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Techno environmental assessment of Flettner rotor as assistance propulsion system for LH_2 tanker ship fuelled by hydrogen

Abdullah NFNR Alkhaledi [a,b,*], Suresh Sampath [a], Pericles Pilidis [a]

[a] *Thermal Power & Propulsion Engineering, Cranfield University, Bedfordshire MK430AL, United Kingdom*
[b] *Department of Automotive and Marine Engineering, College of Technological Studies, PAAET, P.O. Box 42325, Shuwaikh, Kuwait*

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ABSTRACT

This study presents a novel design and development of a 280,000 m^3 liquefied hydrogen tanker ship by implementing a set of 6 Flettner rotors as an assistance propulsion system in conjunction with a combined-cycle gas turbine fuelled by hydrogen as a prime mover. The study includes assessment of the technical and environmental aspects of the developed design. Furthermore, an established method was applied to simulate the LH_2 tanker in different voyages and conditions to investigate the benefits of harnessing wind energy to assist combined-cycle gas turbine in terms of performance and emission reduction based on engine behaviour for different voyages under loaded and unloaded, normal as well as 6 % degraded engine, and varying ambient conditions. The results indicate that implementing a set of 6 Flettner rotors for the LH_2 tanker ship has the potential to positively impact the performance and lead to environmental benefits. A maximum contribution power of around 1.8 MW was achieved in the winter season owing to high wind speed and favourable wind direction. This power could save approximately 3.6 % of the combined-cycle gas turbine total output power (50 MW) and cause a 3.5 % reduction in NOx emissions.

Introduction

Limiting the overall global temperature rise to 1.5 degreesC to save the global environment, as agreed by a majority of member nations at the 2021 UN Climate Change Conference held in Glasgow, represents a significant challenge [1]. In April 2018, The International Maritime Organization (IMO), London, adopted the initial GHG strategy that included, among others, reducing GHG emissions from international shipping by at least 50 %, in comparison to emissions in 2008, by 2050. Additionally, the initial GHG strategy set a target to reduce CO_2 emissions from shipping by at least 40 % by 2030 and 70 % by 2050, in comparison to emissions in 2008 [2]. Furthermore, the United Kingdom published the Clean Maritime Plan in July 2019 as an environmental route map to achieve the UK vision of maritime 2050. The government published it to transition to a future zero-emission shipping in UK waters with the expectation that by 2025 all-new vessels in UK waters will be designed with zero-emission propulsion capability. The plan suggested that hydrogen fuel and renewable energy for vessel propulsion systems could be substantial and applicable solutions in the global transition to zero-emission shipping and transportation in the maritime sector [3].

Renewable energy technologies are attractive options to achieve the zero-emission target in the marine sector. Hence, there is a global effort to develop the use of sustainable renewable energy as a ship's propulsion technology. However, renewable energy is an old concept and modern technology; in the past 150 years, there has been significant transformation in the propulsion energy sources of ships, such as switching from the sail (renewable energy) to using coal, heavy fuel oil (HFO) and marine diesel oil (MDO).

Abbreviations: COGAS, Combined-cycle gas and steam turbine; LH_2, Liquid hydrogen; IMO, International Maritime Organisation; NOx, Nitrogen oxide; CO_2, Carbon Dioxide; CO, Carbon monoxide; SOx, Sulphur oxide; N–S–L, Normal engine – Summer season – Loaded condition; *N*-M−L, Normal engine – Middle season – Loaded condition; *N*-W-L, Normal engine – Winter season – Loaded condition; D-S-L, Degraded engine – Summer season – Loaded condition; D-M−L, Degraded engine – Middle season – Loaded condition; D-W-L, Degraded engine – Winter season – Loaded condition; N–S–UN, Normal engine – Summer season – Unloaded condition; *N*-M−UN, Normal engine – Middle season – Unloaded condition; *N*-W-UN, Normal engine – Winter season – Unloaded condition; D-S-UN, Degraded engine – Summer season – Unloaded condition; D-M−UN, Degraded engine – Middle season – Unloaded condition; D-W-UN, Degraded engine – Winter season – Unloaded condition.

* Corresponding author at: Thermal Power & Propulsion Engineering, Cranfield University, Bedfordshire MK430AL, United Kingdom.
E-mail address: a.alkhaledi@cranfield.ac.uk (A. NFNR Alkhaledi).

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Consequently, utilising clean hydrogen and renewable energy can be promising solutions for global decarbonisation and achieving climate change targets [4,5]. Furthermore, application of renewable energy technologies as a complementary propulsion system for ships could be an effective solution to overcome the negative impact of fossil fuel consumption and emissions [6]. Wind assisted propulsion obtained through application of Flettner rotor technology has significant potential as a ship assistance propulsion system to the ship's prime mover in saving fuel consumption, increasing thermal efficiency, and decreasing emissions [5]. Therefore, a hydrogen fuelled combined cycle power plant in conjunction with Flettner rotor technology as a new concept could be a successful alternative ship propulsion system to reach the maritime sector's high-efficiency and low-emission targets. To achieves maritime emission reduction targets, there is a need for development of alternative ship propulsion system designs and assess them in terms of the performance and environmental impact. For example, design and development of a clean ship prime mover such as a liquefied hydrogen tanker ship fuelled by hydrogen and powered by combined cycle gas turbine as the ship prime mover in conjunction with a sustainable renewable energy powered propulsion system as an assistance to the prime mover could help ensure sustainability and achievement of maritime emission reduction targets [7,5]. The achievement of sustainability by utilising renewable energy technologies as assistance propulsion systems for several types of ships in the marine sector could be a successful solution to increase fuel saving, increase the main propulsion system thermal efficiency and reach the future maritime zero-emission targets. Previously completed research works have focused on designing and evaluating Flettner rotors as an assistance marine propulsion system. In 2018 Talluri et al. [5] applied a Techno-economic, Environmental and Risk Assessment (TERA) methodology to assess the performance and economic benefits of utilising a 4.5 MW simple cycle, twin-shaft marine gas turbine fuelled by natural gas and twin-diesel engines, each of 3 MW rating, operating on marine diesel oil as ship power plants in conjunction with three Flettner towers. The results show that installing three Flettner towers on commercial vessels could save 20 % in terms of fuel consumption and similar percentage in emission reduction. Additionally, Traut et al., [8] assessed the potential for harnessing wind power for shipping using a Flettner tower and towing kite technology in five trade routes. The results show that the average savings attained by applying the propulsive power contribution of the kite technology is lower when compared to propulsive power contribution of single Flettner rotor technology [8]. Zhang P. et al. [9] investigated the environmental and economic advantages of the Flettner rotor and parafoil systems based on the TERA framework. Bordogna et al. [10] discussed the aerodynamic performance and efficiency of Flettner rotors while mainly focusing on the fuel-saving potential during ship operation. Nyanya et al. [11] optimised the installation of a combination of wind sail and solar power systems as an assistance propulsion system for a bulk carrier using two models. The first model optimised the rigid wind sail angle under varying wind conditions and the second model optimised the available deck area of the ship assigned to wind and solar systems. The optimisation results show that maximizing renewable power can achieve CO2 emissions reduction by 36 % when compared to the ship without renewable energy technologies. Also, the results show that the ship could be only dependent on wind and solar energy captured onboard if the shipping speed was reduced to 56 % compared with the ship's original speed. In 2016 Talluri et al. [12] applied a techno-economic and environmental assessment framework for a two Vertical Axis Wind Turbine (VAWT) on the deck of a ship as an assistance propulsion system in conjunction with other propulsion technologies such as diesel engine and gas turbine to achieve the fuel saving and the global emission reduction targets. The work aimed to demonstrate the consistent assessment potential of the method in the context of the VAWT as an assistance propulsion system and its application. The results of this study show that the performance of the two wind turbines can contribute 14 % to 16 % as a fuel savings percentage. Schonborn [13] investigated the potential of utilising a cyclic pitching motion applied at a specific phase angle of the blades on a vertical-axis Darrieus rotor sail to generate a combination of rotational power and propulsive thrust for vessels. This study aims to develop a wind propulsion system that can combine the capability of providing direct thrust in different directions, and at the same time generating rotational power from the wind energy, for onboard electricity generation.

To the best of the authors' knowledge, the design and techno-environmental evaluation of hydrogen-fuelled combined-cycle gas turbines in conjunction with Flettner rotor technology for marine applications has not been considered yet. This study aims to design and assess the performance and environmental impacts of a novel hydrogen-tanker ship powered by hydrogen-fuelled combined-cycle gas turbines in off-design conditions in conjunction with 6 Flettner rotors as assistance sustainable propulsion system, using the techno-environmental analysis method.

Flettner rotors

The Flettner rotor is a pioneering technology invented by Anton Flettner in the 1920 s to serve as an alternative marine propulsion technology to the traditional sails that were in use for shipping at that time [14]. Historically, Flettner rotors were utilised and examined as a propulsion system for ships, but the technology was deserted after the manufacture of steam and diesel engines became widespread. However, consequent to the shipping crisis of the 1980 s, the shipping sector reconsidered utilising Flettner rotors [15]. Recently, the shipping sector is focused again on developing and utilising this technology as an alternative propulsion solution to achieve the maritime zero-emission target. In 2010, the Flettner rotor was further developed by ENERCON which has launched the E-SHIP1 as its first trial ship [16]. Lately, the Flettner rotors have been classified as a promising alternative maritime shipping propulsion system owing to their ability to significantly lower fuel consumption and the corresponding emission reduction [17]. The physical principle of the Flettner rotor is that rotations induce the Magnus effect to produce thrust perpendicular to the wind direction. The generated force is linearly related to the wind speed and direction resulting in an affirmative forward thrust at the various ship/wind speeds [18]. Several studies considered the Flettner rotor's general characteristics and aerodynamic performance using computational fluid dynamics (CFD) [19,20]. Lu R. et al. [21] compared three wind-assisted ship propulsion technologies, viz. the Flettner rotor, a wind sail, and the DynaRig concept, in the Aframax Oil Tanker in the route between Gabon and Canada. This study revealed that the ship type, speed, voyage routes, and weather conditions significantly influence the extent of fuel savings possible. Moreover, the results showed that the Flettner rotor achieved the most significant fuel-saving percentage in comparison with the other technologies [21]. In 2015, a 9700 DWT Ro-Ro Carrier achieved an annual 5 % fuel saving after installing two Norsepower rotors with a dimension of 18 m in height and 3 m in diameter (www.norsepower.com). This research study examines the ability of the Flettner rotors to assist the ship prime mover increase the engine's thermal efficiency thereby reducing fuel consumption and maritime emission, in different voyages as well as conditions.

Methodologies

In 2021, an authentic method was established by Alkhaledi A.N. et al., [4] and [7] to design a 370 m long, 75 m wide LH_2 tanker ship with a total capacity of 280,000 m^3 of liquefied hydrogen powered by COGAS fuelled by hydrogen as a main propulsion system for the LH2 tanker. In this study a set of 6 Flettner rotors to be installed on the deck of the designed ship as a clean assistance propulsion system. An analytically expanded methodology was applied to evaluate the performance and emission of the suggested designs of the LH_2 tanker ship using a techno-environmental assessment framework by employing a

TERA computational method developed for marine propulsion systems [22]. In this study, a COGAS power plant fuelled by hydrogen [7] in conjunction with 6 Flettner rotors was developed as a novel integrated propulsion system for an LH_2 tanker ship design to achieve the twin objectives of high efficiency and eliminate the carbon footprint by integrating three different technologies (gas turbine fuelled by hydrogen, heat recovery system and Flettner rotors as clean sustainable technology). This integration represents a developed and efficient propulsion system for large ships compared with the current unclean propulsion systems in the maritime sector. The method developed in this study will assist the implementation of the design of a COGAS power plant fuelled by Hydrogen as the prime mover system and assisted by sustainable renewable energy technology to increase the prime mover thermal efficiency and reduce the engine emissions for LH_2 carrier vessels. Several numerical design models and simulation tools were employed to integrate the Flettner towers with the LH_2 tanker ship hull and assess this design in terms of LH_2 tanker ship engine performance and emissions. In terms of design, SOLIDWORKS software was used to integrate all the 6 Flettner towers with the LH_2 tanker ship hull. Moreover, COGAS power plant fuelled by hydrogen as the prime mover was designed and examined using in-house "TURBOMATCH gas turbine performance code" [23] and MATLAB software [24]. After the design of the LH_2 tanker ship integrated with a set of 6 Flettner rotors and the COGAS engine examination, the inclusive ship design was simulated. The purpose of the simulation was to investigate the Flettner towers' harnessing into the prime mover of the LH_2 tanker ship in terms of COGAS fuelled by hydrogen performance and emissions in different ambient conditions and voyages using in-house "Poseidon" Cranfield university simulation software.

In addition, the evaluation of the ship's performance and emissions analysis takes into account the influence of the cargo weight, which is estimated as 20,000 tonnes [4], and a degradation of 6 % in the case of COGAS fuelled power plant as a ship prime mover [25]. Furthermore, the assessment offered a techno-environmental evaluation method to be an applicable method for evaluating the capability of the suggested LH_2 tanker ship to meet the emission reduction target with a highly effective integrated ship propulsion system.

Design philosophy

The renewable energy enhancement model is designed using a Flettner rotor model, considering the technology size, weight, and distance between towers based on the LH_2 tanker ship size. A set of 6 Flettner rotors was installed as an assistance propulsion system on the deck of the LH_2 tanker ship, which was designed and assessed by [4,7]. The Flettner towers were designed as an assistance propulsion system for the COGAS power plant prime mover of the LH_2 tanker ship fuelled by hydrogen. Each Flettner rotor is 8 m in diameter, 40 m in height, and equipped with a 12 m rotor disc; the dimensions were chosen based on the ship size and deck area. Technically, the design spacing distance between each Flettner tower is equal to one tower height, which is 40 m. This distance ensures avoidance of aerodynamic interference between each other [5]. Moreover, the ship's overall length being only 370 m is a serious limitation of the deck area and there is no room to install additional Flettner towers. Additional design details are provided in the following sections.

Techno-environmental modelling modules

Vessel module

A new design of LH_2 carrier vessels was designed and simulated in this study. The modern JAMILA ship design includes a COGAS power plant as the ship prime mover and a set of 6 Flettner rotors as an assistance propulsion system. This research study is an assessment of a LH_2 tanker ship that is 370 m long, 75 m wide, and has a draft of 9.263 m and 10.012 m under unloaded and fully loaded conditions, respectively. The fully loaded displacement tonnage is 230,000 tonnes of liquefied hydrogen. Table 1 presents the main characteristics of the new design of liquefied hydrogen carrier ship.

In addition, 6 Flettner rotors with dimensions of 40 m height and 8 m diameter were installed on the ship deck to function as an assistance propulsion system to the ship's prime mover, which is a 50 MW single pressure combined-cycle gas turbine, to achieve the fuel-saving and emission reduction targets. The main characteristics of the LH_2 tanker ship have been described in detail in reference [4]. However, from the ship's stability point of view, considering the lightweight of the Flettner rotors in comparison to the LH_2 tanker's overall size and weight, the installation of the 6 Flettner towers is not expected to influence the ship's stability performance or maximum allowable vessel displacement [4]. To reach the simulation accuracy target for the LH_2 tanker in this research, the authors have assumed that the ship maintains a maximum operating speed of 18 knots during all voyages and follows linear and direct routes with no weather related or physical, geographical obstructions during the different simulated voyages.

Prime mover and Flettner rotor module

The LH_2 tanker ship simulated in this study, which has been named as JAMILA ship, is equipped with a prime mover of 50 MW single pressure non-reheat combined-cycle gas turbine fuelled by hydrogen to achieve the high efficiency and low emission targets; this prime mover and propeller module are described in detail in reference [7]. The characteristics of the gas turbine and steam cycles are presented in Tables 2 and 3, respectively.

Furthermore, six Flettner rotors were designed, simulated, and located based on the size of the upgraded design of the liquefied hydrogen ship. The Flettner rotors with 40 m height, 8 m diameter, 6.3 spin ratio, and 12 m diameter rotor disc function as an assistance propulsion system with COGAS to achieve the optimum output power from the wind energy technology and increase the propulsion system thermal efficiency by decreasing the prime mover fuel consumption and emissions. The spin ratio of the Flettner rotor was assumed to be 6.3 in this study based on iterative calculations for a different spin ratio using the marine gas turbine performance application and simulation software

Table 1
Main characteristics of the simulated liquid hydrogen (LH2) tanker [4,7,25].

LH2 tanker parameters	Values	Units
Class	JAMILA	–
Vessel type	LH2 Tanker	–
Total displacement (Δ_{total})	230,000	tonnes
Lightweight	208,000	tonnes
Deadweight	22,000	tonnes
Length overall (LOA)	370	m
Length between perpendiculars	367.5	m
Length on the waterline	367.9	m
Extreme breadth (*B*)	75	m
Depth (*D*)	35	m
Full-loaded condition		
Draught (*T*)	10.012	m
Block coefficient (C_B)	0.819	–
Prismatic coefficient (*Cp*)	0.824	–
Midship coefficient (*Cm*)	0.995	–
Water plane coefficient (*Cwp*)	0.900	–
Wetted surface area	29,550.906	m^2
Unloaded condition		
Draught (*T*)	9.263	m
Block coefficient (C_B)	0.813	–
Prismatic coefficient (*Cp*)	0.818	–
Midship coefficient (*Cm*)	0.994	–
Water plane coefficient (*Cwp*)	0.894	–
Wetted surface area	28,916.458	m^2
Vessel speed	18	knots
Minimum propulsion power required for the full-load condition	27.3	MW
Output power of combined-cycle gas and steam	50	MW

Table 2
General specifications of a gas turbine cycle [7,25].

Gas turbine cycle	Values	Units
Ambient temperature	288.15	K
Ambient pressure	101.3	kPa
Pressure ratio	23.1	–
Specific fuel consumption	0.07416	kg/kWh
Exhaust gas mass flow rate	84.948	kg/s
Exhaust gas temperature	840.3	K
Turbine inlet temperature	1,550	K
Fuel flow	0.7485	kg/s
Output power	36.2	MW
Thermal efficiency	40.3	%

Table 3
General specifications of a steam cycle [7,25].

Steam plant parameters	Values	Units
Superheated steam temperature (T_a)	559.8	℃
Steam pressure (P_S)	60	bar
Pinch point temperature difference (ΔT_p)	7.5	℃
Approach point temperature difference (ΔT_a)	20	℃
Steam mass flow rate (m_s)	10.51	kg/s
Condenser pressure (P_{cond})	0.06	bar
Feed water temperature (T_e)	36.2	℃
Steam turbine output power (W_{ST})	14.35	MW
Steam turbine isentropic efficiency (η_{ST})	89.9	%
Pump work (W_{pump})	4.1388	MW

"Poseidon". Table 4 lists the main characteristics of the Flettner rotors. Two forces are generated by the Flettner rotor on board the vessel: the lift force (L) working vertically to the local apparent wind direction and the drag force (D) working in the same direction as the local wind direction. Those forces are expressed using force coefficients which can be estimated using the equations (1), (2), (3), and (4) [26,18,5]. In this study, the lift and drag coefficients related to spin ratio 6.3 equal 12.8 and 4.3, respectively.

$$L = \frac{1}{2}\rho_a A v_a^2 C_L \tag{1}$$

$$D = \frac{1}{2}\rho_a A v_a^2 C_D \tag{2}$$

$$C_L = -0.0046SR^5 + 0.1145SR^4 - 0.9817SR^3 + 3.1309SR^2 - 0.1039SR \tag{3}$$

$$C_D = -0.0017SR^5 + 0.0464SR^4 - 0.4424SR^3 + 1.7243SR^2 - 1.641SR + 0.6375 \tag{4}$$

where ρ_a is the density in kg/m^3, A is a Flettner rotor area in m^2, v_a is apparent wind velocity in m/s, C_L and, C_D are lift and drag coefficients, respectively, and SR is the spin ratio.

Table 4
Flettner rotor characteristics.

Tower features	value	units
Aspect ratio value	5	–
Endplates to cylinder diameter ratio	1.5	–
Spin ratio	6.3	–
Flettner rotor diameter	8	m
Flettner tower height	40	m
Number of Flettner towers	6	–
Distance between each Flettner tower	40	m
Maximum power required to rotate all the towers	0.3	MW
Maximum total output power from all the towers	1.8	MW
Fuel saving percentage achievement	3.6	%
Flettner rotor disc diameter	12	M

Each Flettner rotor needed electric power to rotate around its axis; this power can be estimated using the method explained in reference [26]. The consumed power must be considered in the Flettner rotors performance prediction. This power (p_{req}) can be estimated using equation (5) and (6), where C_p is the power coefficient.

$$c_p = \frac{p_{req}}{0.5\rho_a A v_a^3} \tag{5}$$

$$C_p = 0.0001SR^5 - 0.0004SR^4 + 0.0143SR^3 - 0.0168SR^2 + 0.0234SR \tag{6}$$

Design of the Flettner rotors was undertaken based on the characteristics presented in Table 4; the LH_2 tanker engine performance was estimated assuming the installation of 6 rotors on the ship deck. The space between the installed rotors play a key role in the performance of the Flettner rotors because of the aerodynamic interference between each other which could directly affect the towers' performance. Consequently, based on the size of the ship deck, 40 m spacing, which is equal to the height of one tower, was determined to be the appropriate space between each other on the ship deck to avoid any aerodynamic interference. However, certain assumptions were made to simulate the actual operating conditions under the vessel's new design. First, it was assumed that each tower can achieve its maximum power capability under all weather conditions except during headwind conditions. Second, when the resultant forces generated by the rotors are directed against the ship's direction of motion all the towers are assumed to be out of service and function as additional wind resistance surfaces.

Ship resistance and engine performance estimation

The LH_2 tanker ship resistance model that influences the ship and power requirements in calm water is described in detail in a previous study for propulsion of liquefied hydrogen fuelled LH_2 carrier design [7]. The vessel shape and dimensions of the JAMILA ship lead to the estimation of the total resistance model and power requirements using the Holtrop and Mennen method [27,28]. In this study, the authors have considered the added wave and wind resistance models in addition to the total calm water resistance to increase the accuracy of resistance estimates in loaded and unloaded conditions for the liquefied hydrogen

Table 5
The key input parameters to estimate the total ship resistance and engine power performance for LH2 tanker design [7].

Resistance calculation model parameters	Value	Units
Reynolds number (R_n)	3×10^9	–
Frictional resistance coefficient (C_F)	1.33×10^{-3}	–
The wetted surface area of the bare hull (S_{BH})	28500	m^2
Frictional resistance (R_F)	1671	*KN*
The specific shape of the afterbody coefficient (c)	1	–
The length of the run (L_R)	96.5*m*	*m*
Form factor $(1+k_1)$	1.32	–
Appendage resistance (R_{APP})	49.2	*kN*
Froude number (F_n)	0.1541	–
The angle of the waterline at the bow (i_E)	60.98	Degree
Coefficients values $(C_1, C_2, C_3, , C_5, C_{16})$	5.1,1,0,0.19,0.15	–
The values of m_1, m_4	$-1.85,\ -7.77\times10^{-8}$	–
The wavelength of the dynamic load case (λ)	1.04	–
Wave resistance (R_w)	94.2	*kN*
Correlation allowance coefficient (C_A)	3.311×10^{-4}	–
Correlation resistance (R_A)	390	*kN*
Total resistance (R_T)	2740	*kN*
Power estimation model parameters		
The effective wake fraction (w)	0.213	–
Thrust dedication factor (t)	0.218	–
Relative rotational efficiency (η_R)	99.2	%
Effective horsepower for the ship hull (P_{EH})	25.4	MW
A speed of advance (V_A)	7.28	*m/s*
Propeller thrust required (T_H)	3503.5	*KN*
The ship required thrust horsepower (P_{TH})	26100.6	*MW%*
The hull efficiency (η_H)		

tanker ship in different weather conditions and voyages. Table 5 shows the key input parameters to calculate the total ship resistance and engine performance for the LH2 tanker in this study. More details on these additional resistance modules are presented in previous studies [7,5]. The engine performance model embodied as a leading model in a numerical "Poseidon" software to simulate the performance of LH_2 carrier ship powered by COGAS hydrogen-fuelled in conjunction with the Fletther rotors technology in different voyages and conditions is presented in reference [22]. The engine performance module is described in detail by reference [25].

Weather and voyages conditions module

The ambient temperature of air and sea, sea state, and wind speed between the hydrogen exporting and importing ports are considered the most important input variable in the weather model [22]. For this research, 330 days per year were assumed under three seasons (summer, winter, and autumn) as an operational period of the LH_2 tanker ship to achieve authentic assessment results of the ship performance and emission. The following two voyage routes were selected for the study, viz., Marseille to Algeria (22 h sailing time) and Tangier to Southampton (81 h sailing time). The ports that were expected to transform as future hydrogen hubs and the countries that benefit from extensive sunshine with a coastline were the criteria used to select the voyage routes. The voyages were simulated for all three seasons to achieve authenticity in the engine performance and emission analysis. Considering the existing hydrogen storage technologies in vogue as well as the relatively high boil-off percentage, short voyages not exceeding four days have been considered for the study. The Marseille–Algeria journey showed that the maximum temperature in summer was more than 30 °C, compared to 25 °C for the Tangier–Southampton journey. The maximum temperature during the Marseille–Algeria journey in this season was approximately 22 °C, compared to 24 °C for the Tangier–Southampton journey. In winter, the maximum temperature during the Marseille–Algeria journey was less than 15 °C, compared to 21 °C for the Tangier–Southampton journey. Fig. 1 shows the weather conditions in the three seasons (Winter, Summer and Middle season) during the Tangier–Southampton journeys and Marseille–Algeria [25]. Additional details of the voyage management model is described in reference [22].

Wind routine estimation. The authors used the Climatology of Global Ocean Winds (COGOW) database and the data obtained from Oregon State University's Cooperative Institute for Oceanographic Satellite Studies [29] to extract the wind speed and direction data. The data selection was made based on determining the voyage's itinerary and taking the average wind velocity and direction angle of the wind throughout the one-way voyage in all three seasons in a year, as shown in Table 6. Wind data was determined based on studies over around ten years from September 1999 to October 2009 using the SeaWinds scatterometer. The wind speed and direction data are collected at 10 m above sea level. The approximate errors of the model are ± 1.7 m/s for wind speed and ± 14 degrees for wind direction [29,5].

Table 6
Presents the mean wind speed and direction in three different seasons for the voyage of marseille- algeria and tangier-southampton.Credits (COGOW) database.

Navigation routes	Season	Mean wind speed (V_T) (Knots)	Mean wind direction angle (β) (Deg)
Marseille- Algeria	Mid-season	14	165
	Summer	10.3	157
	Winter	17.5	155
Tangier-Southampton	Mid-season	15	167
	Summer	14	170
	Winter	17	155

Environmental module

In this research, zero-carbon green hydrogen is assumed to be carried in as well as fuel the JAMILA ship, producing a low NOx gaseous emission only [30]. The environmental description of the modules utilised in this research has been described in detail in reference [25]. The simulation of the ship NOx emission was evaluated under the impact of COGAS normal condition and degradation at 6 % for loaded and unloaded ship conditions. Additionally, the 6 Flettner rotors are assumed to be a renewable energy assistance propulsion system to reduce NOx emissions. The simulation of the LH_2 carrier ship was carried out for three different seasons (mid, summer, and winter) in terms of COGAS NOx emission estimation with the ship operation hours for two voyages (Marseille to Algeria) and (Tangier to Southampton). An established method was applied in this study for assessing the NOx output emissions from the LH_2 tanker powered by the hydrogen-fuelled COGAS in conjunction with a Flettner rotors technology in different off-design operation conditions and was predicted using the emission factor estimation method. The emission factor of the hydrogen-fuelled COGAS as a prime mover can be calculated using equation (7) [31]:

$$EF_{i,k} = \left(E_{i,k} \times 10^{-6}\right)\left(\frac{P.V}{R.T} \times \frac{MW_k}{P_p}\right), \tag{7}$$

where $EF_{i,k}$ is the emission factor (g/kWh); i refers to the engine type; k refers to the emission type; E is the concentration of gaseous species (ppm); P is the pressure (N/m^2); V is the engine exhaust flow rate (m^3/h) which, can be calculated using Table 2; R is the ideal gas constant, which equals 8.3145 J/(mol K); T is the exhaust gas temperature (K)

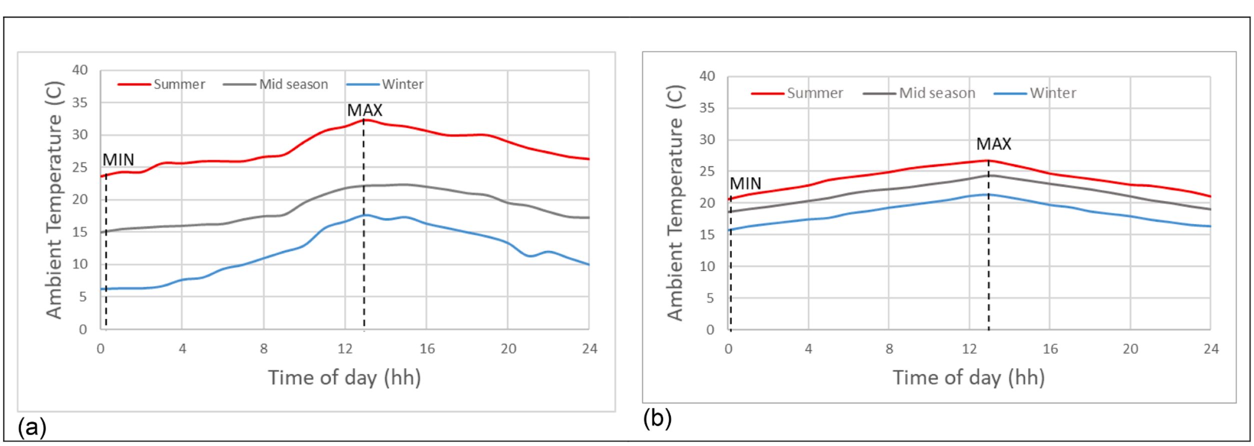

Fig. 1. Weather conditions in different seasons during the (a) Marseille–Algeria and (b) Tangier–Southampton journeys. Credits: timeanddate.com. [25].

which, can be calculated from Table 2; MW is the molecular weight; and P_p is the engine power (kW) which, can be calculated using Tables 2 and 3. The LM2500 + gas turbine, which was used in this study, was not designed to be exclusively fuelled by hydrogen, and there is much scope for future research in this field. For this reason, the authors assumed that the maximum value of the concentration of gaseous species for this type of gas turbine, which is 25 ppm [32]. The input values for the environmental module in this research are presented in Table 7. Consequently, the NOx emission for each journey hour using fuel flow can be calculated by using equation (8) [33]:

$$E_{NOx} = F.F. \times EF_{i,k}, \tag{8}$$

where E_{NOx} is the NOx emission and $F.F.$ is the gas turbine fuel flow per hour during the journey.

Discussions

In this study, the author designed renewable energy technology to assist the JAMILA LH_2 tanker ship; the new design that included 6 Flettner rotors as a ship assistance clean propulsion system will be shown in the next section. The influence of the 6 Flettner rotors in the COGAS performance and emission were analysed based on engine behaviour for different voyages under loaded and unloaded conditions, normal and 6 % degraded engine, and varying ambient conditions to directly compare the prime mover by itself as well as with the assistance of the Flettner rotors as a clean propulsion system. This comparison primarily contributes to the study's techno-environmental assessment outcomes.

New design result description

The LH_2 carrier ship design has been developed by adding 6 Flettner rotors on the ship deck. Fig. 2 shows the new design, which includes 6 Flettner rotors as an assisted propulsion system to achieve high ship performance and low emission targets. The positions of the Flettner rotors onboard the LH_2 carrier ship depend on different factors such as the ship size, design, and empty spaces onboard the ship deck. The location of the LH_2 tanks offers free onboard ship space to install the Flettner rotors technology considering the optimum space between each rotor. As an expected design result, the additional Flettner rotors positively influence the ship's prime mover efficiency and emission results details of which are presented in the ship's performance and environmental sections.

Ship performance analysis

The performance analysis of the liquefied hydrogen tanker ship prime mover in conjunction with a set of 6 Flettner rotors as a wind energy-assisted technology was carried out during two selected voyages. In this study, consideration for the weight and the influence of the Flettner rotator system on the ship's resistance and stability was not taken into account because the Flettner rotor system weight and resistance represent a small percentage compared with the ship's weight and size and in this case, the 6 Flettner rotors have been assumed not to have an impact on the ship performance on terms of ship resistance and stability and this additional weight is assumed to represent a small additional part of the cargo capacity [4]. The result shows that the COGAS as a prime mover could achieve the required power with a ship speed of 18 knots as a maximum design point speed in all conditions except in the journey from Marseille to Algeria in summer with a degraded engine; in summer, the vessel speed required reducing to 17 knots because the required ship power was more than the COGAS power output due to the high ambient temperature and the influence of 6 % degradation [7,25]. For this reason, the ship will be simulated in the journey from Marseille to Algeria under different speeds 18 and 17 knots.

Table 7
The key input values for the environmental module [7,25].

Environmental module main values	Value	Units
The concentration of gaseous species (E)	25	ppm
Engine exhaust flow rate (V)	305.6	(m^3/h)
exhaust gas temperature (T)	840.3	K
Engine power (P_p)	50,000	kW

The influence of the Flettner towers in the overall thermal efficiency of COGAS as ship prime mover in off-design conditions was analysed. The LH_2 carrier ship voyages propelled by COGAS with enhanced Flettner rotors were simulated from Marseille to Algeria in all three seasons (mid, summer, and winter) in terms of power output and thermal efficiency under the impact of normal condition and 6 % degradation for loaded and unloaded ship conditions. Fig. 3 shows that the Flettner rotor attained a maximum contribution power range of 1.7 and 1.8 MW in the winter season in both standard and degraded conditions in the case of a loaded and unloaded ship, respectively, owing to the high wind speed and favourable wind direction.

Furthermore, in the winter season, the Flettner rotor generated power caused an increase in the COGAS thermal efficiency to 56.5 and 56 % in unloaded and loaded condition, respectively, as shown in Fig. 4, compared to 55.5 and 55 % without installing Flettner rotor [25]. In the case of degraded condition, the thermal efficiency increased to 55 and 54.7 % in unloaded and loaded conditions compared to 54 % and 53.7 % without Flettner rotor power contribution [25]. On the contrary, in the mid and summer, the Flettner rotor power output was lower than 0.5 MW while at certain times in summer negative power, i.e., − 0.2 MW, was realised due to slow wind speed and unfavourable wind direction. Under these conditions, the Flettner rotor is creating additional resistance causing additional power requirement for the ship in both loaded and unloaded conditions.

Similarly, the LH_2 tanker ship powered by the integration of COGAS fuelled by hydrogen as a prime mover and 6 Flettner rotors as assistance clean propulsion system was simulated under different conditions from Tangier to Southampton. Fig. 5 shows that the 6 Flettner rotors maximum outpower contribution in the winter season for Tangier to Southampton voyage is 1.6 MW, lower than the maximum power generated in the Marseille to Algeria voyage; this slight drop in the power is due to lower wind speed influence.

Fig. 6 shows that the maximum efficiency achieved was 55.9 % for the normal unloaded condition in the winter season, whereas an efficiency of 55 % was achieved without installing Flettner rotors technology for the Tangier to Southampton voyage [25]. Considering ship engine degradation of 6 % and fully loaded condition for the LH_2 tanker, the overall thermal efficiency decreased to a minimum of 49.9 % in the summer while it remained at 49.2 % for the same voyage without installing Flettner rotors [25].

The wind-energy assisted scenario results demonstrate that the maximum power output from the 6 Flettner rotors decreased by 0.2 MW in the Tangier–Southampton voyage as compared to the Marseille–Algeria voyage. This fall in the power output is due to variation in the wind speed and the unfavourable wind direction in winter season; this variation corresponds to 17.5 knots and 155 degrees for the Marseille–Algeria voyage compared to 17 knots and 155 degrees for the Tangier–Southampton voyage. Environmentally, this difference in the power output would slightly impact the LH_2 carrier ship prime mover emissions analysis.

Emission analysis results

The emissions assessment of the LH_2 carrier ship propelled by COGAS enhanced with 6 Flettner rotors during two different voyages, viz., Marseille–Algeria voyage and Tangier–Southampton voyage, is described in this section. In this study, the influence of Flettner rotors in terms of NOx emissions only were considered because zero-carbon green Hydrogen fuel was selected to fuel the COGAS engine. The NOx emissions of the LH_2 carrier ship propelled by COGAS with Flettner rotors

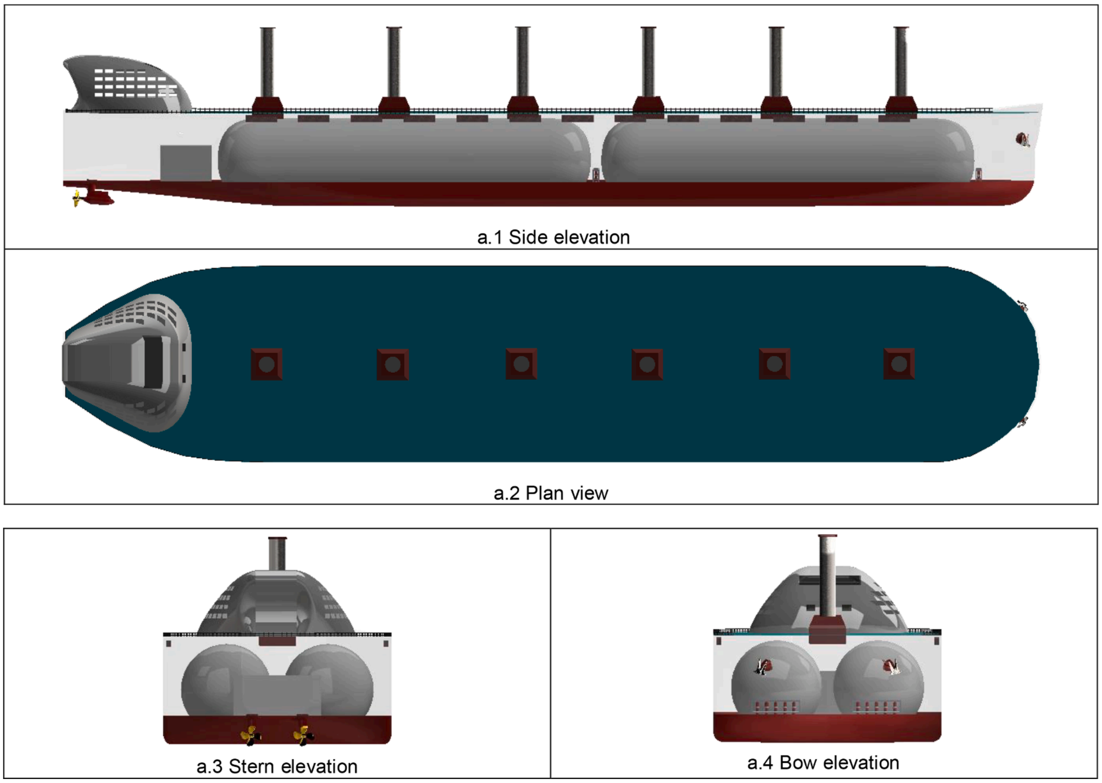

Fig. 2. JAMILA LH_2 tanker ship 3D design including 6 Flettner rotors design; (a1) Side elevation (a2) Plan view; (a3) Stern elevation and, (a4) Bow elevation.

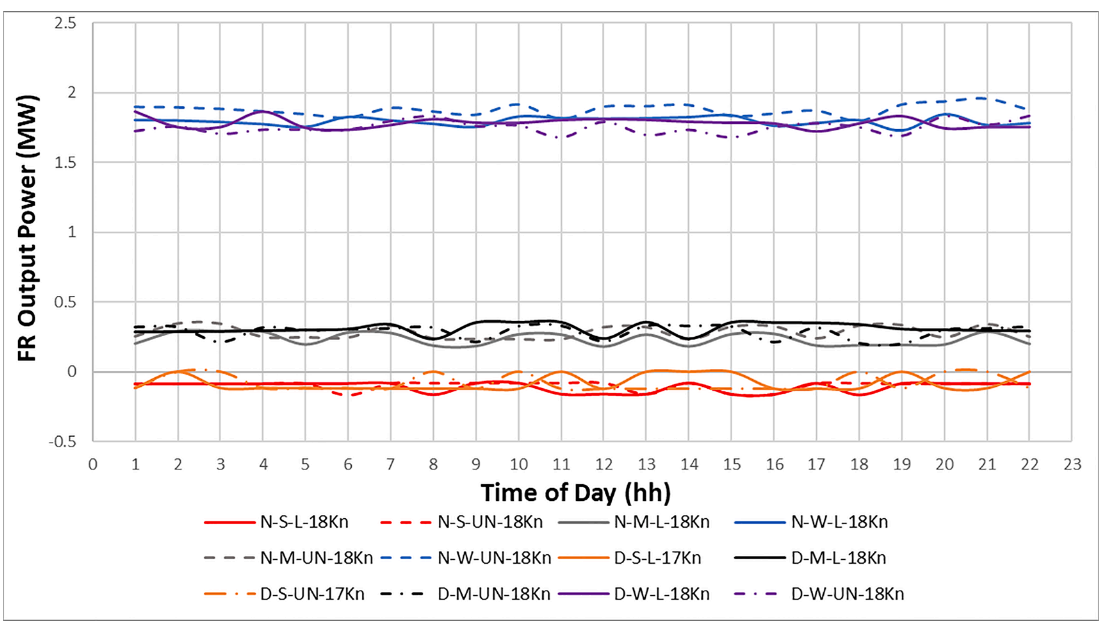

Fig. 3. Power output in MW of 6 Flettner rotors integrated with COGAS of LH_2 tanker ship as a function of voyage time per hour in different conditions (Marseille- Algeria).

was estimated for a one-way voyage from Marseille to Algeria and Tangier to Southampton in different ambient conditions. Fig. 7 shows the results of the NOx emission estimation for the Marseille to Algeria voyage in all the three seasons (mid, summer, and winter) in the engine normal condition and with 6 % degradation at loaded and unloaded ship conditions. The results show that the maximum NOx emission amount is 3.4 kg/hr in the mid with a fully loaded ship and at 6 % degraded engine for one way 22 h route. The same figure shows that the minimum NOx emission for the same period is 2.6 kg/hr with the 6 % degraded engine at unloaded condition at a speed of 17 knots.

Fig. 8 shows the NOx emissions for the LH_2 tanker ship simulated for the Tangier–Southampton voyage under different conditions. The results show that the maximum NOx emission is 3.5 kg/hr in the summer season in the degraded engine for the fully loaded ship at 18 knots speed, whereas the minimum NOx emission is 2.8 kg/hr in the winter season for an unloaded ship under normal engine condition.

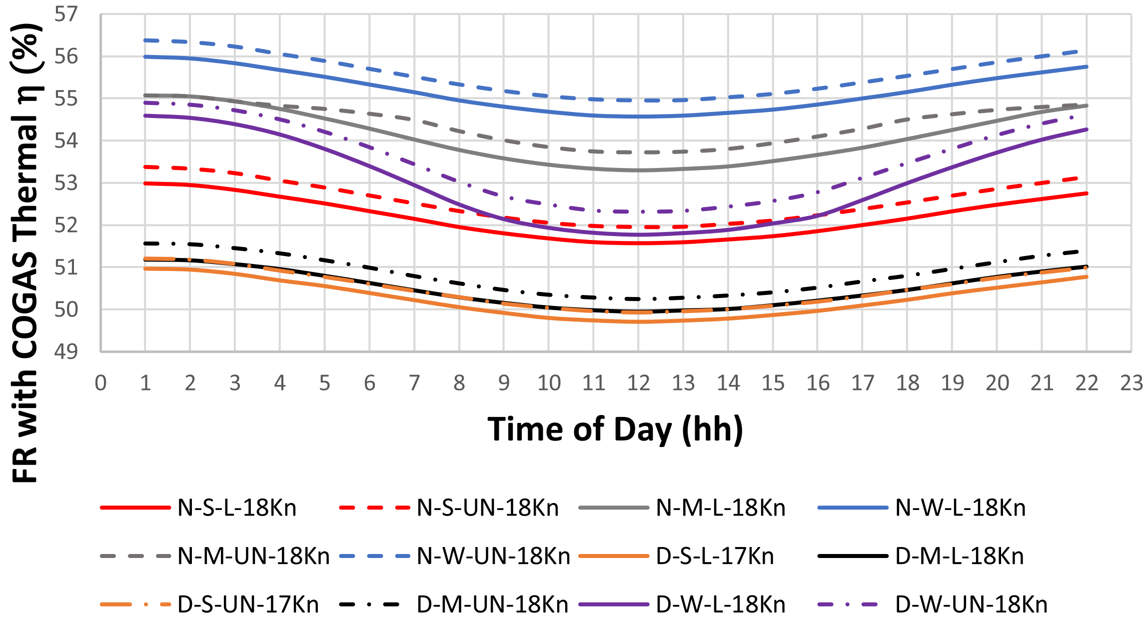

Fig. 4. The overall thermal efficiency of LH_2 tanker ship COGAS integrated with 6 Flettner rotors as a function of voyage time per hour in different conditions (Marseille- Algeria).

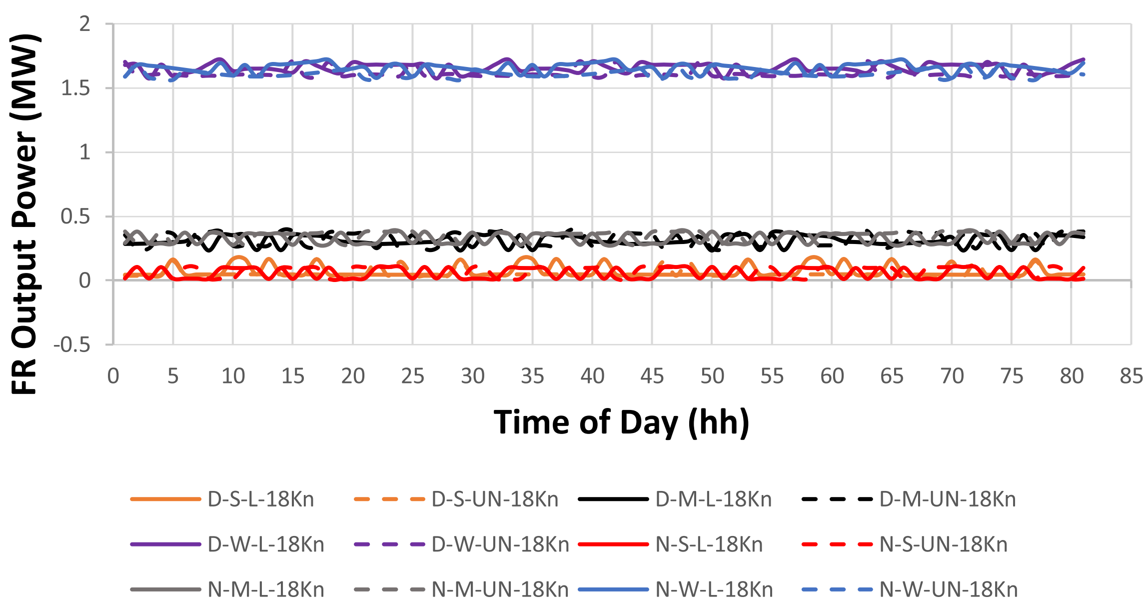

Fig. 5. Power output in MW of 6 Flettner rotors integrated with COGAS of LH_2 tanker ship as a function of voyage time per hour in different conditions (Tangier-Southampton).

However, when NOx emission of the two voyages after installing the 6 Flettner rotors as an assistance propulsion system was compared, the results show that the maximum NOx emission decreased by approximately 3 % for the Marseille to Algeria voyage in comparison to the Tangier to Southampton voyage. This reduction percentage is due to the increase in the wind speed in the mid-season in comparison to that in the summer season. Conversely, the minimum NOx emission amount decreased approximately 6 % for the Marseille to Algeria voyage in comparison to the Tangier to Southampton voyage. This reduction is due to reduction in the ship speed from 18 to 17 knots.

Overall discussion for Techno-Environmental results

This section offers technical and environmental assessment results by comparing the COGAS fuelled by hydrogen only, which is described in reference [25], with wind energy-assisted scenario. In both voyages, i.e., Marseille–Algeria and Tangier– Southampton, the results estimate the increase in the COGAS overall maximum thermal efficiency after installing the Flettner rotors as an assistance propulsion system as 1 %. Furthermore, the increase in the overall thermal efficiency percentage positively affects the engine NOx emission in the winter season by decreasing the NOx emission to approximately 3.4 to 3.5 % in comparison with the engine NOx emission when utilising COGAS fuelled by hydrogen alone, as shown in the Table 8. However, the analysis indicates that the utilisation of the Flettner rotors in conjunction with COGAS fuelled by hydrogen produced a more significant benefit in terms of saving fuel, increasing overall thermal efficiency, and decreasing engine NOx emission in comparison with the utilisation of the COGAS as

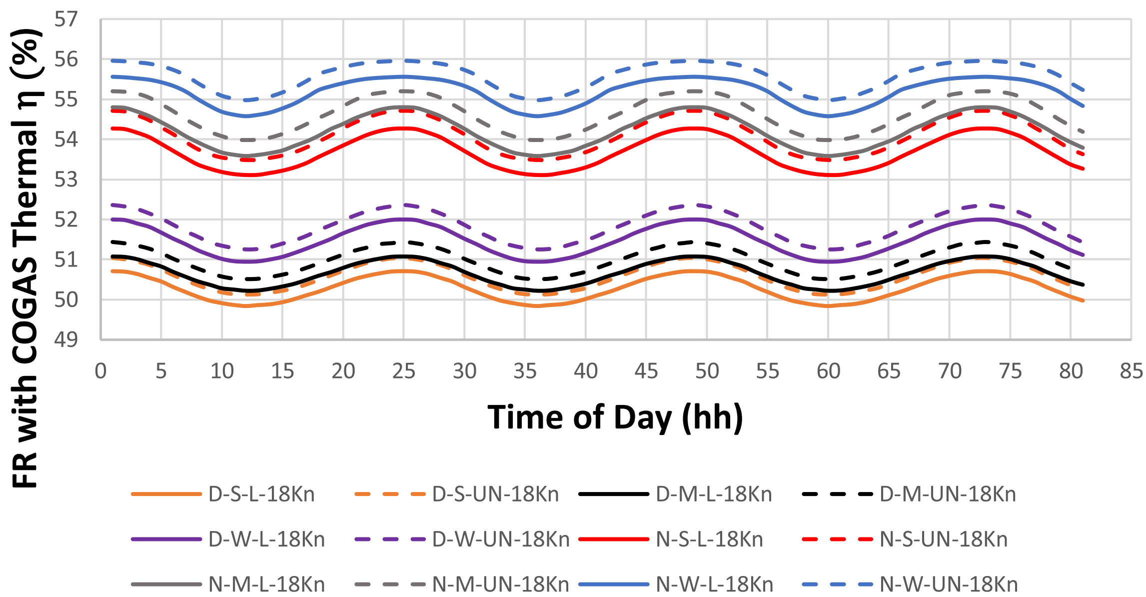

Fig. 6. The overall thermal efficiency of LH_2 tanker ship COGAS integrated with 6 Flettner rotors as a function of voyage time per hour in different conditions (Tangier- Southampton).

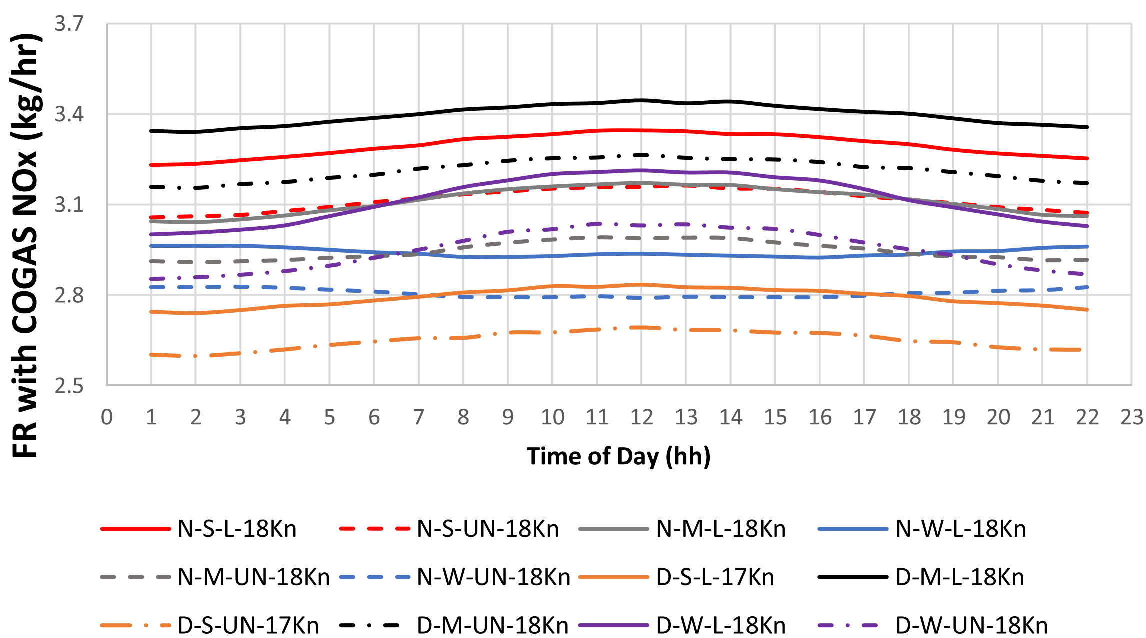

Fig. 7. NOx emissions for LH_2 tanker ship COGAS integrated with 6 Flettner rotors as a function of voyage time per hour in different conditions (Marseille- Algeria).

a prime mover of LH_2 tanker ship without Flettner rotors as a renewable energy assistance propulsion system [25].

Conclusion

A 280,000 m^3 liquefied hydrogen tanker ship with new propulsion system was designed and assessed by applying a techno-environmental method. The assessment covered the performance and environmental advantages that may be achieved by utilising a set of 6 Flettner rotors as renewable energy assistance propulsion system for the combined-cycle hydrogen fuelled gas turbine prime mover of the ship. The influence of the 6 Flettner towers on the behaviour of combined-cycle gas turbine for different voyages, under loaded and unloaded conditions, normal and 6 % degraded engine, and varying ambient conditions was analysed in terms of the engine's performance and emission.

Promising results that contribute to the performance enhancement and reduction in overall environmental emissions were obtained; the significant outcomes may be summarised as follows:

- A set of 6 Flettner rotors were designed, simulated, and located on the vessel deck based on the ship size and location of the cargo tanks. Each Flettner rotor was 40 m in height, 8 m in diameter, with 12 m diameter rotor disc, and had a 6.3 spin ratio. The Flettner rotors functioned as an assistance propulsion system with COGAS to achieve optimum output power from the wind energy technology and increase the propulsion system thermal efficiency by decreasing the prime mover fuel consumption. The results show that the design philosophy of the Flettner towers' installation was significantly dependent on the empty spaces on board the ship deck and the cargo storage locations.

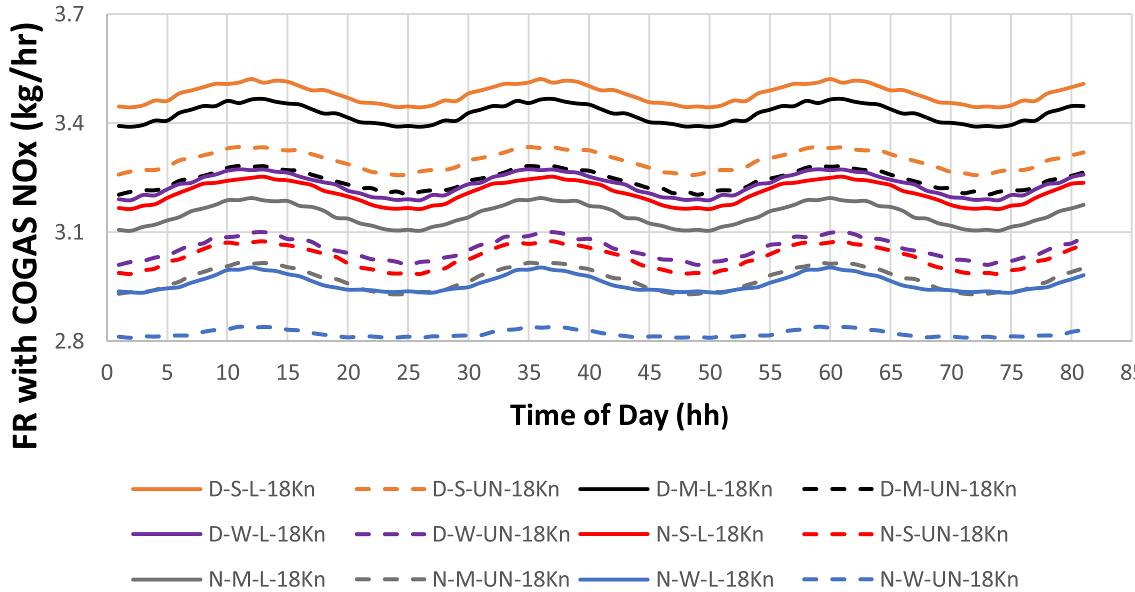

Fig. 8. NOx emissions for LH_2 tanker ship COGAS integrated with 6 Flettner rotors as a function of voyage time per hour in different conditions (Tangier-Southampton).

Table 8
The influence of the Flettner rotors in the ship engine performance and emissions in different voyages (Marseille- Algeria) and (Tangier- Southampton).

Marseille-Algeria	Maximum engine efficiency (%)	NOx emission in Max engine efficiency (kg/hr)	Case	NOx reduction (%) Compared with B.L. S
COGAS only	55.5 % [22]	2.9 [22]	*N*-W-UN-18Kn	–
Flettner rotor	56.5 %	2.8	*N*-W-UN-18Kn	3.5 %
Tangier - Southampton				
COGAS only	55 % [22]	2.94 [22]	*N*-W-UN-18Kn	–
Flettner rotor	56 %	2.84	*N*-W-UN-18Kn	3.4 %

- The hydrogen tanker ship powered by COGAS and assisted by 6 Flettner towers was simulated for two different voyages, viz., Marseille– Algeria and Tangier–Southampton, during three seasons, i.e., mid, summer and winter. The results demonstrate that there is a requirement to decrease the vessel speed from 18 to 17 knots because the ship power required is more than COGAS power output due to the high summer ambient temperature and the 6 % degradation influence. The engine degradation and ambient temperature variation play an essential role in the ship's speed.
- The ship propulsion system performance assessment results for both voyages indicated an increase of approximately 1 % in the COGAS overall maximum thermal efficiency, after implementing the 6 Flettner rotors as an assistance propulsion system. Moreover, the Flettner rotor maximum contribution power achieved was in the range of 1.7 to 1.8 MW in the winter season owing to the high wind speed and favourable wind direction. This power could save around 3.6 % of the combined-cycle gas turbine design output power (50 MW). On the contrary, in mid and summer, the Flettner rotor power output was lower than 0.5 MW while at certain times in summer negative power, i.e., − 0.2 MW, was realised due to slow wind speed and unfavourable wind direction.
- The Flettner rotors installation positively impacted engine NOx emission of the liquefied tanker ship, especially in the winter season. The reduction in the NOx emission achieved was approximately 3.4 to 3.5 % in both voyages in comparison to the COGAS NOx emission achieved without utilising the set of 6 Flettner rotors as an assistance propulsion system.

The assessment results indicate that the utilisation of the set of 6 Flettner rotors in conjunction with a combined-cycle gas turbine fuelled by hydrogen for JAMILA LH_2 tanker ship could contribute substantial benefit in terms of increasing overall thermal efficiency, fuel-saving, and reducing ship prime mover NOx emission in comparison to the utilisation of the combined-cycle gas turbine as the primary propulsion system of LH_2 tanker ship without implementing the Flettner rotors as a renewable energy assistance propulsion technology.

CRediT authorship contribution statement

Abdullah NFNR Alkhaledi: Conceptualization, Software, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software. **Suresh Sampath:** Supervision. **Pericles Pilidis:** Supervision.

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

The data that has been used is confidential.

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