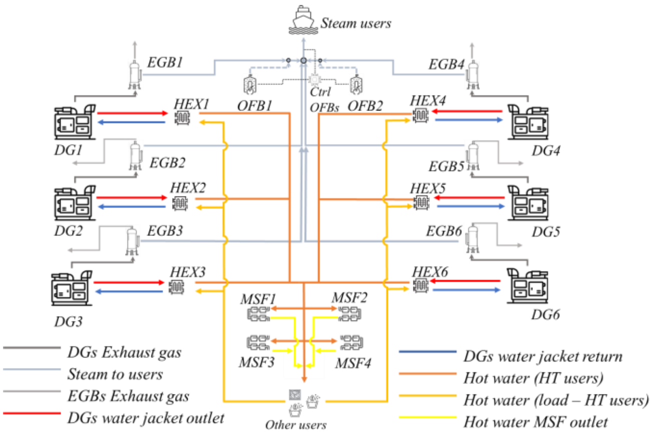

Figure 3. Sketch of the existing heat energy system.

The energy system was modelled in *TRNSYS* and *MATLAB*, where all components and their logical and physical connections were implemented to simulate the operation of the existing ship generation plant. The *MATLAB* tool takes detailed *EnergyPlus* simulation results and the information retrieved by the ship building model developed in the BIM environment as inputs. The performance curves provided by manufacturers, physical algorithms, and conversion coefficients were considered to account for all operating conditions [27]. For the propulsion power input, a cubic curve was obtained as a function of the ship speed provided by the RCG data measurements [27]. A route was established to evaluate the electrical needs of the most energy intensive user of the ship; its itinerary is depicted in Figure 4.

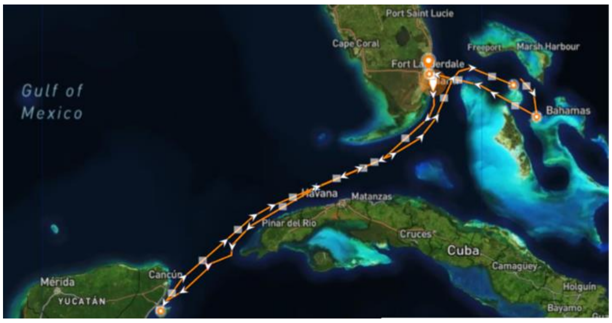

Figure 4. Simulated route of the ship.

Simulations were performed considering a 6-day round trip in the Western Caribbean Seas. The weather files used in the analysis includes historical data for the outdoor temperature, solar irradiance, and other relevant variables.

A brief explanation of the ship system function is reported below. Each main engine (DG) is equipped with an independent low-temperature (LT) cooling system for the generator, lubricating oil, and charge air cooler second stage, as well as a high-temperature (HT) cooling water circuit for the cylinders, charge air cooler first stage, and turbochargers. By carefully mixing with the LT cooling circuit and by heating the waste heat recovery (WHR) circuit, the HT circuit's inlet temperature is maintained between 77 and 79 °C. The sea water pump speed is adjusted by a frequency converter setpoint to maintain the temperature of the LT circuit between 36 and 38 °C (all extra heat discharged into the sea).

Four multi stage flash (MSF) evaporators and two reverse osmosis (RO) systems are used to produce fresh water while the ship is sailing. With a storage capacity of 6216 m^3, the theoretical production capacity is 4100 m^3/day. The WHR secondary circuit and steam booster heaters heat the evaporators. The heating medium of the evaporator, the WHR water, moves through the heat exchangers. According to the design specifications, a steam booster provides extra heat if necessary. RO plants are made up of high-pressure filtering units that filter seawater using semipermeable reverse osmosis membranes; a high-pressure pump aids in the filtration process by forcing water through them.

The heating and cooling needs of the air-conditioning plant are met by the air conditioning system of the ship. The intended summertime cooled water temperature is 6°C, whereas the maximum reheated water temperature is 80/60°C. WHR circuit preheats domestic hot water (DHW). The MSF receives heat from the diesel engines' WHR before being transferred to the AC and DHW heat exchangers. Steam is the main source of heat transfer on the cruise ship. Six exhaust gas boilers (EGB), one for each engine, and two oil fired boilers (OFB), which serve as backups, make up the steam generation system. The EGBs produce steam at a pressure of 8 bar by recovering heat from the main engine exhaust gases. Heavy Fuel Oil (HFO) is used to power diesel engines, and Marine Gas Oil (MGO) to power oil-fired boilers.

According to the simulations, the main energy, economic and environmental parameters of the RL are listed in Table 2.

Table 2. Reference system (RL) key parameters.

Parameter (per itinerary)		unit
Primary energy	8.82	(GWh)
Primary energy w/o propulsion	4.51	(GWh)
Operating cost	477	(k€)
CO_2 emissions	2369	(t)

2.2 Optimization procedure: methodology, investigated technologies, and layouts

To meet the energy efficiency and sustainability goals for the case study ship and, more generally, for the Oasis class ships from RCG, a full design-oriented optimization of the ship-energy system is carried out. The objective of optimization is to identify the best set of technologies and design approaches for a ship's (new or redesigned) construction that will enable energy savings and, thus, achieve stringent environmental goals. Additionally, economic and environmental criteria were considered to simultaneously evaluate the system financial feasibility and cost-effectiveness, as well as its potential in terms of environmental sustainability. An example of the optimization process is reported in Figure 5.

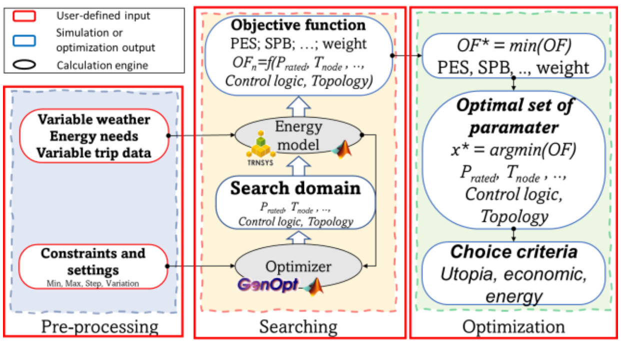

Figure 5. Optimization process

As energy objective function, the Primary Energy Saving (PES) is evaluated as:

$$PES = \sum_t \left(\frac{PE_{RL} - PE_{PL}}{PE_{RL}} \right)_t = \sum_t \left(\frac{m_{RL} - m_{PL}}{m_{RL}} \right)_t \quad (1)$$

where *PE* and *m* are the primary energy referred to the considered fuel and related burned mass, respectively, in the reference (subscript RL) and proposed (subscript PL) system layouts. *PES* can be calculated by considering propulsion (*PES w/ prop.*) or neglecting it (*PES w/o prop.*). This objective function must be maximized to reduce the ship energy needs and its pollutant emissions; accordingly, the associated avoided carbon dioxide emissions (ΔCO_2) are calculated as:

$$\Delta CO_2 = \sum_t f_{HFO} (m_{RL} - m_{PL}) \quad (2)$$

where f_{HFO} is the CO_2 equivalent emission factor of the considered fuel. Note that, similar formulas can be adopted for all pollutants (e.g. SO_x, NO_x, and $PM_{2.5}$) [18].

Conserning the economic evaluation, the Simple Payback Period (SPB) is evaluated as:

$$SPB = J_i \cdot \left(\sum_t \begin{matrix} (m_{RL} - m_{PL})_{HFO} c_{HFO} + ... \\ (m_{RL} - m_{PL})_{MGO} c_{MGO} + ... \\ (m_{fw,RL} - m_{fw,PL}) c_{fw} + ... \\ M_{RL} - M_{PL} \end{matrix} \right)^{-1} \quad (3)$$

where J_i is the capital cost calculated as in equation (4), *m* is the mass of consumed fuel, c_{HFO} and c_{MGO} are the unitary cost of consumed fuels (HFO and MGO), m_{fw} and c_{fw} are the mass and unitary costs of bunkering freshwater at port, *M* is the maintenance cost. The denominator of equation (3) represents the reduction in operating cost (ΔOPEX).

$$J_i = m_i x_i^{n_i} \quad (4)$$

When compared to the reference layout (RL), each proposed system (PL) involves modifications to the size of the system components or the introduction of new energy-efficient technologies; therefore, similar objective functions should be considered. The expenditure (CAPEX) and operating (OPEX) costs considered in this analysis are reported in Table 3 and Table 4 [13], [28].

Table 3. Capital cost of each technology.

CAPEX	Technology	*m*	unit
J_{RO}	*Reverse osmosis*	4175	(€·d/ m^3)
J_{MSF}	*Multi stage flash*	12035	(€·d/ m^3)
J_{SAC}	*Single stage absorption chiller*	300	(€/kW$_c$)
J_{DAC}	*Double stage absorption chiller*	390	(€/kW$_c$)
J_{VCC}	*Vapour compressor chiller*	150	(€/kW$_c$)
J_{ORC}	*Organic Rankine Cycle system*	6500	(€/kW$_e$)
J_{MCFC}	*Molten Carbonate Fuel Cell*	4500	(€/kW$_e$)
J_{ST}	*Steam Turbine*	1140	(€/kW$_e$)

Table 4. Operative costs.

Operative costs		unit
HFO	627.0	(€/t)
MGO	838.5	(€/t)
Green LNG	2124	(€/t)
LNG	708	(€/t)

A number of *cutting-edge technologies*, including promising thermal and non-thermal devices, have been proposed and investigated to increase the on-board energy efficiency. Starting from RL, the PLs, not fully described for the sake of briefness, are as follows:

1. **Layout 1**: RL + a wet steam turbine (WST) that exploits excess steam otherwise wasted.
2. **Layout 2**: RL + a single effect absorption chiller (SAC) implemented on HT WHR circuit.
3. **Layout 3**: RL + a double effect absorption chiller (DAC) that exploits excess steam otherwise wasted.
4. **Layout 4**: RL + an Organic Rankine Cycle machine (ORC) implemented on HT WHR circuit.
5. **Layout 5**: RL + a combination of a WST, a SAC and a DAC. Here, two scenarios are considered: i) *scenario 1* without an efficient engine activation strategy: the reduction of the electrical power from engines due to the use of WST and SAC/DAC causes lower part load ratios and electrical efficiencies; ii) *scenario 2* with an efficient engine activation strategy: the engines are run in a way that ensures the best electrical efficiency.
6. **Layout 6**: RL + a mix of *different high-performance technologies*, such as WST, SAC, DAC, and a Molten Carbonate Fuel Cell (MCFC), plus *operating logics* for the exploitation of *waste heat recovery from the LT circuit*, the control of the return temperatures on the HT secondary circuit, and the proper and optimal activation of RO and MSF units *for variable freshwater production*. The MCFC also provides heat to high temperature users. Because the fuel cell run on a variety of fuels (hydrogen, natural gas, biofuels, etc), the use of Liquified Natural Gas (LNG) or bio-LNG has been investigated.

A summary of the range of variation, with minimum and maximum values, of all parameters considered in the optimization procedure relative to each investigated Layout (from 1 to 6), is provided in Table 5.

Table 5. Optimization process parameters.

Parameters	Range (min - max)
WST, nominal flowrate (t/h)	3 - 12
WST, outlet pressure (bar)	0.7 - 2
SAC, cooling power (kW)	105 - 4571

DAC, cooling power (kW)	176 - 3868
MCFC, electrical power (kWe)	1400 - 2800
RO, number of units (-)	2 - 4
MSF, number of units (-)	1 - 3
Return tempererature HT secondary circuit (°C)	71 - 74
Return temperature LT circuit (°C)	36 - 40
Use of bio-LNG to power fuel cell (-)	Yes or No

3. RESULTS AND DISCUSSION

Previous layouts were analysed by focusing on three different selection criteria: *economic*, *energy*, and *utopia point*. The latter corresponds to the ideal solution in the objective space, which simultaneously represents the best possible value for all objectives. The *utopia point* may not be reachable in practice but can be considered to find the solution closer to the ideal one. The point of the real optimum is the point on the Pareto front at the minimum geometric distance from the utopia point. Focusing on the entire procedure, the potential PES (w/ prop.) versus CAPEX for each configuration is shown in Figure 6.

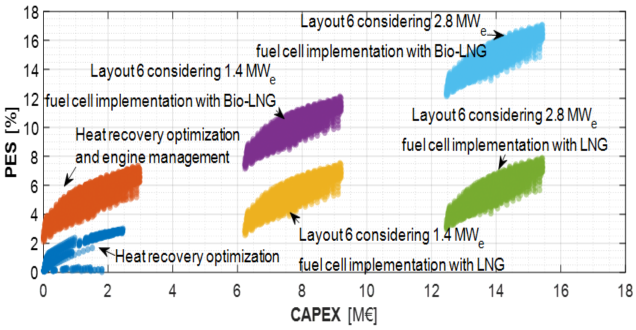

Figure 6. Possible configurations analysed: results.

On the *left side* of Figure 6, it is possible to see two clouds of results:

- *Blue cloud*: it includes the configurations relative to the *heat recovery optimization* obtained considering Layouts 1, 2, 3, 4 and Layout 5 scenario 1 (with no efficient engine activation strategy). PES values range from 0 to 3% corresponding to CAPEX up to 2.5M€.
- *Orange cloud*: it refers to all configurations relative to the *heat recovery optimization* plus the *engine management* control logic; thus, all configurations were obtained considering Layouts 1, 2, 3, 4, Layout 5 scenario 2, and Layout 6 without a FC. The energy management control logic allows for a remarkable increase of PES (from approximately 2 to 7%), without changes in CAPEX with respect to the blue cloud results.

On the *right side* of Figure 6, configurations incorporating the MCFC (two different sizes are considered, 1.4 and 2.8 MW_e), fuelled by either LNG or bio-LNG, are explored:

- *Yellow cloud*: it refers to the configurations of Layout 6 implementing a MCFC of 1.4 MW_e fuelled *with LNG*. These configurations show a similar range of PES (from approximately 2 to 7.5%) obtained by the *heat recovery optimization* plus the *engine management* (orange cloud), while CAPEX is up to four times higher (from approximately 6.2 to 9.2 M€).
- *Violet cloud*: it refers to the configurations of Layout 6 implementing a MCFC of 1.4 MW_e fuelled *with bio- LNG*. The use of bio-LNG offers a large rise in PES, almost doubled (from roughly 7 to 12%), with the same CAPEX.
- *Green cloud*: it refers to the configurations of Layout 6 implementing a MCFC of 2.8 MW_e fuelled *with LNG*. These configurations show a similar range of PES obtained by the *heat recovery optimization* plus the *engine management* (orange cloud) and by *Layout 6 with 1.4 MW_e MCFC fuelled with LNG* (yellow cloud), while CAPEX is significantly higher (from roughly 12.5 to 15.5 M€).
- *Sky-blue cloud*: it refers to the configurations of Layout 6 implementing a MCFC of 2.8 MW_e fuelled *with bio-LNG*. In comparison to the previous configurations (green cloud), the use of bio-LNG allowed PES to increase significantly (from 12 to 17.5%), which was helpful into meeting the strict energy efficiency and environmental targets imposed on the maritime industry and to gross tonnage ships, such as cruise ships (as well as the HEMOS project target of 14% reduction in fossil fuel consumption).

Although there is a remarkable increase in capital costs due to the current stage of fuel cell technology, significant savings in non-renewable primary energy can be observed, particularly with the use of bio-LNG. In any case, it is equally important to evaluate the implementation of these solutions in terms of operating expenses, occupied volume, and fuel availability. From this point of view, it is worth noticing that, with respect to other promising fuels, bio-LNG bunkering, which is necessary to reach medium term targets, is currently available (and scalable for the future) in almost 70 ports in Europe, North America, and Asia, according to the Bunker Navigator tool [29], suggesting that the investigated solutions are immediately applicable.

Although a substantial number (approximately thousands) of configurations were analysed, Figure

6 allows for an immediate comparison of the PES and CAPEX performances of the various systems under consideration; note that the CO_2 emission performance is similar to that of the PES. The results of Figure 6 can be considered for renovation initiatives or *decision-making aims* at the early stages of designing an on-board energy system. From each cloud a Pareto front can be evaluated; an example relative to the configurations that allow achieving medium term EU' emission reduction targets (by 6% by 2030) is depicted in Figure 7. The figure shows non-dominated configurations that provide the Pareto front (highlighted by blue dots) for each subgroup under analysis.

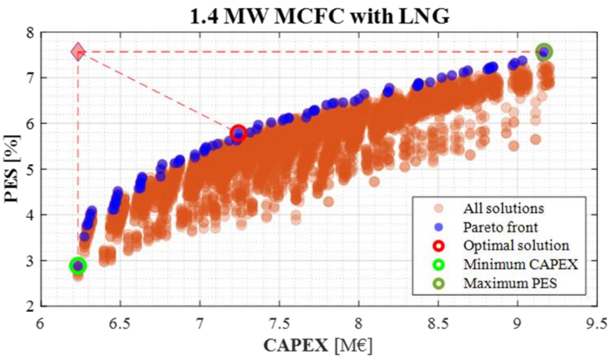

Figure 7. Pareto frons for diverse Layouts.

The optimal solutions depending on the criteria employed are reported in Table 6 for the previously described configurations (defined in the table by FC size and fuel and relative to Layout 6).

PES values greater than 2%, 6% and 14.5% (associated with fuel consumption and emission savings) are reported in italic, underlined, and bold, respectively. The implementation of the MCFC (Layout 6) significantly affects the CAPEX, due to its remarkable cost. Moreover, the fuel cell electrical efficiency is only marginally higher than that of the currently installed DGs; therefore, the difference in PES is negligible when considering the primary energy of non-renewable fuel cells. Higher PES values can be achieved by considering the use of bio-LNG (configurations (b) and (d) in Table 6), ensuring a reduction in fuel consumption from non-renewable sources, but also a decrease in emissions. These variations in CAPEX and PES and variations in thermal energy recovery (due to different waste heat vectors) are crucial factors in determining the best configuration according to the specific criteria adopted (energy, economic, and utopia criteria).

For each of the above configurations reported in Table 6, Table 7 shows the main operating parameters along with the PES, CAPEX and ΔOPEX, which results refer to the optimization process and utopia criterion. The optimal sizes of the considered technologies (e.g. WST, SAC, DAC, or ORC), along with the required operating parameters (flowrates and pressures), are reported. The table also shows the return temperatures (HT and LT) of the waste heat recovery circuits and the number of RO and MSF units.

Table 6. Optimization results for Layout 6.

FC size and fuel	Index	Utopia	Economic	Energy
(a) 1.4MWe MCFC *LNG*	PES w/ prop (%)	*5.79*	*2.88*	7.57
	PES w/o prop (%)	11.3	*5.64*	**14.8**
	CAPEX (M€)	7.24	6.23	9.17
	ΔOPEX (k€/trip)	27.8	13.9	36.3
	ΔCO_2 (t/trip)	161	91.8	203
	SPB (years)	4.74	8.12	4.59
(b) 1.4MWe MCFC *bio-LNG*	PES w/ prop (%)	10.4	7.48	12.2
	PES w/o prop (%)	**20.3**	**14.6**	**23.8**
	CAPEX (M€)	7.24	6.23	9.17
	ΔOPEX (k€/trip)	-16.1	-29.9	-7.55
	ΔCO_2 (t/trip)	246	177	287
	SPB (years)	-	-	-
(c) 2.8MWe MCFC *LNG*	PES w/ prop (%)	6.42	*3.25*	8.28
	PES w/o prop (%)	12.6	6.36	**16.2**
	CAPEX (M€)	13.6	12.5	15.4
	ΔOPEX (k€/trip)	30.9	15.7	39.7
	ΔCO_2 (t/trip)	199	124	243
	SPB (years)	7.99	14.4	7.06
(d) 2.8MWe MCFC *bio-LNG*	PES w/ prop (%)	**15.6**	12.4	**17.5**
	PES w/o prop (%)	**30.5**	**24.3**	**34.2**
	CAPEX (M€)	13.6	12.5	15.4
	ΔOPEX (k€/trip)	-56.8	-71.9	-48.0
	ΔCO_2 (t/trip)	370	294	413
	SPB (years)	-	-	-

Table 7. Layout 6 with FC - utopia criterion results.

	(a)	(b)	(c)	(d)
PES w/ prop. (%)	5.79	10.4	6.42	**15.6**
CAPEX (M€)	**7.24**	**7.24**	13.6	13.6
ΔOPEX (k€)	27.8	-16.1	**30.9**	-56.8
WST steam flowrate (kg/h)	9000	9000	6000	6000
WST outlet pressure (bar)	0.70	0.70	0.70	0.70
WST electric power (kWe)	493	493	328	328
SAC cooling power (kWc)	2391	2391	3428	3428
DAC cooling power (kWc)	527	527	0	0
ORC HT source flowrate (t/h)	-	-	-	-
ORC electric power (kWe)	-	-	-	-
MCFC electric power (MWe)	1.4	1.4	2.8	2.8
HT circuit return temp. (°C)	71	71	71	71
LT circuit return temp. (°C)	38	38	38	38
Engine optimization	Yes	Yes	Yes	Yes
Number of activated RO	3	3	4	4
Number of activated MSF	2	2	1	1
Fuel DG	HFO	HFO	HFO	HFO
Fuel FC	LNG	Bio LNG	LNG	Bio LNG

Through the optimization process, it was possible to see: i) configuration (d), with the highest MCFC size and the use of bio-LNG, shows the highest PES (15.6%); ii) configurations (a) and (b), with the smallest MCFC size, achieves the lowest CAPEX (7.24 M€); and iii) configuration (c), with the highest MCFC size and the use of LNG, shows the best OPEX (30.9 k€). Each design includes a WST, with a capacity of 493 (*a* and *b*) or 328 (*c* and *d*) kW_e (according to the availability of waste heat, with a steam flow rate of 9000 or 6000 kg/h and an output pressure of 0.70 bar).

Layout 6 configurations shown in Table 7 include the exploitation of the waste heat from the LT circuit (used for the preheating of air conditioning and domestic hot water) and the implementation of freshwater production strategies (utilizing thermal energy for MSFs and electrical energy for RO) coupled with a lower return temperature of the HT waste heat recovery circuit. When the latter decreases (from 74°C in the RL to 71°C), an *increase in the availability of thermal energy from the HT circuit* is always observed, allowing for the implementation of larger SAC sizes, due to the better heat exchange inside the heat recovery connected to each engine. It is also noteworthy that by considering the implementation of a MCFC, the number of MSF units decreases from four to two or even one, whereas the number of RO units increases from two to three or four. This suggests that the use of an extra RO unit will also be covered by the MCFC, reducing the need for MSFs and releasing up thermal energy (to be exploited by the SAC or DAC). Finally, due to its low efficiency, the ORC machine was not included in the mix of technologies with the MCFC.

Focusing on the configuration relative to Layout 6 with a 2.8 MWe MCFC powered by bio-LNG, its PES exceeds 30%, excluding propulsion (the higher electric power demand on-board the ship, which is unlikely to vary significantly due to diverse routes and travel times). Although the type of fuel utilized has no effect on capital costs, CAPEX, it does have an impact on operating cost. The cost of bio-LNG (2124 €/t) is now much greater than that of HFO (627 €/t) or even LNG (708 €/t). Therefore, a negative return on investment is obtained in configurations (b) and (d), where the use of bio-LNG is considered because of the greater operating cost reached for each individual route, which leads to a negative variation in the operating costs (ΔOPEX < 0). Figure 8 shows the price point at which bio-LNG becomes economically feasible and competitive with conventional fuels (HFO and LNG). The red dots refer to the target bio-LNG purchase price for achieving OPEX variation of 0% for each HFO purchase cost. Lower bio-LNG costs imply a positive ΔOPEX; these threshold values mark the points at which ΔOPEX becomes null.

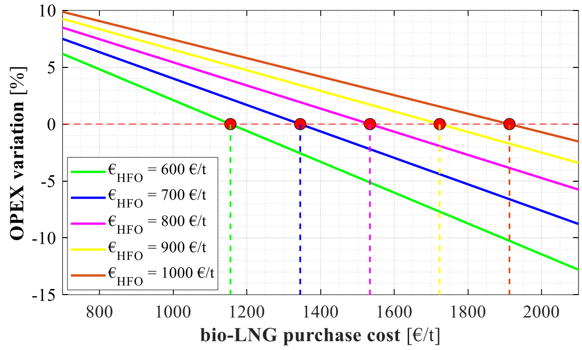

Figure 8. Parametric analysis of operating expenses variation based on fuel purchase costs.

The most energy-efficient technologies currently in use are not economically viable, according to the optimization results, as they have not yet attained a level of widespread adoption and practical use. Therefore, creating a roadmap that defines *realistic goals and activities for the near future* is crucial. The roadmap summarized in Figure 9 and created by exploiting the optimization results presented here, is intended as a guideline to support the sustainable transition of the shipping sector.

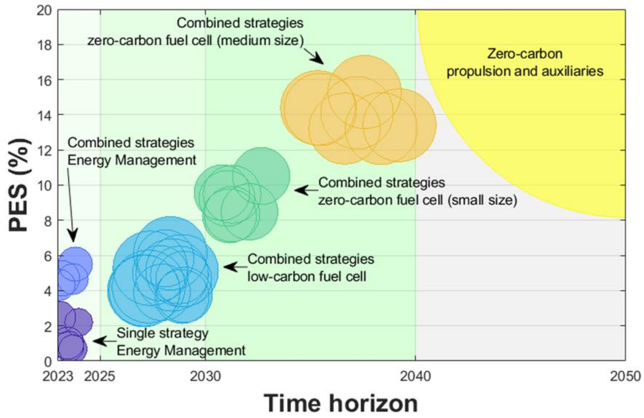

Figure 9. Towards a decarbonised future: roadmap in the maritime sector.

Figure 9 highlights that to accomplish the ambitious environmental targets established for 2040 and 2050, investments in cutting-edge propulsion technologies, such as hybrid systems or the use of alternative fuels, which result in significant fuel savings and emissions reductions, are crucial. The use of renewable energy sources is another viable method. When physically possible, replacing traditional energy sources and significantly reducing the overall fuel usage by integrating solar panels or wind turbines, can be an interesting option. Given that they have the highest PES potential, these solutions are shown in the yellow area (*zero-carbon propulsion and* *auxiliaries*) in the top-right corner of Figure 9. The application of these solutions has the potential to reduce non-renewable primary energy use (as well as emissions) by a variety of tens of percentage points, and theoretically even completely decarbonize the ship, depending on the degree of integration with the ship system and the ratio of renewable power to ship required power, which is negligible in the case of cruise ships.

4. CONCLUSION

This paper provides the results of a research study aimed at proposing a holistic approach for the identification of energy efficient technologies and measures for ship applications based on dynamic simulation and optimization. Waste heat recovery technologies and strategies, as well as additional power technologies, are considered to find the set of potential layouts to be implemented on the Allure of the Seas, from Royal Caribbean Group, to increase energy efficiency and reduce fuel consumption.

Based on the numerical results obtained, it was possible to determine the mix of strategies and technologies that enhance fuel efficiency, reduce emissions, and effectively ensure compliance with environmental regulations and targets. For this purpose, the EU's short, medium and long term targets on cleaner maritime fuels are considered: ship emissions must be reduced by 2% by 2025, 14.5% by 2035, and 80% by 2050 in comparison to levels in 2020 [3]. Note that these targets apply to 90% of CO_2 emissions from ships with a gross tonnage exceeding 5000, such as the case study ship, but also to all energy used on board in or between EU ports, 50% of energy used on journeys where the departure or arrival port is outside the EU, and most EU remote areas. So, considering the EU agreement for the maritime transition, for the investigated cruise ship (and for same class ships) the research findings highlight that it is possible to reach emission reduction targets, *in the short and medium term*, by:

- 2% (by 2025) with the *optimization of waste heat recovery on-board* (blue cloud configurations in Figure 6). The implementation of single or combined technologies, which are currently available on the market, including a wet steam turbine, a single or double effect absorption chiller, and an ORC machine, allows for achieving a *PES* higher than 2%.
- 6% (by 2030) with the *optimization of the on-board heat recovery and engine operation*. This enables the achievement of a PES of approximately 8%, including propulsion, which is an impressive result, especially considering that it can be achieved by optimizing engine operation and implementing commercially available waste heat devices, without the introduction of novel technologies or innovative fuels (orange cloud configurations in Figure 6). The same emission target can be achieved by implementing a MCFC fuelled *with LNG*; however, considering a fuel cell of 1.4 MW_e (yellow cloud) or 2.8 MW_e (green cloud), the CAPEX increases significantly, up to 9 and 15 M€, respectively.
- 14.5% (by 2035) with *the implementation of a mix of technologies (Layout 6) including a fuel cell* capable of providing 2.8 MWe, *fuelled with bio-LNG* (sky-blue cloud). PES values (including propulsion) higher than 14.5% can be attained to achieve current energy efficiency goals. Intermediate targets (between 6% and 14%) can be reached by considering a smaller fuel cell of 1.4 MWe (violet cloud).

The results of this study demonstrate that short-term sustainability goals for ships can be achieved nowadays, whereas to reach long-term goals, each step must be planned with proper regulations and support for the advancement of technology and green fuel. By following a clear path, it is possible to achieve energy efficiency and environmental goals. Finally, the proposed holistic approach aims to pave the way for the successful integration and utilization of innovative technologies and fuels for fostering maritime energy transition through the energy efficiency of large ships.

ACKNOWLEDGMENTS

The research has been founded by the European Union through the HEMOS "Holistic heat energy management on ships by implementing innovative dynamic calculation models towards maximum waste heat capture and energy efficiency" project (101056909), within the Horizon Europe RIA program (HORIZON-CL5-2021-D5-01, https://hemosproject.eu/).

NOMENCLATURE

Symbols

c	energy price (€/kg)
DAC	Double stage Absorption Chiller
f	Pollutant emission factor (kg/kWh)
J	Capital cost (€)
LNG	Liquefied Natural Gas
m	Fuel consumption (kg/s)
MCFC	Molten Carbonate Fuel Cell
MSF	Multi Stage Flash machine
OC	Operating costs
ORC	Organic Rankine Cycle machine
PE	Primary energy (kWh)
RO	Reverse Osmosis machine
SAC	Single stage Absorption Chiller
WST	Wet Steam Turbine

Subscripts and superscripts:

c	*cooling*
e	*electrical*
PL	proposed layout
RL	reference layout

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