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Enhancing shipboard waste heat management with advanced technologies

Giovanni Barone [a], Annamaria Buonomano [a,b], Gianluca Del Papa [a], Robert Maka [a,*], Adolfo Palombo [a]

[a] Department of Industrial Engineering, Università Degli Studi di Napoli Federico II, Naples, Italy
[b] Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Canada

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ABSTRACT

The complexity of the energy systems onboard ships, combined with the different operating/weather conditions and the availability of cutting-edge technologies, makes analyses for improving the energy and environmental performances of ships time consuming and challenging. From this point of view, this article provides new criteria for the sustainable design and management of energy systems of existing or new ships. In particular, the impact of the adoption of organic Rankine cycle units, wet steam volumetric expanders, and single or double effect absorption chillers is here investigated. Two types of ships are examined as suitable case studies, evaluating the impact of each technology and their combinations by varying the shipping cruises. By using a dynamic simulation approach, potential savings and optimal solutions are assessed for different energy system layouts by also comparing their economic, energy and environmental impact performance. Results are reported in specific performance matrices for helping stakeholders in preliminary energy efficiency analyses.

In particular, outcomes show that high cooling demands of ships in the Caribbean Sea enable primary energy savings close to 4.5 %, compared to 3.5 % in the Mediterranean Sea and 3 % in the North Sea. In the latter case, cooling needs can be almost fully balanced through the examined energy recovery technologies. Screw expanders integrate best in all operating conditions with short paybacks, whilst organic Rankine cycles (with electrical efficiency above 8%) are advantageous especially in cold climate routes. Benefits on environmental impact are significant, with avoided CO_2 emissions around 6 kt/y, depending on the selected ship cruise.

1. Introduction

The maritime sector is currently going through several changes as part of the drive toward decarbonization and the goal of being carbon neutral [1]. The regulatory framework has introduced different indexes to evaluate the ship performance in order to promote the energy transition. These include energy efficiency design index (EEDI) [2], energy efficiency operational index (EEOI) [3], ship energy efficiency management plan [4], energy efficiency existing ship index (EEXI) [5], and carbon intensity indicator (CII) [6]. However, suitable adjustments could be proposed after the assessment of actual effects of these parameters [7]. Specifically, for some parameters, information for the evaluation has not been well defined [8] or it is not possible to use them univocally for all types of ships [9]. Therefore, different technologies and strategies depending on the ship type will be considered [10]. Even if adopted fuel and installed propulsion system can allow to meet the EEXI and CII targets [11], to accomplish the targets imposed by the International Maritime Organization (IMO) – 40 % reduction of carbon intensity by 2030 compared to 2008 and 70 % of total greenhouse gas (GHG) by 2040 [12] – the energy efficiency of the complex energy system of ships must be improved. The implementation of renewable energy has been investigated in research field, with solar [13] or wind [14] implemented as power source; however, when it comes to large ships, high energy demand allows only to consider renewable energy as an auxiliary solution [15]. Also, the use of shore power connection allows emissions reduction up to 10 % according to ship type considered [16]. To enhance the ship energy efficiency, different solutions are considered by the research community. These include hull design [6], propulsion systems [8], alternative fuels [8], operating conditions [6], thermal [17] and/or electric [10] storage systems, management strategies [10], innovative technologies [10], after-treatment technologies [18], and waste heat recovery [18]. The following discussion thoroughly explores different themes analysing strategies that have been studied by research communities. A special focus is dedicated to the adoption of

* Corresponding author.
E-mail address: robert.maka@unina.it (R. Maka).

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Nomenclature

Abbreviations

AC	Air conditioning
BIM2BEM	Building information modelling to building energy modelling
CII	Carbon Intensity Indicator
DGs	Diesel generators
DAC	Double absorption chiller
DHW	Domestic hot water
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
EEXI	Energy Efficiency Existing Ship Index
EGBs	Exhaust gas boilers
EMSA	European Maritime Safety Agency
GHG	Greenhouse gases
GT	Gross tonnage
HEX	Heat exchanger
HT	High temperature
LT	Low temperature
MSF	Multi-stage flash
ORC	Organic Rankine cycle
RMSE	Root mean square error
SAC	Single absorption chiller
WSE	Wet steam expander

Greek letters

β	Beta
Δ	Delta
CAPEX	Capital expenditure [M€]
CO_2	Carbon dioxide [t]
c	Unitary cost
E	Energy ratio [-]
EEVI	Energy utilization and performance index [-]
f	Emission factor [t/t]
m	Mass [t]
M	Maintenance cost [€]
OPEX	Operating expenditure [k€]
PE	Primary energy [GWh]
PES	Primary energy saving [%]
SPB	Simple payback [y]
V	Volume [m^3]
x_i	Size of the technology [kW]

Subscripts

c	Cooling
e	Electrical
i	i-th solution
fuel	Fuel
fw	Fresh water
PS	Proposed system
rating	Rating
RS	Reference system
Use	Utilization

alternative control strategy methods that effectively manage and improve the energy efficiency of ships. Moreover, technologies developed to exploit waste heat generated during ship operations are examined. The approaches used to simulate these systems within the energy context of vessels are also deeply examined. This thorough analysis aims to provide a comprehensive understanding of the state-of-art in optimizing energy and utilizing waste heat in the maritime industry.

In the transportation sector, where sustainable energy sources are becoming important, alternative fuels are one of the main solutions to minimize GHG emissions [4]. Alternative fuels including liquified natural gas, ethanol, biodiesel, and biogas, can be considered for the maritime sector. As such, the effects on environmental and human health, as well as its suitability and availability, must be assessed [19]. Fuels such as methanol proved to be already a solution to be implemented, without major problems in infrastructure and production and with economic issues that can be overcome [20]. However, its use is probably not enough to meet the EEDI and CII targets from 2025 to 2031 [21]. Ammonia is also a valuable alternative, due to its carbon absence and high environmental performance [21]; nevertheless, nitrogen oxide emissions should be considered from the fuel combustion [22]. Policies to reduce the purchase cost and advancements in storage and transportation technologies will allow a wider diffusion of hydrogen. Specifically, it seems to be an interesting solution since high thermodynamics performances can be achieved, as well as regulations can be adhered [21]. Nevertheless, a renewal of the ports [23] and continuous collaboration with researchers is essential to overcome the numerous problems (e.g. power density, safety, etc.) [24]. EMSA investigated the feasibility of hydrogen as marine fuel, underlying how safety issues such as flammability range, leakage potential, flame speed, and detonation/deflagration must be considered [25]. The production of green hydrogen through the utilization of thermochemical processes and renewable solar thermal energy sources is analysed in literature [26,27]. However, based on the authors' knowledge, no applications specifically tailored for direct onboard ship production were identified. Alternatively, production through ammonia decomposition can be evaluated, with a hybrid of electrochemical and thermal decomposition considered the most suitable option, especially in terms of temperature efficiency (with relatively lower temperature requirements, around 250 °C) [28]. To properly investigate the fuel and configuration to be implemented, multi-objective optimization can be considered; specifically, objective function such as lifecycle cost and carbon dioxide (CO_2) emissions should be evaluated [29]. Anaerobic digestion or co-digestion can be considered to exploit organic waste generated on board cruise ships; however, implementation of large-scale biogas plant, as well as strict regulations for the onboard gas handling need to be considered [30]. For this reason, the exploitation of organic waste is primarily considered in ports, facilitated by continuous interaction with docking ships and fewer constraints regarding the space required for the various infrastructure to be implemented [31,32].

The implementation of control strategies also enables the improvement of the ship energy efficiency. Properly operating on-board engines, and varying the operating part load ratio, allows to improve electrical efficiency, resulting in significant fuel savings [33]. The operation of on-board engines can be analysed using increasingly widespread techniques, such as machine learning, to provide reliable results and enhance monitoring activities [34]. The complexity of the ship energy system necessitates different management solutions. Firstly, efforts are made to define the optimal operating parameters aimed at reducing fuel consumption [35]. Secondly, power distribution is optimized, considering both economic and environmental performance metrics [36,37]. Additionally, efficiency enhancements are adopted through the integration of waste heat recovery technologies [38] and the implementation of advanced technologies like fuel cell [39]. The investigated management strategies have demonstrated their effectiveness in improving energy exploitation, reducing time effort, and enhancing the overall ship efficiency. Through these strategies, operators can gain better control over energy usage, streamline operating processes, and achieve higher levels of efficiency across various aspects of ship operations.

The high fluctuation of energy demands, which occurs in every ship condition (e.g. cruising, manoeuvring, port operations), poses significant challenges [40]. These demands include both electrical and thermal requirements, necessitating a complex energy system [41]. Consequently, achieving optimal energy utilization while minimizing energy dissipation becomes imperative in such context [8]. Energy storage system, waste heat recovery, and the implementation of thermal activated technologies result as a promising solution [42]. These innovations not only enhance energy efficiency but also offer the potential to streamline energy consumption [43]. By integrating such solutions, ship can optimize their energy usage, mitigate waste, and improve their environmental sustainability. Several solutions exist for electrical energy storage, each with its own set of characteristics and considerations [10]. These include factors such as energy density, power density, available capacity, response time, cycle life and efficiency [10]. Additionally, practical aspects like weight and size, cost, environmental impact and durability must be taken into account [10,44]. Evaluating these factors in tandem is crucial in selecting the most suitable energy storage solution for a given application [44]. Moreover, the implementation of hybrid energy storage system allows to control power fluctuations, proposing itself as an alternative to the single energy system storage [44]. The implementation of batteries on-board ro-ro passenger ship proved to reduce the life cycle carbon dioxide emission and lifetime total cost, compared to a diesel-engine energy system [45]. To meet the objectives set by International Maritime Organization, thorough analysis is imperative, particularly due limitations of relying solely on a single technology or altering operating strategies. Achieving these objectives, especially the long-term ones, requires a holistic approach that considers various factors and potential challenges [46]. The organic Rankine cycle (ORC) unit is often subject of investigation due to its adaptability. With different heat sources, cycle architectures and working fluids available, ORC presents a flexible solution that can be tailored to suite different scenarios [47]. Several solutions have been proposed to optimize the performance of the ORC units. These include: i) the implementation of an internal heat exchanger, which enhances heat transfer efficiency within the cycle [48], ii) careful selection of operating fluids and layout, to maximize energy conversion efficiency [49], iii) the implementation with vapour compression cycle, enabling further energy recovery from waste heat sources [50], iv) coupling with steam turbine, a more complex waste heat recovery circuit that allows to increase the operation pressure of the turbine and avoiding vacuum systems [51], v) implementation with carbon separation and capture systems, hydrocarbon adsorption and the cold recovery from liquified natural gas [52] or alternatively, coupling with a Rankine cycle and desalination system which exploit exhaust gases and jacket water heat from engines for additional energy recovery [53]. Each of these approaches offers advantages and challenges, providing flexibility in tailoring ORC systems to specific application requirements and environmental considerations. Furthermore, heat source from the ORC, depending on the temperature level, can be exploited for other implemented technologies, e.g. thermal activated desalination system, in order to produce freshwater [54]. The implementation of different fuel cells – and therefore different operating conditions - can be taken into account [55]. Particular attention is given to fuel cells powered with liquified natural gas or methanol or the low-temperature proton exchange membrane fuel cells, with varying EEDI and EEOI values attainable [56]. Safety considerations should be taken into account, since hydrogen leakages may occur, putting the safety of passengers at risk [57]. The possible installation of fuel cell strongly depends on the operation of the ship [58]. For example, solid oxide fuel cells proved to be feasible for cruise ships, with the benefit of reducing vibrations and noises, but higher costs must be considered [59]. Overall efficiency can be improved through the implementation of thermal activated technologies, such as absorption chiller, in order to recovery the waste heat from fuel cells [60]. Gas turbines are identified as another solution, offering advantages such as reduced environmental impact and lower weight and volume requirements, compared to an internal combustion engine [61]. However, it is important to note that gas turbines typically exhibit lower efficiencies, leading to higher fuel consumption [62]. The efficiency gap can be however reduced through the implementation of additional thermal activated technologies that can improve the overall energy utilization [61]. Also the implementation with solid oxide fuel cell can improve overall efficiency [63]. Waste heat can be recovered on-board with possible fuel consumption reduction ranging from 4.0 to 16 % [43]. Cold energy recovery from vaporisation of liquified natural gas offers diverse potential applications. Firstly, it can be utilized to liquify the captured carbon dioxide, aligning with regulatory requirements for carbon capture and storage initiatives [64]. Additionally, this recovered cold energy can serve on-board cooling needs, providing a sustainable solution for temperature control systems aboard ships [65]. In this scenario, given the low mass flow, integration through electric chiller or the coupling of absorption refrigeration cycle is needed, in order to improve heat recovery from engines [66].

Different aspects of ship operation require informed decision from stakeholders to minimize energy consumption, reduce environmental impact, and improve the overall efficiency [67]. These includes simulation of propulsion systems, route optimization, analysis of the ship envelope, examination of specific components and overall energy system simulation, etc [6]. The scientific literature present numerous analysis highlighting the advantages of simulation and/or optimization techniques [41]. The most important of these is the capability to address challenging issues and provide insightful analysis and solutions [41]. Envelope modelling and simulation allows to define on-board thermal needs and, therefore, waste heat recovery use [68]. Several software can be used in order to obtain the profile that allows to meet the thermo-hygrometric conditions imposed. Building Information Modelling coupled with Building Energy Modelling proved to be a solution to model several aspects of the ship, from the set point temperature to the humidity to be maintained within the air-conditioned areas, considering numerous thermal zones and the effect of weather boundary conditions (e.g. solar radiation, air temperature, etc.) [68]. Software such as IDA Indoor Climate and Energy [69] or SketchUp with TRNSYS [40,70] are also considered to simulate the ship envelope behaviour and the relative impact on thermal demands. The simulation of the ship envelope is related to the boundary conditions that must be considered [68]. Specifically, simulating suitable weather data files is of paramount importance as it enables the accurate representation of variable such as temperature, humidity, solar radiation, and other environmental factors [40]. These elements play a crucial role in determining the heat loads occurring on-board [68]. This information is critical for designing effective heating, ventilation, and air conditioning systems on ships, ensuring optimal thermal comfort for passengers and crew members [69]. Different dataset can be considered, i.e. IWEC, in order to obtain parameters such as temperature, wind speed, relative humidity, etc. [69], TRY and TMY [70] or it is possible to evaluate properties, i.e. solar azimuth and tilt angles, through implemented equations [40]. The simulation of reliable weather data file allows to optimize voyage planning in accordance with different objective functions that can be considered [71]. The optimization can result in significant reductions in fuel consumption and sailing time [72]. Additionally, such optimized planning can lead to lower pollutant emissions [73]. Also, the simulation of on-board energy system plays a crucial role since it is essential to understand the dynamic behaviours of the system and propose effective solution to optimize it [74]. Indeed, it is possible to identify inefficiencies, assess the impact of different variables, and ultimately enhance overall efficiency [40]. The adequacy of shipboard components, as well as alternative solutions to aid in the future decision-making process can be reported through careful analysis [74]. The implementation of new structures, technologies and control strategies can be considered, aiming at enhancing energy use on-board [40, 69] and identifying the optimal sizes to be implemented according to the considered scenario and configurations [75].

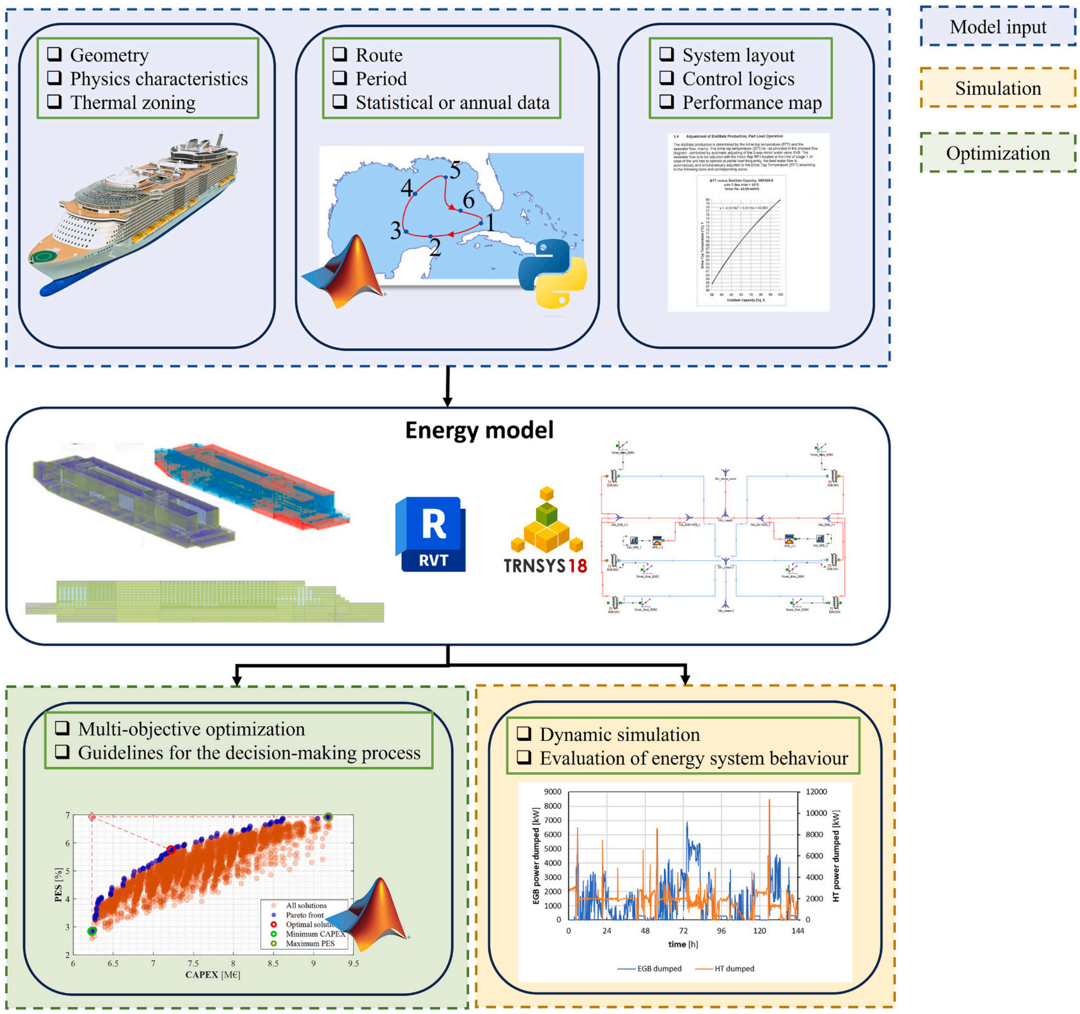

Fig. 1. Holistic approach to simulate ship operation.

Scientific literature showed how improvements in the ship envelope only marginally enhanced the ship efficiency, therefore implementation of heat pumps [69] or innovative technologies (i.e. ORC, steam turbine, fuel cells [40] or absorption chillers [70]) should be foreseen, with a saving in the primary energy of several tens of percentage points, depending on the proposed solution, the size of the ship considered and the reference energy system [40,69]. The energy system optimization, beyond efficiency improvements, should takes into account also factors such as equipment failures and the associated downtime and repair costs, in order to conduce a more comprehensive evaluation [76]. Moreover, variability of fuel price and carbon pricing, especially for future trends dictated from regulations, should be considered, since the life cycle cost and the optimal solution may vary [77]. Analyses like this can be a starting point for policymakers when choosing future changes to regulations.

While existing literature mostly focuses on specific aspects such as the implementation of single technologies, optimization of parameters, varying routes, or different control strategies, a more comprehensive approach considering the overall complexity of the ship is less common. To address this gap, a suitable tool based on dynamic simulation, considering weather data, envelope characteristics, and the ship energy system, is proposed to analyse ships through a holistic approach. Furthermore, the analysis aims to answer key questions that have been relatively unexplored in the existing literature. These questions include:

- What is the impact of different technologies under varying climatic conditions?
- What configurations are optimal to implement for enhanced energy efficiency?
- What recommendations should be followed in the case of refurbishment, and what considerations apply when designing a new ship?
- How can the implementation of a specific technology or control logic impact both energy and economic performance, and what are some initial benchmark values that could be considered?

This study involves the analysis of different ships, each characterized by different energy systems and operating logics. The research explores how the performance of energy-efficient technologies varies across different climatic conditions, including the North Sea, the Mediterranean Sea, and the Caribbean Sea. Therefore, this study aims to provide practical insights for decision-makers in the maritime industry, by utilizing dynamic analysis, to ensure more reliable results. The goal is to offer a better understanding of energy-efficient configurations, considering both changing climatic conditions and the overall complexity of ship operations. Furthermore, in order to make a comparison between different configurations, novel indexes and a novel tool for the PES prediction are proposed that define the ship performance, considering factors such as investment cost, achievable energy savings, occupied volume, and the utilization of the energy produced on board. With this study, the authors hope to contribute to the decarbonization process in the maritime industry.

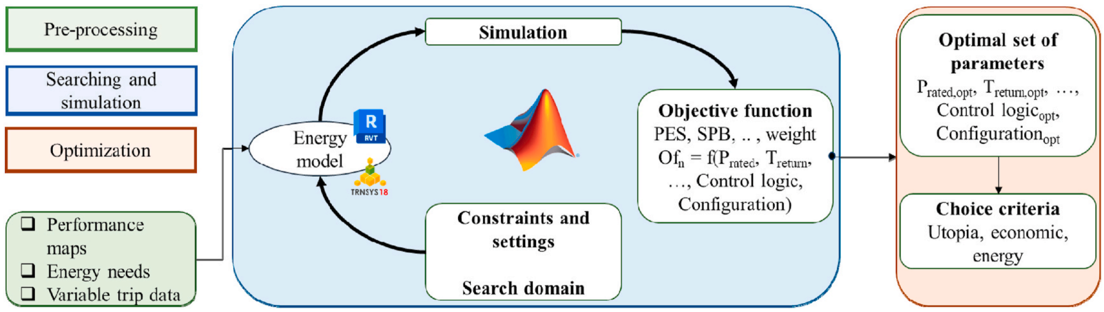

Fig. 2. Synoptic block diagram - optimization procedure.

2. Material and method

2.1. Ship modelling and simulation

In addressing the research question, a customized simulation tool is developed. It relies on different software; specifically, the ship envelope is modelled through Autodesk Revit, a customized weather data is obtained through the exploitation of MatLab and Python, while TRNSYS is considered for the simulation of the on-board energy system. Fig. 1 summarizes the proposed approach.

Different inputs are necessary to consider the multiplicity of parameters to be considered; the latter can be grouped into:

- geometry of the ship - definition of the thermal zones, thermo-hygrometric characteristics to be achieved, occupancy profiles, etc.
- customized weather data for the defined route - parameters such as solar radiation, sea water temperature, air temperature to evaluate the effect on the thermal loads to be satisfy and on the performance of the different technologies.
- definition of the energy system - implemented technologies, connections, performance maps and operating logics.

These inputs must be defined to make the model results as reliable as possible. Ship modelling relies on the BIM2BEM approach, with software such as Autodesk Revit exploited for the modelling of the ship envelope and Open Studio and EnergyPlus for the development of the energy model. A detailed description of the proposed approach is reported in Ref. [68]. Customization of the weather data is crucial for refining the ships thermal and energy load to the dynamic simulation, clearly based on the influence of changing external weather and indoor conditions.

The customized weather data is obtained defining information such as arrival, departure, geographical position, and orientation of the ship based on its speed and the dataset to be considered; indeed, different databases are available, such as Meteonorm, TRY, TMY, IWEC, ERA5. A proper definition of the thermal loads and boundary condition will allow a more reliable analysis on the sizes to be considered. The simulation of the on-board energy system occurs through the exploitation of TRNSYS, a well-known dynamic simulation tool, widely used to model energy systems [40]. Definition of operating parameters, performance maps and operating logics are therefore required to model the system. The propulsion system needs to be defined; specifically, propulsion demand results as the primary on board user. To obtain an estimation of propulsion power demand, propulsion curve depending on ship speed is considered. The implemented propulsion characteristic curve can be derived from the analysis of experimental data collected under various operating conditions, providing a reasonable approximation of the probable power requirement since resistances due to currents and other factors are taken into account. While this approach provides a valuable estimation tool, it is important to acknowledge that not all factors, especially those time-dependent ones like hull or propeller maintenance, are fully accounted for. Indeed, there is no unique factor to determine the impact of maintenance or fouling for the hull and propeller, as it greatly depends on the degree of fouling or maintenance neglect, as well as the type and size of the ship [78,79]. However, it should be noted that the different investigated solutions do not affect the maintenance actions applied to the reference case. Therefore, these maintenance operations may be considered equal as well as their effects on the energy needs of the cruise ship. For this reason, they are not studied both in the reference system and proposed scenarios. The various technologies implemented on board (e.g., diesel engines, multi-stage flash evaporators, etc.) and the different utilities (domestic hot water, air conditioning, fuel preheating, etc.) and their interaction can be modelled and analysed through dynamic simulation to consider the operating variability present on board the ship. In this perspective, it is possible to assess how power, flowrates, and temperature levels vary, and in a more general sense, the amounts of energy that are used or dissipated. It is therefore possible to evaluate the implementation of innovative technologies, assessing the correspondence of thermal levels, achievable efficiencies, and the sizes required or that can be considered. The interaction of these three investigated factors - ship envelope, weather data, and energy system - enables a more detailed evaluation of the overall ship efficiency. This comprehensive approach provides greater clarity on the proposed implementations and their potential effects. The energy model derived can be used to simulate specific operating conditions or, in the context of a design process, it becomes a valuable tool for analysing and compare different technologies and strategies. Through an optimization procedure involving objective functions and constraints, it will be possible to define the optimal solution to be implemented in order to increase the overall ship efficiency.

2.2. Optimization procedure

To enhance the overall ship energy efficiency, several technologies and control logics can be analysed and implemented. Most of the decision support methods relies on a single objective/criterion method, while trade-offs among objective functions should be considered to define the optimal solution [41]. The proposed tool, therefore, considers a multi-objective optimization where energy, economic, and environmental performance are considered. As depicted in Fig. 2, considering the variable weather conditions and energy needs to be met, defining constraints, settings, and the research domain for simulation (such as the size of the technology to be implemented, the temperature level to be reached, control logic, etc.), the developed energy model enables the simulation of various plant configurations, obtaining indications on the performance of the system considered. Through defining objective functions (e.g., primary energy saving, simple payback, weight, occupied volume), it is possible to define the optimal solution and their corresponding parameters through Pareto front optimization and appropriately chosen selection criteria. As the considered objective functions vary, the optimal solution may change. This flexibility allows, based on the predefined design requirements, an assessment to determine the most suitable configuration to consider.

As economic objective function, it is possible to evaluate the capital (CAPEX) and variation in operating (ΔOPEX) expenditure as:

$$CAPEX_i = c_i x_i \tag{1}$$

$$\Delta OPEX = \sum_t \left[(m_{RS} - m_{PS})_{fuel} c_{fuel} + (m_{RS} - m_{PS})_{fw} c_{fw} + M_{RS} - M_{PS} \right] \tag{2}$$

where the CAPEX is evaluated by considering the technology size and unitary cost c_i, and ΔOPEX is assessed by taking into account the following parameters: m is the mass (fuel or fresh water), c_{fuel} is the unitary cost of consumed fuels, c_{fw} is the unitary purchase cost of bunkering fresh water in port, and M is the maintenance costs. Furthermore, the subscript RS refers to the reference system, while PS refers to the proposed system. Unitary cost of technologies and fuels were obtained from literature [75,80] or sourced from official online platforms [81].

The energy performance of the ship can be obtained through the evaluation of the primary energy needed and, therefore, the Primary Energy Saving (PES):

$$PES = \sum_t \left(\frac{PE_{RS} - PE_{PS}}{PE_{RS}} \right)_t = \sum_t \left(\frac{m_{RS} - m_{PS}}{m_{RS}} \right)_{fuel,t} \tag{3}$$

where PE is the primary energy, that can be defined through the related fuel consumption. The amount of fuel consumption allows also to consider the environmental impact of the solution under investigation; indeed, the avoided pollutant emission, as an example carbon dioxide is reported, can be calculated by considering the fuel emission factor, f_{fuel}:

$$\Delta CO_2 = \sum_t f_{fuel} (m_{RS} - m_{PS})_{fuel} \tag{4}$$

Similarly, other pollutants (e.g. SO_x, NO_x, and $PM_{2.5}$) can be evaluated.

Moreover, for each analysed solution, it is possible to assess:

$$CAPEX_{rating} = 1 - \frac{CAPEX_i}{\max(CAPEX_i)} \tag{5}$$

$$PES_{rating} = \frac{PES_i}{\max(PES_i)} \tag{6}$$

$$V_{rating} = 1 - \frac{V_i}{\max(V_i)} \tag{7}$$

For CAPEX and volume (V), the complement to one is considered, represented by 1 minus the evaluated value ($CAPEX_i/\max(CAPEX_i)$ and $V_i/\max(V_i)$). This choice is made to favour solutions with lower assessments of CAPEX and volume, as a higher score is desirable in these categories. The implementation of new technologies or control strategies can be considered for two cases: refurbishment of an existing ship or design of a new ship. For the existing ship the main constraint is given by the few spaces available, while for the new ships it's imperative to maximize energy savings in order to meet the targets set for the next years. For these reasons, it is decided to classify the configurations by taking into account these considerations. To provide indications on what could be the best configurations to implement as the climate file considered varies, two novel rating indexes are proposed. Specifically the energy, economic and volume index (EEVI) is introduced as:

$$EEVI = CAPEX_{rating} + PES_{rating} + V_{rating} \tag{8}$$

since it is possible to assign weights to the three criteria, it is assumed that in the case of the refurbishment of ships, volume will account for 50 % of the total rate, while for newbuilt ships PES will account for half of the total rate. EEVI ranges from 0 to 3. For this index a scale from 1 (● - bad) to 4 (●●●● - excellent) is reported in the discussed results with the following criterion:

- ● for $0 < EEVI \le 0.75$
- ●● for $0.75 < EEVI \le 1.50$
- ●●● for $1.50 < EEVI \le 2.25$
- ●●●● for $2.25 < EEVI \le 3.00$

Table 1
Investigated cruise ship.

	Large cruise ship	Small cruise ship
Gross tonnage (GT)	225,282	153,516
Engines (kW)	3 × 14,400 3 × 18,480	2 × 14,400 2 × 16,800
Additional producers (kg/h)	Oil fired boiler - steam production at 170 °C 2 × 20,000	Oil fired boiler - steam production at 170 °C 2 × 12,500
Fresh water production	4 × Multi-stage flash evaporators 2 × Reverse osmosis unit	2 × Multi-stage flash evaporators 2 × Reverse osmosis unit
LT circuit exploitation	No	Yes
Hot water users	Multi-stage flash evaporators Air conditioning Domestic hot water	Multi-stage flash evaporators Air conditioning Domestic hot water Laundry preheating
Steam users	Multi-stage slash evaporators Air conditioning Domestic hot water Laundries Galleys Swimming pool Engine auxiliary Fuel preheating	Multi-stage flash evaporators Air conditioning Domestic hot water Laundries Galleys Swimming pool Engine auxiliary Fuel preheating
Fuel used	Heavy fuel oil and marine gas oil	Heavy fuel oil and marine gas oil

The second proposed index – energy, utilization and performance index (EUPI) – takes into account, in addition to $CAPEX_{rating}$, PES_{rating} and V_{rating}, also the energy utilization (E_{use}).

$$E_{use} = \left(1 - \frac{\text{Energy use}_i}{\max(\text{Energy prod}_i)} \right) \tag{9}$$

$$EUPI = CAPEX_{rating} + PES_{rating} + V_{rating} + E_{use} \tag{10}$$

Also for E_{use} the complement to one of Energy use_i/max(Energy $prod_i$) is considered, in order to reward those configuration that allows high energy savings with a lower energy utilization – and therefore the possibility to implement other technologies for the enhancement of the energy system. EUPI ranges from 0 to 4. Also for this index a scale from 1 (● - bad) to 4 (●●●● - excellent) is reported in the discussed results with the following criterion:

- ● for $0 < EUPI \le 1.00$
- ●● for $1.00 < EUPI \le 2.00$
- ●●● for $2.00 < EUPI \le 3.00$
- ●●●● for $3.00 < EUPI \le 4.00$

2.3. Proof of concept

The above-presented methodology is preliminary applied to two different case-study cruise ship, a large and a small one, and three different route (i.e. representing of different climate conditions) – North Sea, Caribbean Sea, and Mediterranean Sea. The reference energy systems are modelled in TRNSYS environment, and the real performance map and operating parameters are considered with the actual operating logic. A comparison of the two energy systems is reported in Table 1. The considered existing cruise ships present several engines fuelled with heavy fuel oil to produce electrical energy to power the propulsion system and all the users on-board; waste heat at high (HT) and low temperatures (LT) is recovered through suitable heat exchangers that cool the engines jacket water circuit and engines lube oil circuit, respectively; steam is produced with the recovery of the heat included into exhaust gases through exhaust gas boilers (EGBs); further steam is produced with fuelled boilers. Thus, three different temperature levels

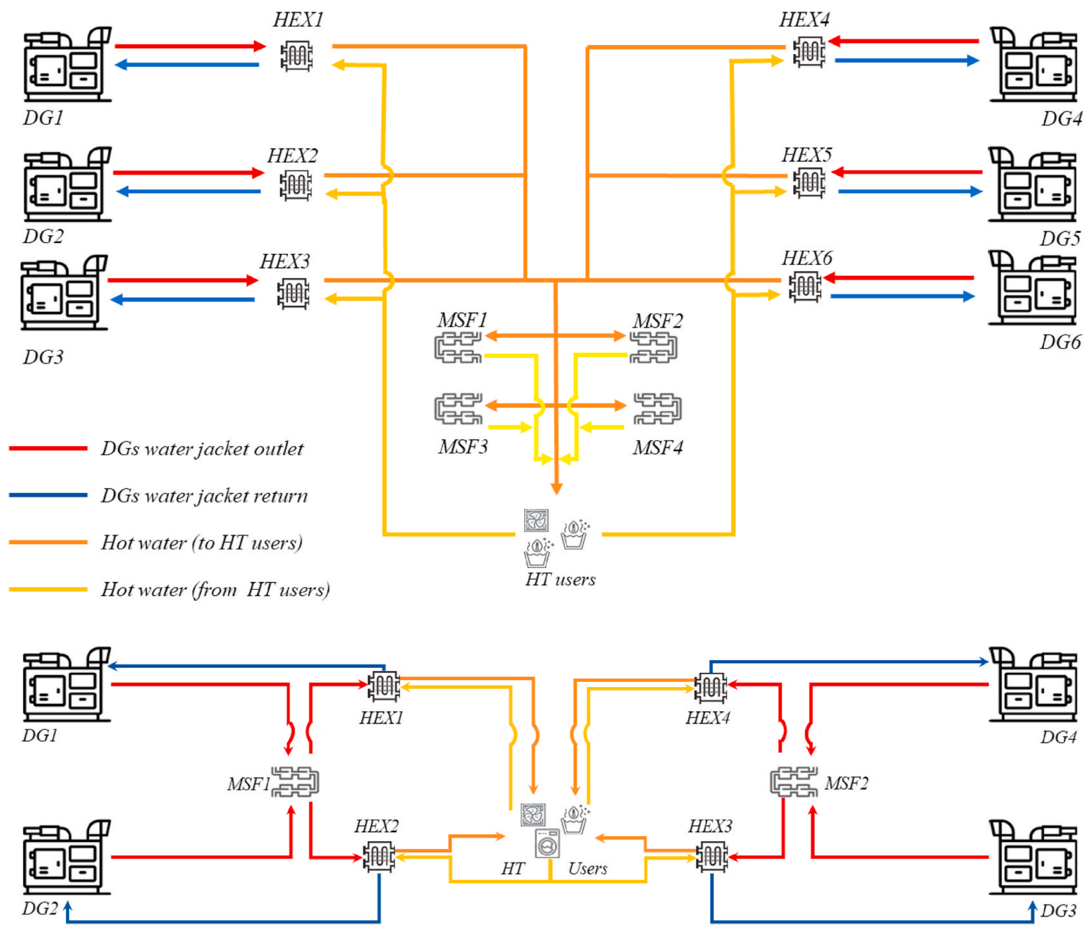

Fig. 3. HT recovery circuit: top - large cruise ship, bottom - small cruise ship.

can be exploited onboard the ship: low temperature (LT circuit), medium temperature (HT circuit), and high temperature (steam). The amount of thermal power recovered depends on the electrical power demand, which determines the number of engines in operation and their respective part load ratios. Thus, while sailing, when propulsion demands are high, a substantial amount of thermal energy can be recovered, with any surplus often dissipated through seawater cooling. However, when docked in port, with only one engine running, additional thermal energy might be needed from oil-fired boilers to meet the demand. Therefore, dynamic simulation is essential to account for this variability and evaluate the feasibility of integrating thermal activated technologies at different thermal level and with different sizes.

The waste heat recovery strategy is implemented to improve the efficiency of the ship and limit the utilization of the boilers - powered with marine gas oil. Furthermore, fresh water production occurs only in cruising – to treat clean water – with multi-stage flash (MSF) evaporators mainly used. The two energy systems differ above all in the power supply strategy of the various users which exploit the recovery of HT and LT circuits.

- for the large ship, six diesel generators (DGs) have a waste recovery heat exchanger (HEX) for cooling the engines: in the primary circuit, engines jacket water is flowing, while the secondary circuit is utilized for feed users that requires a high temperature level. Specifically, the recovered heat is exploited by giving priority to the MSFs (possibly steam integration may be envisaged) and subsequently air conditioning (AC), and domestic hot water (DHW). The heat at LT coming from the lube oil cooling is not exploited.
- for the small ship, MSFs are directly fed by engines jacket water through the primary circuit (thus exploiting a higher temperature; steam integration can also be envisaged in this case), and only then a heat exchanger is adopted for feeding users that require a high temperature level. The heat at LT is exploited to power several users.

A simplified block scheme of the two configurations is reported in Fig. 3.

Steam produced from EGBs and from boilers is used to feed all the steam users and eventually, if needed, as backup for all the HT users. Schedules for hot water utilization were considered from Ref. [82], where the benefits of implement a thermal storage to reduce the peak of thermal demand were investigated. The implementation of different thermal activated technologies, i.e. wet steam expander (WSE) - with a heat exchanger to exploit the outlet steam to reheat the HT circuit, organic Rankine cycle unit, single effect absorption chiller (SAC), and double effect absorption chiller (DAC), was considered to reduce the dependency of electrical production from diesel engines (WSE and ORC) or the dependency on electrical chillers (SAC and DAC). The steam produced on board is often in a saturated state; for this reason, a wet steam screw expander - WSE- has been chosen as a solution, allowing operation with saturated steam without the need for an additional boiler to produce superheated steam. A specific control logic has been implemented, as the activation of the technologies is set only when excess thermal energy is obtained, without increasing the use of boilers. The choice of routes, on the other hand, was made with the intention of analysing the most recurring climatic conditions in the case of ships, especially cruise ships, as in the case analysed. Specifically, it was assumed to repeat the same route throughout the year, however varying the surrounding conditions and therefore the loads required. The considered routes are depicted in Fig. 4 and the main characteristics reported in Table 2.

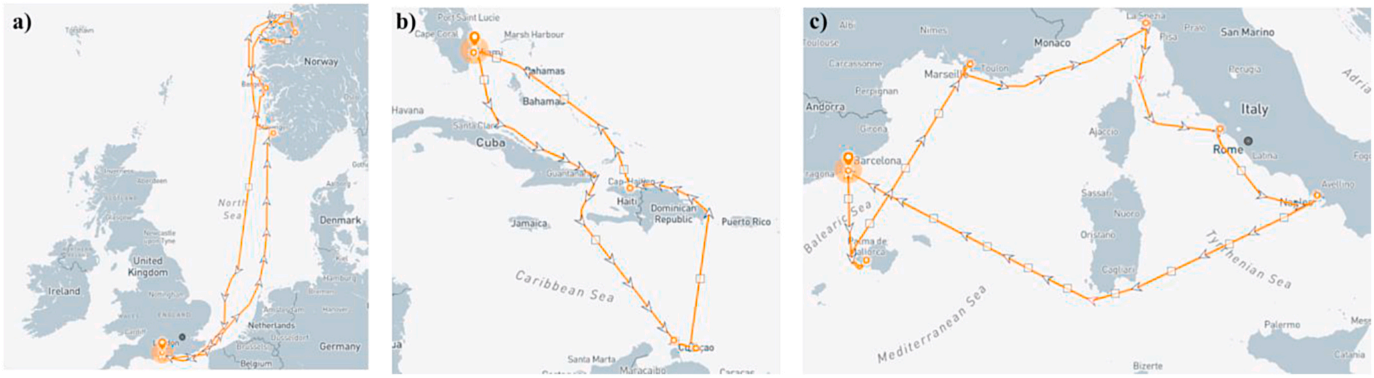

Fig. 4. Considered routes: a) North Sea, b) Caribbean Sea, c) Mediterranean Sea.

Table 2
Considered routes.

	North Sea	Caribbean Sea	Mediterranean Sea
Route	Southampton (UK)	Miami (FL, USA)	Barcelona (ES)
	Stavanger (NO)	Oranjestad (AW)	Mallorca (ES)
	Geiranger (NO)	Willemstad (CW)	Marseille (FR)
	Olden (NO)	Labadee (HT)	La Spezia (IT)
	Bergen (NO)	Miami (FL, USA)	Civitavecchia (IT)
	Southampton (UK)		Napoli (IT)
			Barcelona (ES)
Days (–)	7	8	7
Distance (km)	4051	2468	3008
Average speed (kn)	16.6	13.0	16.1
Maximum speed (kn)	24.1	20.7	22.5

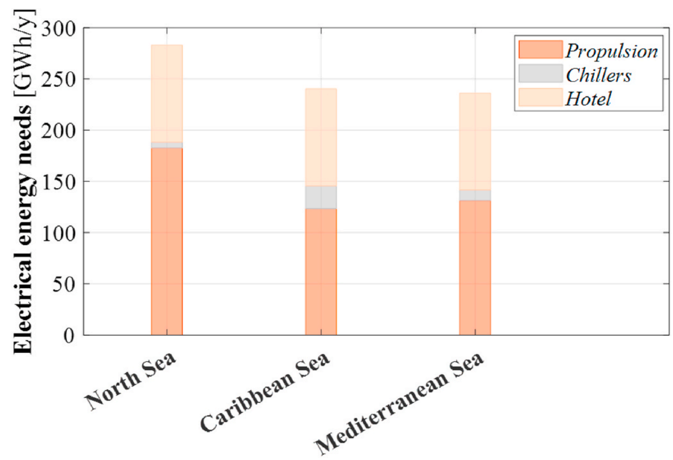

Fig. 6. Electrical needs - large cruise ship.

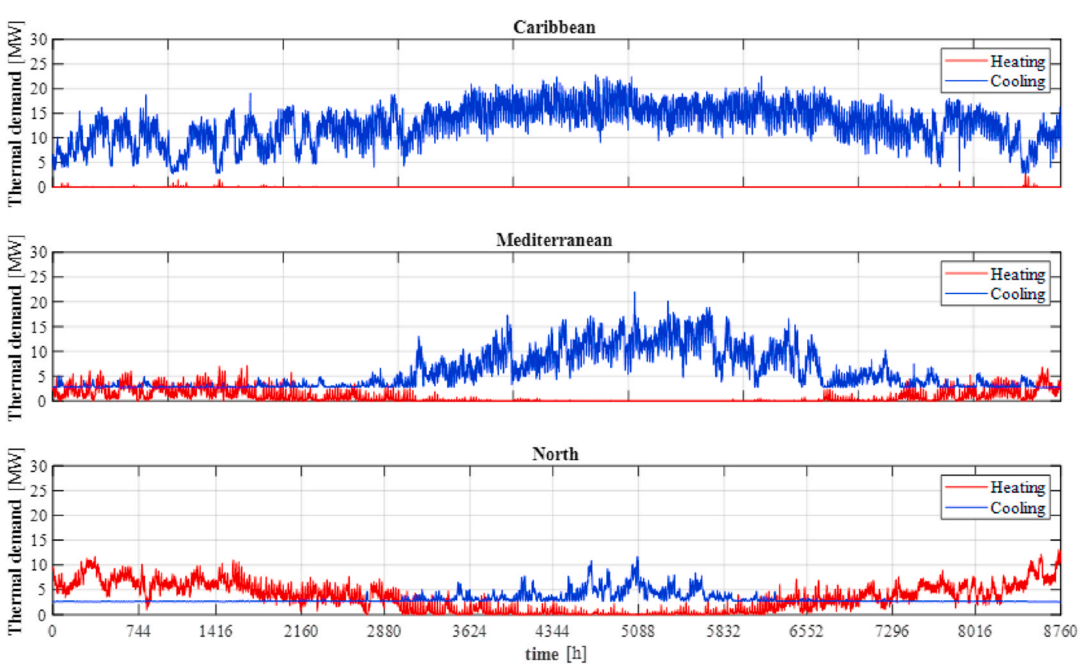

Fig. 5. Cooling and heating needs for the three considered scenarios – large cruise ship.

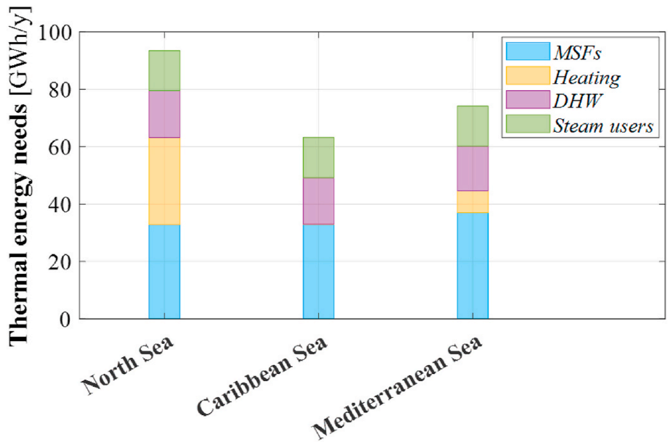

Fig. 7. Thermal needs - large cruise ship.

Table 3
Implemented technologies and control strategies - large cruise ship.

Parameters	Range (min - max)
Wet steam expander, nominal flow rate (t/h)	0–9
Single effect absorption chiller, cooling power (kW)	0–4571
Double effect absorption chiller, cooling power (kW)	0–3868
Organic Rankine cycle unit, nominal flow rate (t/h)	0–500
LT circuit exploitation (–)	Yes or No

The analysis carried out therefore considered two different cruise ships, assuming 3 different climatic zones which can include winter (North Sea), ISO (Mediterranean Sea), and tropical (Caribbean Sea) operation. To consider the electrical and thermal needs to be satisfied, appropriate curves (e.g. propulsion), and thermal requirements deriving from the BIM2BEM model of the analysed ships were implemented; the cooling and heat demand obtained for the three different weather conditions are reported in Fig. 5, for the whole year, considering the large cruise ship. Note that, the Caribbean Sea is characterized by large cooling (variable) needs, while the North Sea present much higher heating needs.

For the first of the two ships analysed, the large one, the cumulative electrical and thermal demands for the various utilities are reported in Figs. 6 and 7, considering the varying sea scenarios. Note that, the highest energy need can be attributed to propulsion, due to the high speeds and distances travelled. In order to carry out the simulation, the DHW profile and the consumption of steam-powered utilities remain unchanged between the scenarios. As regards the production of fresh water, however, a control logic based on the level of the tank and the navigation of the ship is considered, aiming at not having to resort to bunkering. For the large cruise ship, in Table 3 are reported the sizes of the implemented technologies (i.e. wet steam expander, single and double effect chiller, organic Rankine cycle unit) as well as the possibility of exploiting the LT circuit. For heavy fuel oil and marine gas oil, 627.0 and 838.5 €/t were considered, respectively, as fuel price.

3. Results and discussion

The solutions proposed to enhance the energy system on-board of these cruise ships are an organic Rankine cycle, a wet steam expander, a single and a double effect absorption chiller, while for the large cruise ship the exploitation of the low temperature circuit of the engines is also considered – since it is not present in the reference system. For the ORC unit, among the different possible working fluid available (e.g. R134a, R245fa, isobutane, pentane, propane, etc.), R245fa was selected. The main benefit of this technology is that heat can be supplied at low temperatures exploiting the waste heat recovery from the high temperature circuit of the engines jacket water. Thermodynamic efficiencies strongly depend on the level temperatures reached in the cycle; therefore, it is important to also consider the variability of the sea water temperature used as cooling fluid in the condenser. The variability of the weather data file – including sea water temperature – was considered in the model to better simulate the energy behaviour of all components. This temperature strongly depends, both in average value as in variance, from the zone considered as shown in Fig. 8. It can be noted that in the North Sea the lowest temperatures are achieved, as well as that for the Caribbean Sea not only the highest temperatures are reached, but there are no major variations during the year. It is also reported, with a red star, the sea water temperature at which the maximum ORC cycle efficiency is reached. As pointed out by several studies, a lower cooling

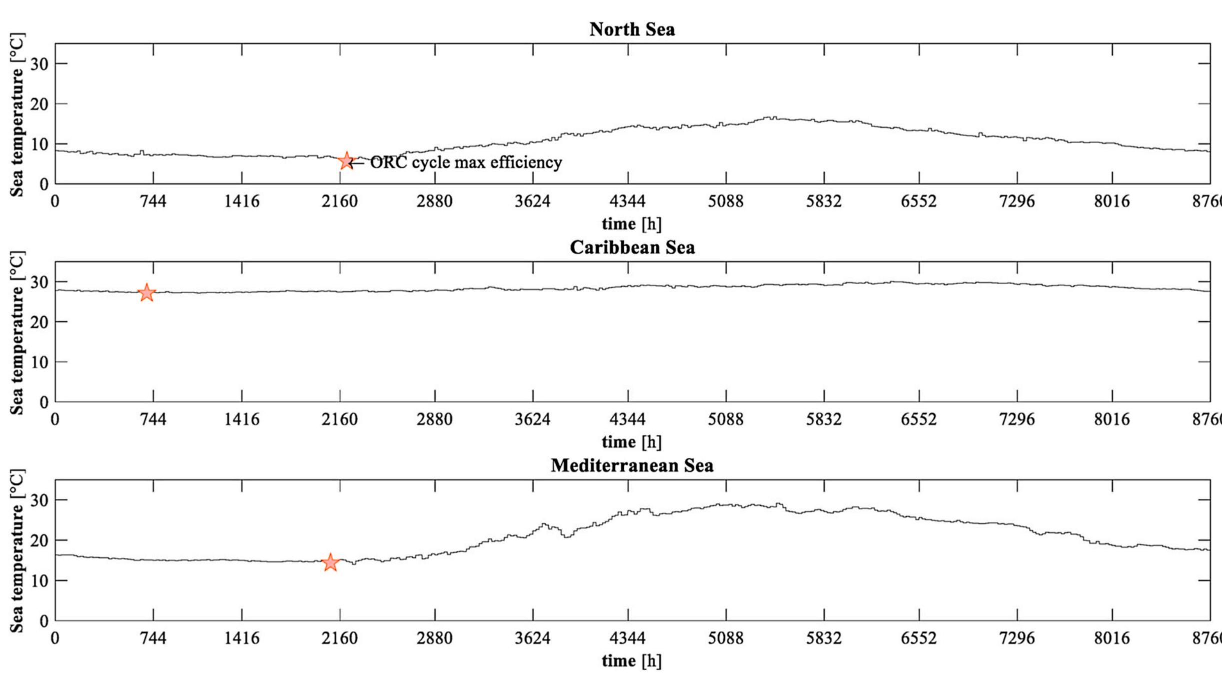

Fig. 8. Hourly sea water temperature profile.

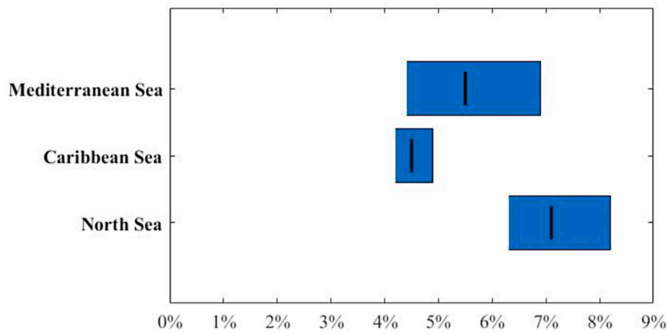

Fig. 9. ORC efficiency range for the three considered routes.

water temperature allows to consider a lower condensation pressure, increasing the electrical production from the ORC [83]. In Fig. 9, instead, the ranges of electrical efficiency obtained for the simulated routes are reported: the low variability of the sea water temperature in the Caribbean Sea allows to consider a narrow range of efficiency, unlike the cases of the Mediterranean, and North Seas. Note that, the maximum temperature values in the Mediterranean (in summer) are comparable to the values measured in the Caribbean, resulting in efficiency values that are close to each other in the summer period.

In addition to influencing the operating characteristics of the different technologies, climatic weather conditions also have a strong impact on heating and cooling demands, as shown in Fig. 5. This implies that the choice of route, and therefore of the climate weather data file, also influences the effectiveness of operating choices. For the large cruise ship in which, from the installation, the exploitation of the low temperature circuit of the engines is not considered, entirely dissipating a considerable quantity of thermal energy in the form of hot water at around 50 °C, the implementation of the LT circuit is hypothesized. It is possible to exploit this source of thermal energy for air conditioning purposes (re-heating during the summer season and pre-heating during the winter one) and for domestic hot water production, thus reducing the requirement on the HT circuit or, if necessary, integration with steam, allowing greater operation of technologies on-board ships. The CAPEX-PES combination obtained from the simulation of different configurations is shown in Fig. 10, where implemented sizes for WSE, ORC, SAC, and DAC have been varied; specifically, in blue are reported the solutions where the LT exploitation is not considered, while in orange the one that also considered the exploitation of the LT circuit. Note that, due to low heating needs, Caribbean Sea is characterized with slightly increase in PES values obtained with solutions that almost overlap; in the Mediterranean Sea a greater difference can be noticed, but it is above all in the North Sea that the use of LT can be noticed, with a substantial detachment of the solutions without and with the use of the low temperature energy carrier for AC and DHW purposes.

For this reason, the influence on the operating hours of various of the proposed solutions is also analysed, depending on whether LT is used or not. Specifically, in Fig. 11 are depicted in blue the range of operating hours of the different sizes implemented without the LT circuit, while in orange the case where LT is considered. The low influence of the LT circuit in the Caribbean Sea is also highlighted in this case, where there are no major variations in operating hours, except for the single effect absorption chiller, powered by the HT circuit, thanks to the thermal energy released for the use of the LT circuit. In the Mediterranean Sea, however, an increase is also obtained for WSE and DAC, since the use of LT allows less steam to be used for integration with consequent more

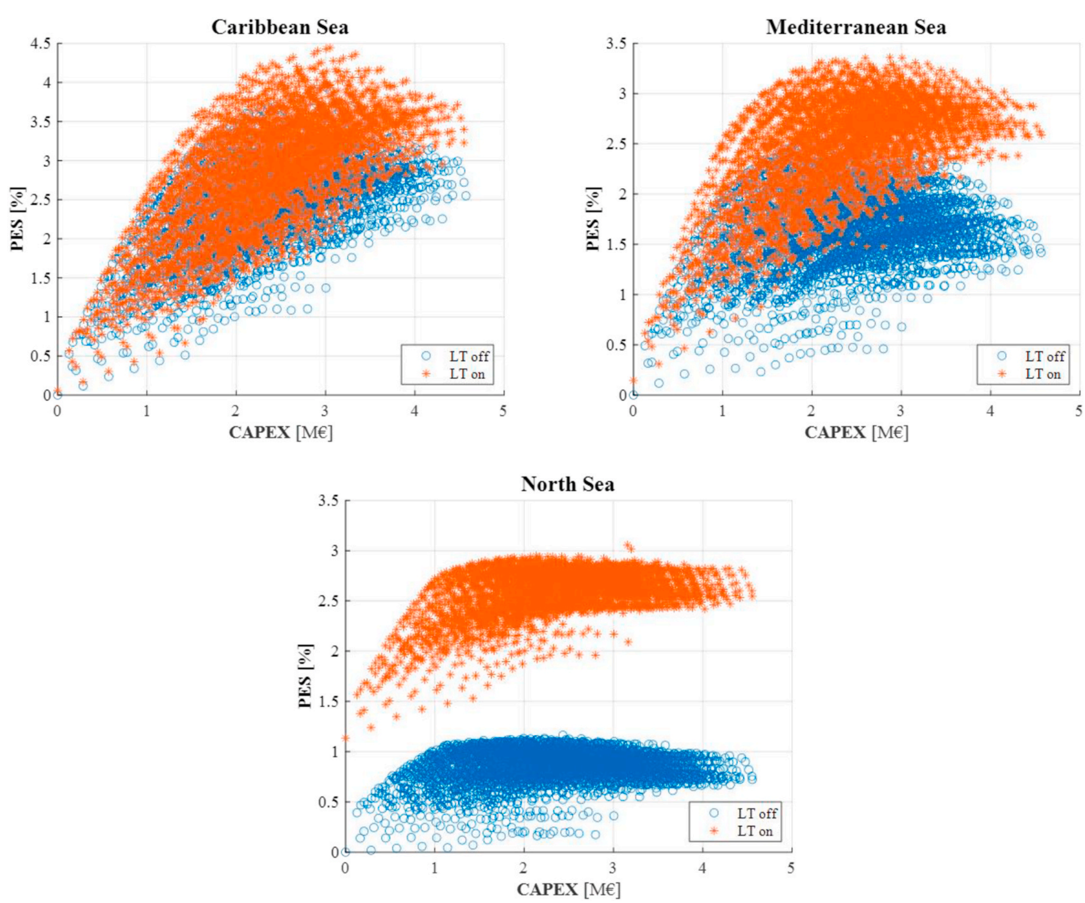

Fig. 10. Low temperature circuit implementation - Caribbean, Mediterranean and North Seas.

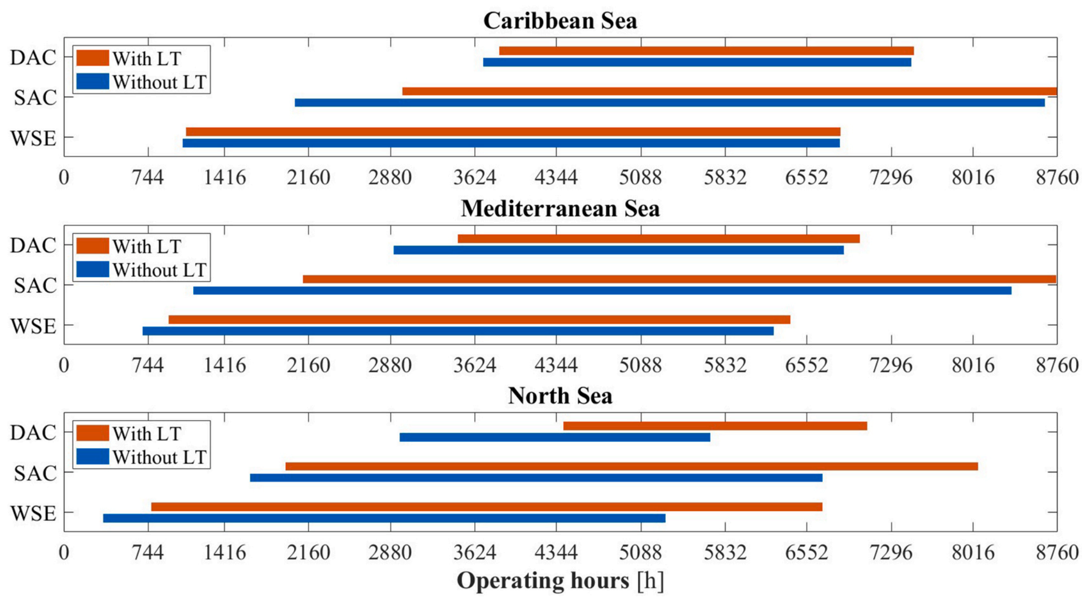

Fig. 11. Range of operating hours with and without the exploitation of the LT circuit - large cruise ship.

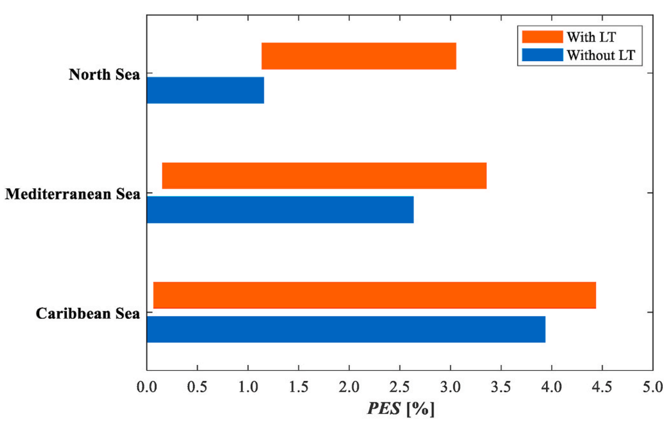

Fig. 12. Range of obtainable PES values with and without the implementation of the LT circuit.

frequent activation of these technologies; specifically, for the DAC, the SAC, and the WSE the minimum operating hours changed from 2907 to 3470, from 1139 to 2103 and from 693 to 920, respectively. In the North Sea the variation is greater, with minimum operating hours that increases from 2956 to 4399, from 1640 to 1949 and from 342 to 770 for the DAC, the SAC, and the WSE, respectively. It is also important to highlight that the SAC maximum operating hours can, theoretically, be equal to the entire duration of the year (not possible in reality due to maintenance operations and non-operation of the ship), unlike the North Sea, thus highlighting how the cooling demand in the Mediterranean Sea requires at least a minimum size for SAC that is always operating and how there is the thermal availability to be able to continuously power this technology, but only if the LT circuit is implemented.

In Fig. 12 the obtainable PES ranges for the three considered scenarios, without and with the implementation of the LT circuit, are depicted. Also in this case, it can be noted that the greatest effect of the implementation of the LT circuit occurs in the case of the North Sea, with greater differences in the minimum and maximum values obtainable for the PES; however, note that the highest PES values, overall, are obtained in the case of the Caribbean Sea. This is due to the high availability of thermal energy, not having to satisfy a high heating load, and the possibility, therefore, of powering thermally activated technologies, especially to satisfy the high cooling load, significantly reducing the energy demand from electric chillers.

It is essential to underline that even the mix of technologies does not allow high percentage values of energy efficiency, therefore it is necessary to implement further strategies to be able to comply with future regulatory obligations, e.g. renewable sources or alternative fuels. In Table 4 the main results for the economic, energy, and utopia criterion are reported for an entire year, as well as the parameters of the

Table 4
Optimization results - economic, energy and utopia criterion. Large cruise ship.

	Caribbean Sea			Mediterranean Sea			North Sea		
	Econ	Energy	Utopia	Econ	Energy	Utopia	Econ	Energy	Utopia
***PES* w/prop** (%)	0.06	4.44	3.00	0.14	3.36	2.59	1.13	3.06	2.68
***PES* w/o prop** (%)	0.12	9.00	6.07	0.33	7.59	5.85	3.18	8.56	7.52
CAPEX (M€)	0	3.05	1.20	0	2.87	1.03	0	3.16	0.96
ΔOPEX (k€)	16.3	1249	842	45.3	924	713	445	1061	935
Volume (m^3)	0	190	85.2	0	178	74.3	0	194	70.5
ΔCO_2 (t)	79.1	6214	4190	189	4567	3519	1713	4816	4224
SPB (years)	0	2.44	1.42	0	3.11	1.45	0	2.98	1.03
WSE power (kW)	0	250	250	0	165	250	0	165	250
SAC cooling (kW)	0	4571	3428	0	4571	2883	0	4571	2637
DAC cooling (kW)	0	3868	0	0	3516	0	0	3516	0
ORC power (kW)	0	0	0	0	0	0	0	71	0
LT (Yes/No)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

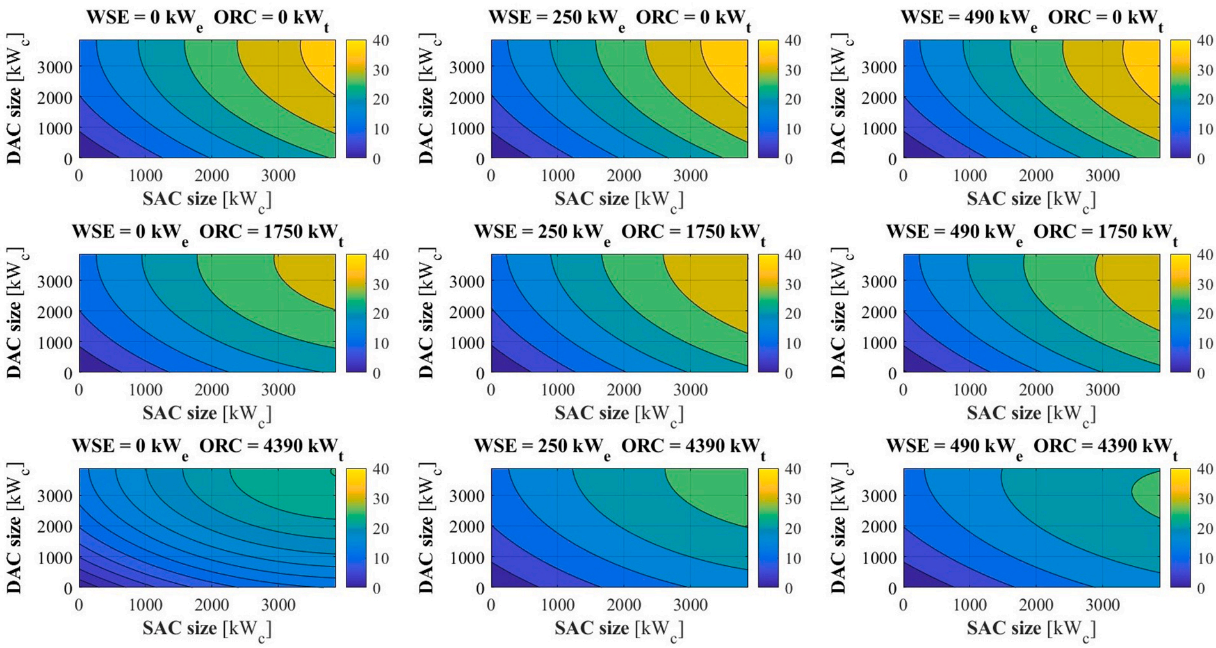

Fig. 13. Contour plot: cooling demand self-sufficiency [%] - Caribbean Sea.

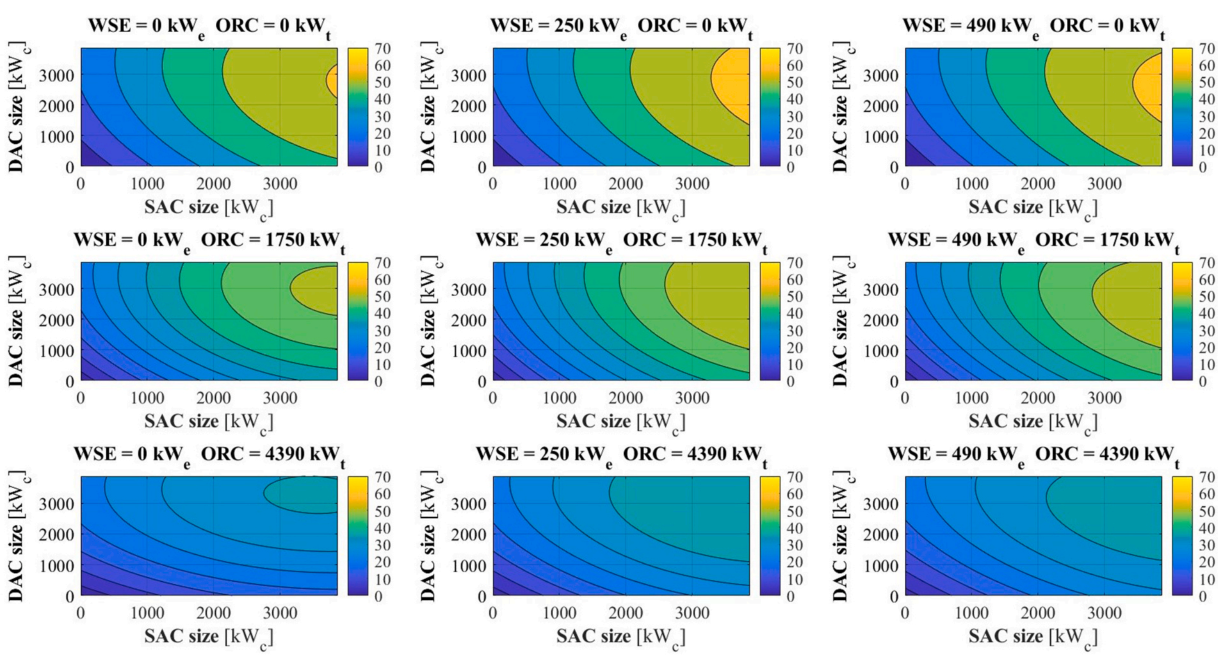

Fig. 14. Contour plot: cooling demand self-sufficiency [%] - Mediterranean Sea.

related implemented technologies. Highest PES values, considering the propulsion energy needs are obtained for the Caribbean Sea scenario, however, due to the high request of energy to power the propulsion system in the North Sea, if the PES is evaluated excluding the propulsion, PES values of 8.56 % are obtained, compared to the 9 % achieved in the Caribbean, and the 7.59 % in the Mediterranean Sea. Differences in the investment cost, operating savings and avoided pollutant emissions are also achieved, as well as for the needed volume. For the latter, a cumulative volume is provided, but a more specific analysis on the correct positioning and connection to the energy system should be carried out, since a 3D analysis for the implementation of the technologies (e.g. evaluation of spaces for maintenance, etc.) was not considered. In the case of the energy criterion, the solution that maximizes the PES is reported, so the maximum sizes are almost always implemented. However, note that in the case of the North Sea, given the low cooling demands, high SAC and DAC sizes do not produce notable variations. This can also be seen from Fig. 10, where a sort of asymptote for the PES is reached. Indeed, comparing the energy case with the utopia solution, it is possible to note that a variation of only 0.4 % is obtained for the PES, with a CAPEX approximately three times lower in the utopia case. This highlights the need for dynamic analysis, where variable profiles are carefully analysed and whereby a correct choice of sizes to implement can be made.

The cooling energy needs self-sufficiency for the Caribbean Sea, the Mediterranean Sea, and the North Sea are reported in Figs. 13–15, respectively. Specifically, for the mentioned figures, the percentage of

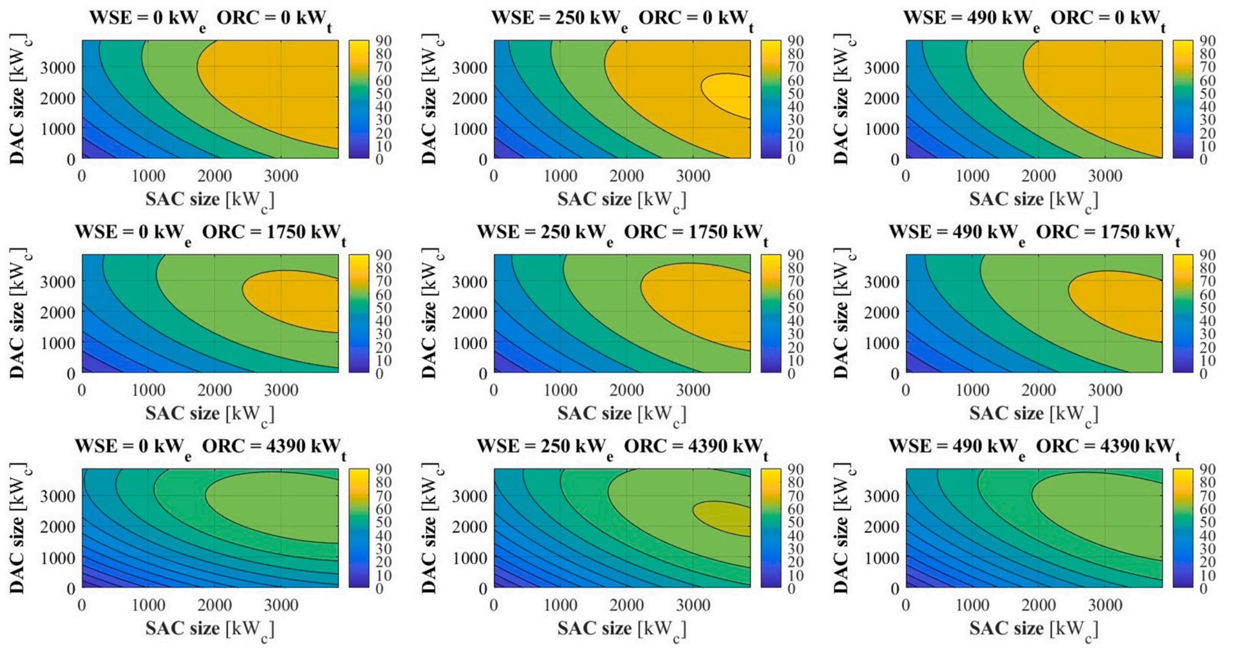

Fig. 15. Contour plot: cooling demand self-sufficiency [%] - North Sea.

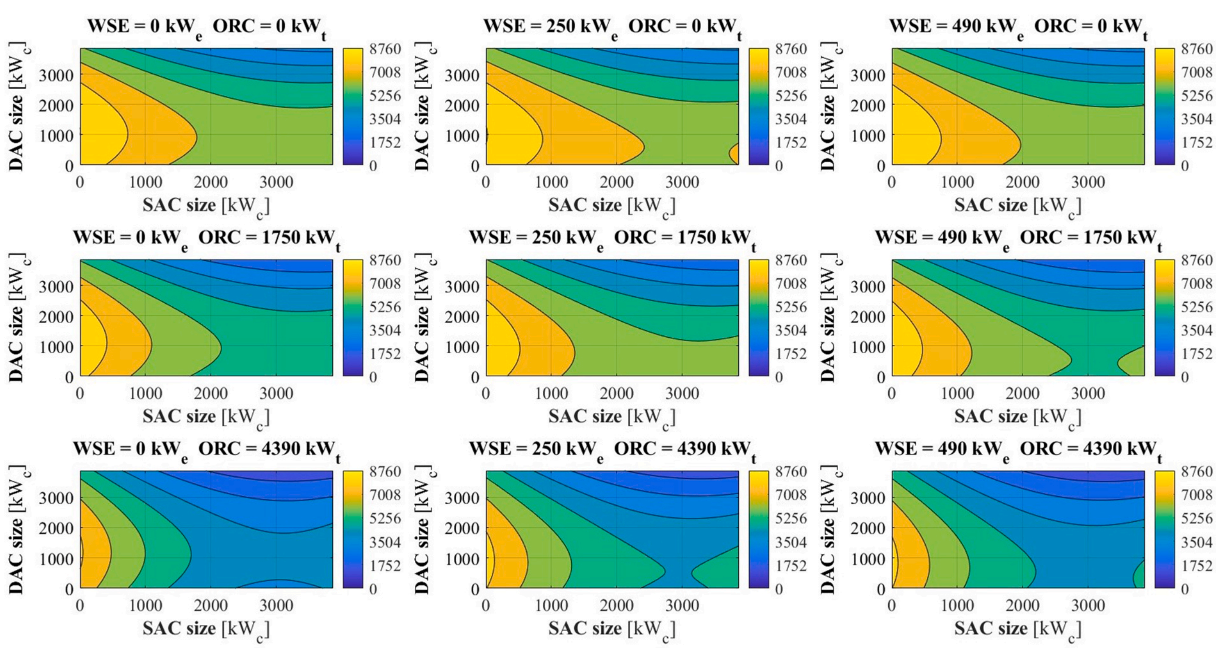

Fig. 16. Contour plot: SAC operating hours - North Sea.

cooling energy covered with SAC and DAC is reported varying the implemented size of the technologies and considering three different sizes for the WSE and the ORC, and their combination. The percentage values that can be obtained are different depending on the considered scenario; indeed, given the high demands in the Caribbean Sea, values lower than 50 % are obtained (Fig. 13), while in the North Sea almost all the cooling needs can be covered (Fig. 15). From the contour plot the influence of the implemented technologies can be defined: the increase in the ORC size decreases the amount of available thermal energy that can be exploited by the SAC, with a reduction of the percentage of cooling needs covered. The implementation of a WSE does not affect notably the variation in cooling needs satisfaction for the three cases, except when the highest size of the ORC is considered. By analysing the results obtained for the North Sea more carefully, it is possible to notice that high self-sufficiency ranges are already reached at smaller sizes of SAC or DAC; this is due to the low cooling demand characterizing a cold climate like the North Sea. Focusing on Fig. 16, where the number of operating hours of the SAC is shown as the different sizes of the technologies implemented vary, it is possible to see how the single effect absorption chiller works for a greater number of hours, especially for sizes between 1600 and 2800 kW_c. For larger sizes, therefore, a greater cooling power will have to be considered, but with a lower number of operating hours, thus covering a comparable amount of cooling energy. This analysis therefore allows to highlight how smaller sizes in the North Sea can be conveniently hypothesized, obtaining economic saving for the initial investment, but also for occupied spaces, a fundamental

Property	Value	Unit
CAPEX	4.57	M€
SPB	10.0	Years
PES	4.44	%
Volume	284	m^3
Integrability	67	Number of optimal solutions

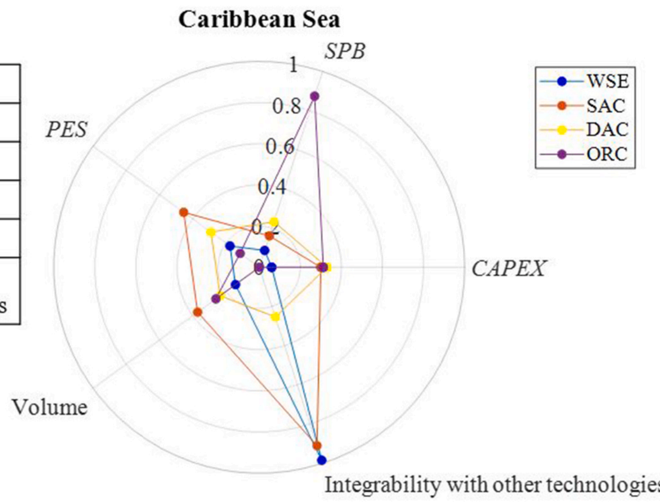

Fig. 17. Evaluation of implemented technologies - Caribbean Sea.

Property	Value	Unit
CAPEX	4.57	M€
SPB	10.0	Years
PES	3.36	%
Volume	283	m^3
Integrability	56	Number of optimal solutions

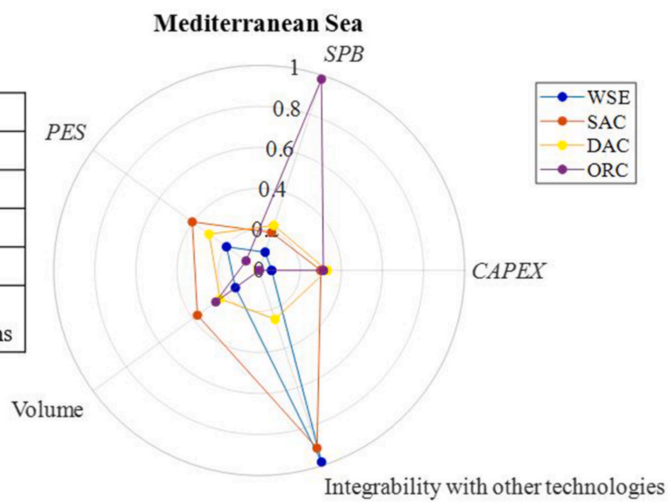

Fig. 18. Evaluation of implemented technologies - Mediterranean Sea.

Property	Value	Unit
CAPEX	4.55	M€
SPB	10.0	Years
PES	3.06	%
Volume	280	m^3
Integrability	48	Number of optimal solutions

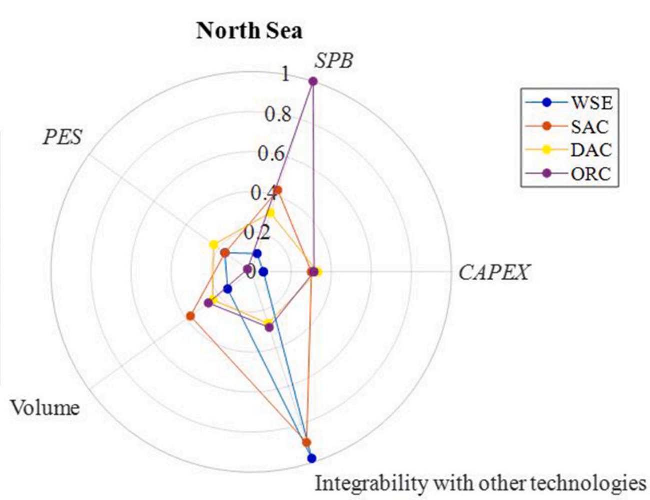

Fig. 19. Evaluation of implemented technologies - North Sea.

Table 5
Minimum and maximum PES values obtainable - Caribbean Sea – large cruise ship.

	WSE		SAC		DAC		ORC		WSE + SAC		WSE + DAC		WSE + ORC		WSE + SAC + DAC		WSE + SAC + ORC		WSE + DAC + ORC		SAC + DAC		SAC + ORC		DAC + ORC		SAC + DAC + ORC	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
WSE	0.53	0.83	0.90	3.63	0.80	1.80	0.64	1.47	–	–	–	–	–	–	–	–	–	–	–	–	1.16	4.44	1.01	3.61	0.91	2.41	1.27	4.36
SAC	0.90	3.63	0.37	2.61	0.69	3.78	0.47	2.45	–	–	1.16	4.44	1.01	3.61	–	–	–	–	1.27	4.36	–	–	–	–	0.79	3.64	–	–
DAC	0.80	1.80	0.69	3.78	0.31	1.33	0.44	1.94	1.16	4.44	–	–	0.91	2.41	–	–	1.27	4.36	–	–	–	–	0.79	3.64	–	–	–	–
ORC	0.64	1.47	0.47	2.45	0.44	1.94	0.12	0.66	1.01	3.61	0.91	2.41	–	–	1.27	4.36	–	–	–	–	0.79	3.64	–	–	–	–	–	–

Table 6
Minimum and maximum PES values obtainable - Mediterranean Sea – large cruise ship.

	WSE		SAC		DAC		ORC		WSE + SAC		WSE + DAC		WSE + ORC		WSE + SAC + DAC		WSE + SAC + ORC		WSE + DAC + ORC		SAC + DAC		SAC + ORC		DAC + ORC		SAC + DAC + ORC	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
WSE	0.49	0.77	0.84	3.09	0.75	1.57	0.62	1.57	–	–	–	–	–	–	–	–	–	–	–	–	1.08	3.36	0.92	3.07	0.86	2.31	1.10	3.31
SAC	0.84	3.09	0.32	2.23	0.64	2.85	0.30	2.12	–	–	1.08	3.36	0.92	3.07	–	–	–	–	1.10	3.31	–	–	–	–	0.56	2.76	–	–
DAC	0.75	1.57	0.64	2.85	0.33	1.21	0.43	1.93	1.08	3.36	–	–	0.86	2.31	–	–	1.10	3.31	–	–	–	–	0.56	2.76	–	–	–	–
ORC	0.62	1.57	0.30	2.12	0.43	1.93	0.12	0.88	0.92	3.07	0.86	2.31	–	–	1.10	3.31	–	–	–	–	0.56	2.76	–	–	–	–	–	–

Table 7
Minimum and maximum PES values obtainable - North Sea – large cruise ship.

	WSE		SAC		DAC		ORC		WSE + SAC		WSE + DAC		WSE + ORC		WSE + SAC + DAC		WSE + SAC + ORC		WSE + DAC + ORC		SAC + DAC		SAC + ORC		DAC + ORC		SAC + DAC + ORC	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
WSE	0.39	1.68	0.54	2.88	0.54	2.40	0.42	2.17	–	–	–	–	–	–	–	–	–	–	–	–	0.69	2.90	0.53	2.93	0.55	2.80	0.62	3.06
SAC	0.54	2.88	0.14	2.20	0.34	2.44	0.12	2.24	–	–	0.69	2.90	0.53	2.93	–	–	–	–	0.62	3.06	–	–	–	–	0.30	2.68	–	–
DAC	0.54	2.40	0.34	2.44	0.21	2.06	0.21	2.45	0.69	2.90	–	–	0.55	2.80	–	–	0.62	3.06	–	–	–	–	0.30	2.68	–	–	–	–
ORC	0.42	2.17	0.12	2.24	0.21	2.45	0.02	1.53	0.53	2.93	0.55	2.80	–	–	0.62	3.06	–	–	–	–	0.30	2.68	–	–	–	–	–	–

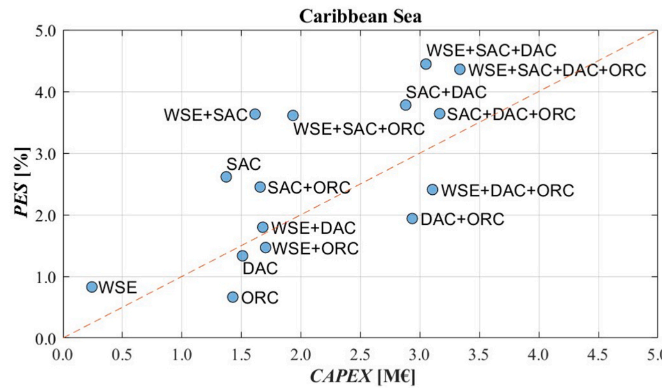

Fig. 20. *CAPEX-PES* performance - Caribbean Sea.

constraint especially in the case in which the refurbishment of an existing ship is considered. Furthermore, since a control logic has been provided for which priority of switching on has been given to the DAC, compared to the SAC, if both can be activated (given the best coefficient of performance obtainable), the greater number of operating hours for the SAC is obtained in correspondence with the lower sizes for the DAC, as shown in Fig. 16.

For the study carried out, different technologies are considered and analysed. As demonstrated, the scenario strongly influences the performance of the implemented technologies. For this reason, an evaluation of the single technology was carried out by considering economic performance, occupied spaces, energy, and integration with other technologies. Results are reported in Figs. 17–19. Specifically, the 5 parameters are normalized by considering the reference values reported in the related table. Integrability with other technologies was evaluated as the frequency with which the specific technology is present in the optimal solutions of the Pareto front. Therefore, it can be understood that the greater the corresponding value, the greater the number of configurations considered as optimal, in which the implementation has been hypothesized. From a careful analysis the following considerations can be deduced.

- WSE turns out to be the best performing technology among those analysed, thanks to the low investment costs, the low volume required for installation, and the high degree of integration with other technologies - it uses steam, but at the outlet it allows the remaining amount of steam for heating the HT circuit, thus allowing greater use of the technologies powered by this source.
- ORC appears to be a technology to be implemented mainly in cold climates, where better performances can be achieved, and integration with different thermally activated technologies for the production of cooling energy is not always required. However, the integrability with other technologies or the implementation of the LT circuit need to be considered. Low PES values achievable in all climates determines high payback times.
- The single effect absorption chiller appears to be a technology that is easier to implement than the double effect one, due to the high demands for steam on board the ship - the main energy carrier - allowing to consider close investment costs, but higher PES and a lower SPB. This is valid for the Caribbean and Mediterranean Sea, while for the North Sea DAC outperform SAC.

The minimum (min) and maximum (max) values of primary energy savings achievable through individual technologies or a combination of multiple technologies are reported in Table 5, 6 and 7 for the Caribbean, Mediterranean and North Seas, respectively. The objective is to provide insights into the potential ranges, offering a tool in the early design phase to anticipate the possible outcomes that can be achieved. The results also consider the exploitation of the LT circuit, since the

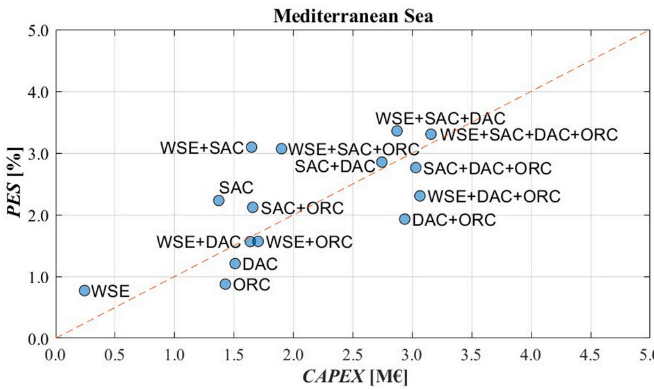

Fig. 21. *CAPEX-PES* performance - Mediterranean Sea.

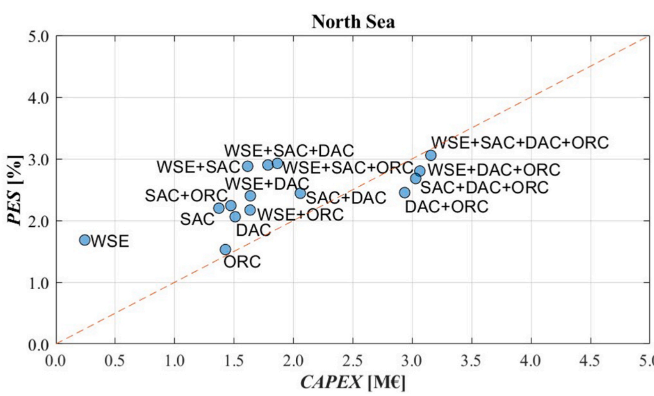

Fig. 22. *CAPEX-PES* performance - North Sea.

enhancement of ships should rely on the exploitation of all the energy vectors on-board. Moreover, since only few users are hypothesized to be powered by the low temperature hot water, a not negligible amount of thermal energy is still dumped. Future studies should analyse solutions for the total exploitation of this energy source, in such a way as to increase the total efficiency of the system (electrical and thermal exploitation) and reduce the total energy demand.

A qualitative evaluation of the performance of the different technology mixes is shown in Figs. 20–22 for the Caribbean Sea, the Mediterranean Sea, and the North Sea, respectively. Specifically, CAPEX and PES are reported, with the bisector (dashed red). These results allow, in a qualitative and visual manner, to identify which solutions allow greater benefits from an energy saving/investment cost point of view for the three scenarios considered. Results are provided considering also the exploitation of the LT circuit. The following indications can be noted.

- For the Caribbean and Mediterranean Seas, the configuration with WSE, SAC, and DAC is the optimal from an energy point of view, and at the same time less expensive than other configurations (i.e. WSE + SAC + DAC + ORC, SAC + DAC + ORC, WSE + DAC + ORC for the Caribbean Sea and WSE + SAC + DAC + ORC, SAC + DAC + ORC, WSE + DAC + ORC, DAC + ORC for the Mediterranean Sea).
- For the North Sea, the optimal solution from an energy-economic point of view is the configuration with the implementation of WSE and SAC with energy savings comparable to those of the most advantageous solution from an energy point of view.
- Most of the configurations implemented in the North Sea are located above the bisector, indicating a higher energy contribution compared to the cases of the Mediterranean Sea, and the Caribbean Sea. Note above all that configurations with the implementation of ORC allow higher PES values to be achieved, thanks to the better efficiencies achieved. If the influence of LT exploitation is not considered, only the configurations with WSE and WSE + ORC (small size) are located above the bisector.

A quantitative evaluation of the configurations is indeed reported in Table 8, where equation (8) – EEVI - and equation (10) – EUPI - are considered. Specifically, 3 different scenarios are analysed.

- Existing: the refurbishment of cruise ship is considered; therefore, due to space constraints greater weight was given to the volume rate (50 % of the rating), with the other 50 % equally divided between energy savings (PES) and economic impact (CAPEX). This rating considers the energy, economic and volume index – EEVI - for existing cruise ships.
- New built: the design of new ships is considered; therefore, due to the energy targets that need to be addressed, greater weight was given to the PES rate (50 % of the rating), with the other 50 % equally divided between economic impact (CAPEX) and volume occupied. This rating considers the EEVI for new cruise ships.
- Energy use: in this case, in addition to considering PES, CAPEX, and volume, also the energy use was evaluated, with configurations that present a lower energy consumption that are rewarded, being able to consider the implementation of further technologies or better exploitation of excess thermal energy. This rating considers the energy utilization and performance index – EUPI.

Table 8
Configuration ranking - large cruise ship.

Configuration	Caribbean Sea			Mediterranean Sea			North Sea		
	Existing (EEVI)	New built (EEVI)	Energy use (EUPI)	Existing (EEVI)	New built (EEVI)	Energy use (EUPI)	Existing (EEVI)	New built (EEVI)	Energy use (EUPI)
WSE	●●●	●●●	●●●	●●●	●●●	●●●	●●●●	●●●	●●●
WSE + SAC	●●●	●●●	●●	●●●	●●●	●●	●●	●●●	●●
WSE + DAC	●●●	●●	●●	●●	●●	●●	●●●	●●●	●●●
WSE + ORC	●●	●●	●●	●●	●●	●●	●●	●●●	●●
WSE + SAC + DAC	●●	●●●	●●	●●	●●●	●●	●●	●●●	●●
WSE + SAC + ORC	●●	●●●	●●	●●	●●●	●●	●●●	●●●	●●
WSE + DAC + ORC	●●	●●	●●	●	●●	●	●●	●●●	●●
WSE + SAC + DAC + ORC	●●	●●	●●	●	●●	●	●●	●●●	●●
SAC	●●●	●●●	●●●	●●●	●●●	●●	●●●	●●●	●●
SAC + DAC	●●	●●	●●	●●	●●●	●●	●●●	●●●	●●
SAC + ORC	●●	●●	●●	●●	●●●	●●	●●	●●●	●●
SAC + DAC + ORC	●●	●●	●●	●●	●●	●●	●●	●●	●●
DAC	●●●	●●	●●●	●●●	●●●	●●	●●●	●●●	●●●
DAC + ORC	●●	●●	●●	●●	●●	●●	●●	●●	●●
ORC	●●	●●	●●	●●	●●	●●	●●	●●	●●

Table 9
Multiple linear regression coefficients – *PES* – large cruise ship.

	Caribbean Sea		Mediterranean Sea		North Sea	
	Without LT	With LT	Without LT	With LT	Without LT	With LT
β_1	2.19×10^{-3}	2.06×10^{-3}	1.92×10^{-3}	2.07×10^{-3}	0.999×10^{-3}	2.58×10^{-3}
β_2	0.944×10^{-3}	1.90×10^{-3}	-0.162×10^{-3}	1.83×10^{-3}	0.342×10^{-3}	2.54×10^{-3}
β_3	0.440×10^{-3}	0.558×10^{-3}	0.282×10^{-3}	0.432×10^{-3}	0.105×10^{-3}	0.314×10^{-3}
β_4	0.316×10^{-3}	0.327×10^{-3}	0.227×10^{-3}	0.246×10^{-3}	0.110×10^{-3}	0.263×10^{-3}
RMSE	0.446	0.431	0.439	0.499	0.245	0.668

Note that, WSE turns out to be a high-scoring solution in all scenarios; specifically, in the North Sea, implementation alone or in pairs with SAC or DAC or ORC presents a high score for both existing ships and the design of new ones. From an energy use point of view in the three climates evaluated, all the solutions have a rating between fair and sufficient, since none of the proposed configurations excels in the four parameters considered. Moreover, since low primary energy savings can be achieved in North Sea considering all the possible configurations, as depicted in Fig. 22, the highest rating is achieved mostly for configurations with single technologies. The configuration with WSE, SAC, and DAC, preferred for the Mediterranean and Caribbean Seas when only economic (CAPEX) and energy (PES) results are considered, performs less efficiently for existing ships due to its substantial volume, which accounts for half of the final rate. The results reported so far must therefore also be contextualised with respect to the design case in question (existing ship or new ship).

An assessment of the advantages achievable through the integration of cutting-edge technologies like WSE, ORC, SAC, and DAC was undertaken. Specifically, a thorough analysis using multiple linear regression was conducted to evaluate these benefits, distinguishing two configurations: non-use and use of the LT circuit. The analysis allows to obtain coefficients for first approach evaluation, therefore indicative, that can be achieved for PES (in %) considering a period of one year. The analysis relies on the results obtained from simulations and, considering the combination of the different implemented sizes, estimates coefficients β_{xy}. Specifically, the forecast can be considered as:

$$\text{PES} = \beta_1 \cdot \text{WSE} + \beta_2 \cdot \text{ORC} + \beta_3 \cdot \text{SAC} + \beta_4 \cdot \text{DAC} \tag{11}$$

where WSE and ORC are the electrical power expressed in kW_e and SAC and DAC are the cooling power expressed in kW_c. The results are reported in Table 9 for the PES.

From an analysis of the coefficients, it is possible to understand how the LT strongly influences the ORC, and in a less marked way, also the SAC. Specifically, the implementation of the ORC, for climates in which a non-negligible heating demand is present (e.g. Mediterranean Sea and North Sea), must be considered if the LT circuit is also exploited, so as to free up a certain amount of HT to be able to power the technology. The exploitation of the LT circuit influences the DAC operation in the North Sea; indeed, a coefficient almost double compared to the case without LT is obtained, thanks to the greater steam available - fewer integrations for AC and DHW - and the possibility of increasing operation of the technology. The maximum value for the RMSE is obtained in correspondence with the North Sea and the use of LT, since this energy vector strongly influences the use and performance of the different technologies, causing greater forecast errors. The benefit obtainable from the implementation of the SAC and/or DAC is greater in hot climates (e.g. Caribbean Sea) where the higher cooling demand allows for a better exploitation of the production of cooling energy.

The analysis reported so far concerns the results considering the large cruise ship. For the small cruise ship an identical analysis was carried out; however, for brevity of discussion the same tables and figures will not be reported, but the main results and differences will be highlighted. Although smaller in size than the large cruise ship, the main energy need remains propulsion, so only a slight difference between the primary energies is obtained. Specifically, considering the Caribbean Sea, the Mediterranean Sea, and the North Sea, a yearly energy needs of 520, 507 and 599 GWh are obtained for the large cruise ship and 468, 478 and 558 GWh for the small cruise ship. In Table 10 results obtained from the optimization procedure considering the energy, economic and utopia criterion, are reported.

Compared to the large ship, the small cruise ship analysed has, due to its size, a smaller energy system, with four engines and not six, characterized by a lower nominal power. This determines a lower availability of heat recovery, both in terms of power and in terms of available flowrates (a fundamental parameter for defining the correct functioning of the on-board technologies). This implies that smaller sizes can be implemented on-board, if compared to the previous case. Furthermore, the exploitation of the LT circuit is already foreseen, so it will not be possible to define the impact of a control strategy in which the latter is implemented, resulting in fewer energy, economic and environmental savings achievable. The PES values obtained are lower than the cases of the large cruise ship; however, it must be taken into account that the request for propulsion has a significant weight in this case, indeed, considering the value of the PES without propulsion, the saving becomes of several percentage points, especially highlighting that the CAPEX expected in this case has also undergone a reduction, while obtaining non-negligible emissions avoided into the atmosphere. The mix of technologies obtained for each scenario and criterion is in line with the

Table 10
Optimization results - economic, energy and utopia criterion. Small cruise ship.

	Caribbean Sea			Mediterranean Sea			North Sea		
	Econ	Energy	Utopia	Econ	Energy	Utopia	Econ	Energy	Utopia
***PES* w/prop** (%)	0.42	3.33	2.22	0.37	2.21	1.76	0.47	1.83	1.64
***PES* w/o prop** (%)	0.77	6.03	4.01	0.73	4.36	3.47	1.08	4.24	3.79
CAPEX (M€)	0.12	2.57	0.82	0.12	2.06	0.71	0.12	2.07	0.71
ΔOPEX (k€)	108	841	559	96.2	568	452	145	554	497
Volume (m^3)	11.3	146	75.1	11.3	139	62.0	11.3	146	62.0
ΔCO_2 (t)	533	4198	2797	475	2840	2261	692	2744	2452
SPB (years)	1.15	3.06	1.47	1.29	3.63	1.57	0.86	3.74	1.43
WSE power (kW)	156	314	470	156	470	470	156	470	470
SAC cooling (kW)	0	2883	1846	0	1846	1477	0	3428	1477
DAC cooling (kW)	0	3868	0	0	2813	0	0	527	0
ORC power (kW)	0	0	0	0	30	0	0	122	0

Table 11
Multiple linear regression coefficients – *PES* – small cruise ship.

	Caribbean Sea	Mediterranean Sea	North Sea
β_1	3.31×10^{-3}	2.61×10^{-3}	2.49×10^{-3}
β_2	1.11×10^{-3}	2.02×10^{-3}	2.99×10^{-3}
β_3	0.212×10^{-3}	0.176×10^{-3}	0.118×10^{-3}
β_4	0.433×10^{-3}	0.234×10^{-3}	0.134×10^{-3}
RMSE	0.676	0.515	0.483

cases of the ship previously analysed; however, the sizes have undergone different proportions. The tendency towards choosing a larger size of the WSE with consequent smaller sizes for the other technologies is obtained. Also for the case of the North Sea, as well as described for larger cruise ship, it is more convenient to consider the solution of the utopia point, compared to the energy criterion, with a reduction in energy savings of less than 0.2 % but an economic saving of 1.36 M€.

Table 11 shows the coefficients and the RMSE obtained from the multiple linear regression to evaluate the PES in the case of a small cruise ship. Unlike the analysis carried out previously, it is not possible to distinguish a case with and without exploitation of LT circuit.

Notice how the ORC implementation coefficient increases when moving from warm to colder climates. Furthermore, while in the previous analysis a greater dependence on the SAC compared to the DAC could be highlighted, in this case the opposite is noted. Specifically, Fig. 23 shows the self-sufficiency for cooling energy implementing different sizes of SAC and DAC, varying the implemented sizes of WSE and ORC in the Caribbean Sea. Similar results can be obtained for the Mediterranean and North Seas. It must be highlighted that this higher dependence on DAC reduces when considering colder climates, until almost equivalent coefficients are obtained in the case of the North Sea.

For the sake of brevity, the main results obtained for the small cruise ship and any differences compared to the case with the large cruise ship are summarized below.

- The lower availability of thermal power and flowrate to be considered for heat recovery above all influences the ORC sizes that can be implemented; however, these smaller sizes integrate better with the entire energy system compared to the large cruise ship. Indeed, in the Mediterranean Sea some of the optimal solutions already include an ORC - in the large ship none (see Fig. 18) - while in the North Sea 56 % of the optimal solutions include the implementation of an ORC.
- DAC increases its integration with other technologies in the Caribbean Sea, with approximately 60 % of the optimal solutions featuring its implementation; however, it is the least integrated technology in the North Sea.
- For the Caribbean Sea scenario, all the solution are located above the bisector (CAPEX-PES), except SAC + DAC, SAC, and SAC + ORC. The case is different in the Mediterranean and the North Sea; indeed, in the Mediterranean Sea many solutions are located under the bisector, with the optimal configuration being WSE + SAC - therefore respecting the utopian criterion. In the case of the North Sea only the configurations with mix in which WSE is implemented are located above the bisector - except WSE + DAC - with the optimal solution also in this case being WSE + SAC.
- Despite being the most advantageous technology, the WSE implemented on the small ship does not present such high-ranking values as in the case of the large cruise ship, especially if the scenario with the North Sea is considered.

4. Conclusion

Energy efficiency in the maritime sector foresees important targets to be achieved, with the aim of providing an important contribution to the decarbonization. From this point of view, scientific research can be today supported by: i) the use of dynamic simulations for assessing the ship energy system performance; and ii) the system multi-objective optimization analysis to obtain different optimal plant layouts and control strategies also from economic profitability purposes. Diverse computer tools are adopted to these aims (e.g. Autodesk Revit, EnergyPlus, MatLab and TRNSYS). Note that, through this approach specific comparisons can be also achieved for different possible system configurations and/or climatic conditions.

Target of this paper is to provide, through the above mentioned tools, new design criteria for the energy design of new and existing ships by analysing different energy saving technologies and control strategies. For this target new performance indexes and tools are presented in this paper:

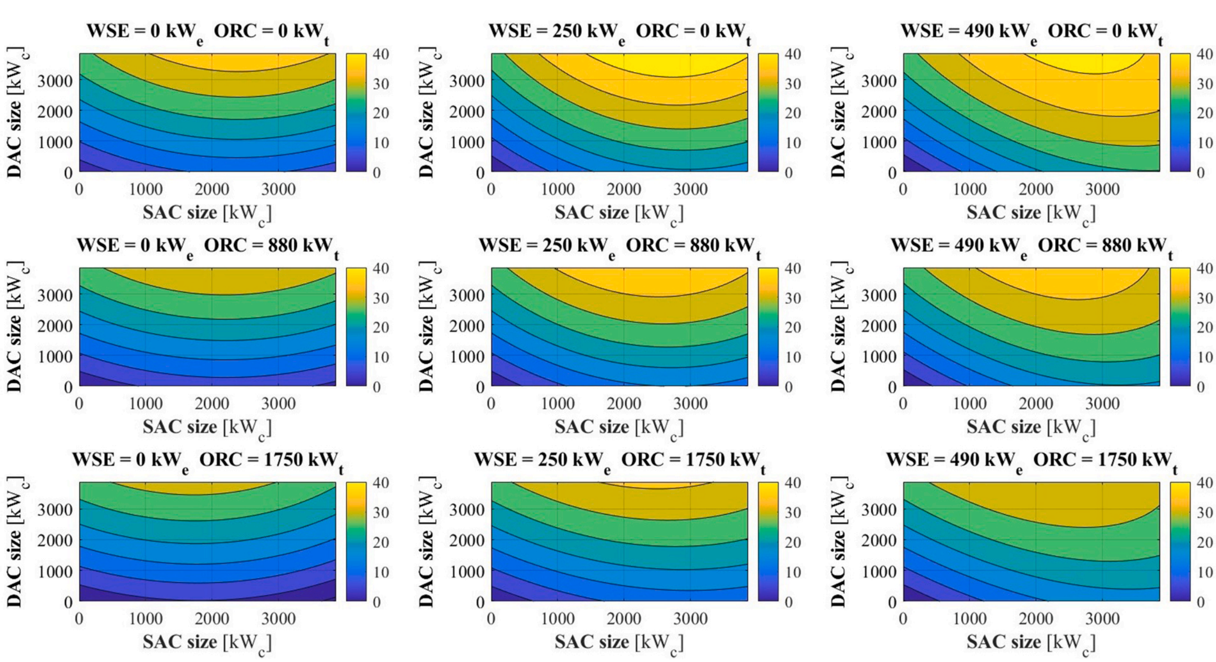

Fig. 23. Contour plot: cooling demand self-sufficiency [%] - Caribbean Sea - small cruise ship.

- EEVI (Energy, Economic and Volume Index) and EUPI (Energy Utilization and Performance Index). These indexes are defined, by taking into account different features of the considered technologies (e.g. the economic saving, used energy, PES, occupied volume). A ranking of the examined energy system configurations can be provided, by distinguishing new or existing ships and by considering different climate conditions.
- PES prediction tool obtained through a suitable multiple linear regression analysis. Results are achieved by varying typologies and sizes of the investigated technologies.

To show the capability of the adopted approach different case studies are developed. Specifically, a large and a small cruise ship are modelled. The related energy and economic performances are assessed for three different weather conditions (hot, temperate and cold) by considering different routes in the Caribbean, Mediterranean, and North Seas. Two innovative energy technologies are investigated for the extra electricity production: i) organic Rankine cycle units; and ii) wet steam screw expanders. For the sustainable cooling energy production, single and double effect absorption chillers are analysed. The energy required to activate all these devices is obtained by the waste heat recoveries of the on-board combustion engines. The most significant obtained results are:

- The sea water temperature strongly influences the performance of the implemented organic Rankine cycle units. In particular, this solution is strongly recommended in cold climates (North Sea), while for small cruise ships also in temperate climates (Mediterranean Sea).
- The use of the low temperature waste heat for pre- and re-heating in the HVAC system and for domestic hot water production resulted very convenient in cold climates where a significant amount of the recovered heat is observed. Here, a PES increase (up to 2%) is detected respect to the case without low temperature heat exploitation.
- The highest PESs are obtained in hot climates where the cooling needs can be balanced by absorption chillers fed by medium temperature waste heat (avoiding the use of electric chillers).
- The implementation of a wet steam expander for extra electricity production, fed through high temperature waste heat (steam produced by engines exhaust gases), resulted the most convenient energy saving technology for both large and small cruise ships. This result is also due to the rather low investment costs, required volumes, and weights of this technology.

The proposed methodology can be applied to all types of ships, energy saving technologies, and alternative fuels. Results can be useful to shipbuilders and shipowners by providing new design criteria for the sustainability of the maritime sector as well as guidance for regulatory policies.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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