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Hydrodynamic and environmental impact assessment of gulet yachts using alternative fuels along the blue voyage route

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ABSTRACT

As iconic vessels of the Aegean and Mediterranean coasts, gulets play a central role in Blue Voyage, presenting a valuable opportunity for advancing sustainable marine tourism through cleaner propulsion solutions. This study investigates the hydrodynamic performance and environmental impacts of two Bodrum Gulet-type hull forms, with overall lengths of 24 and 33.8 m, through Computational Fluid Dynamics (CFD) analyses and environmental sustainability assessments. The hydrostatic characteristics of the modeled hulls are determined, and flow characteristics, total resistance, and power requirements are evaluated. A case study based on a typical Blue Voyage route is conducted to evaluate the environmental implications of operating gulets with marine diesel oil (MDO), liquefied natural gas (LNG), and methanol (MeOH). Emission Ratio (*ER*) and Energy Efficiency Index (*EEI*) are calculated to quantify the performance of each fuel type. Results show that the current gulet hull forms can be optimized to reduce total resistance, enhancing the feasibility of adopting alternative fuels. The use of LNG and MeOH can lower CO_2 emissions by up to 9.8 % and 15.8 %, respectively, compared to MDO, with corresponding reductions in *EEI* of 8.3 % and 12.3 %. In addition, these benefits are found to be more pronounced for larger gulets operating at high occupancy levels. While LNG and MeOH offer notable environmental advantages, their application to gulets presents significant challenges, such as increased space requirements, safety considerations, and retrofitting constraints, making them more appropriate for new constructions or long-term planning.

1. Introduction

The latest regulations for decarbonization in the maritime industry have increased the focus on developing energy-efficient and carbon-neutral designs. According to the Fourth Greenhouse Gas (GHG) Study by the International Maritime Organization (IMO), greenhouse gas emissions from maritime activities accounted for 2.89 % of global anthropogenic GHG emissions in 2018, and this share is projected to increase by 90 % to 130 % of the 2008 level by 2050 [1]. In response to these projections, IMO has adopted a strategy to reduce carbon intensity by at least 20 % by 2030 and 70 % by 2040, relative to 2008 levels [2]. As part of

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these efforts, mandatory measures such as the Energy Efficiency Design Index (*EEDI*) and the Ship Energy Efficiency Management Plan (SEEMP), along with broader emission regulations, have been implemented since 2013. Furthermore, the IMO amended MARPOL Annex VI to expand the scope of carbon intensity reduction by approving the Energy Efficiency Existing Ship Index (*EEXI*), the Carbon Intensity Indicator (*CII*) rating system, and enhanced SEEMP [3, 4]. Besides, the current energy efficiency regulations of IMO primarily target ships of 400 gross tons (GT) and above; consequently, smaller vessels and yachts are generally exempt from these requirements. However, approximately 14000 vessels have a gross tonnage below 400 GT [5], many of which are yachts operating in environmentally sensitive coastal areas. Therefore, the growing environmental concerns and increasing demand for sustainable marine tourism have highlighted the importance of adopting cleaner energy solutions for yachts operating along coastal and Blue Voyage routes.

Marine tourism holds particular significance due to both its economic value and its operation in ecologically sensitive regions. Therefore, efforts to reduce the carbon footprint and emissions of yachts, and transition to alternative fuels – similar to initiatives implemented in commercial shipping – are gaining attention in the marine tourism sector [6, 7]. It is reported that using liquefied natural gas (LNG) or methanol (MeOH) instead of marine diesel oil (MDO) which is the primary fuel for yachts, can reduce particulate matter (PM) by 90 %, nitrogen oxides (NO_X) by 50 %, and sulphur oxides (SO_X) by 90 % [8, 9]. Brewer [10] examined regulatory gaps and mitigation strategies related to black carbon emissions in maritime transport, emphasizing the role of local, incentive-based policies in reducing pollution from commercial vessels. Although the study focused on large-scale ships, the 81 % reduction in particulate matter emissions demonstrates that various emission reduction strategies, when effectively adapted to small-scale vessels operating in environmentally sensitive areas, can lead to significant environmental improvements. Bengtsson et al. [11] conducted a comparative life cycle assessment (LCA) of heavy fuel oil (HFO), marine gas oil (MGO), gas-to-liquid (GTL), and liquefied natural gas (LNG) in marine applications, evaluating multiple environmental impact categories. The study found that LNG could reduce acidification and eutrophication potential by up to 90 %. Brynolf et al. [12] conducted a life cycle environmental assessment of liquefied natural gas (LNG), liquefied biogas (LBG), methanol, and bio-methanol as marine fuels, focusing on their application in the Northern European Emission Control Area (ECA). The study found that LBG and bio-methanol significantly reduce climate change impacts, while LNG and fossil-based methanol improve overall environmental performance but have global warming potential (GWP) comparable to heavy fuel oil. Hwang et al. [13] conducted a life cycle assessment (LCA) of marine gas oil (MGO), natural gas, and hydrogen fuels for a coastal ferry operating in South Korea, evaluating their environmental impacts. Compared to MGO, natural gas showed lower emissions in most impact categories except global warming potential (GWP), while hydrogen achieved zero emissions during operation but resulted in approximately 10-15 % higher life cycle GWP due to emissions associated with its production process. Korberg et al. [14] conducted a techno-economic analysis of renewable fuel options and propulsion systems—including battery-electric, fuel cells, and internal combustion engines—for ferries, cargo ships, bulk carriers, and container vessels, aiming for fossil-free operation by 2030. Their findings indicated that methanol offered the lowest total cost of ownership across most vessel types. Liu and Dong [15] introduced a model-based design and optimization (MBDO) approach for a methanol-fueled hybrid electric tour boat, integrating advanced propulsion power prediction, system optimization, and real-time control strategies. Their study demonstrated that combining clean methanol fuel with optimized hybrid electric propulsion can substantially reduce greenhouse gas (GHG) emissions and air pollutants, offering a promising pathway for cleaner marine operations. Banawan et al. [16] evaluated the environmental and economic impacts of converting a high-power short-voyage passenger ship from marine diesel oil to natural gas, focusing on operations in the Red Sea area. Their results indicated significant reductions in NOx (72 %), SOx (91 %), particulate matter (85 %), and CO_2 (10 %) emissions, along with a 39 % decrease in fuel costs and a 40 % reduction in maintenance expenses. Wang et al. [17] performed a comparative life cycle assessment (LCA) of six alternative marine fuels for a superyacht, evaluating their environmental impacts from a well-to-wake perspective with multiple energy production pathways. Among the alternative fuels considered, biomethanol and biodiesel demonstrated significant potential for emission reduction, achieving GHG savings of 78.96 % and 19.27 %, respectively. Kondratenko et al. [18] outlsolutions andhways for shipping decarbonization: adopting green fuels, implementing ship-based carbon capture with design and operational solutions, and using biodiesel with design and operational solutions. Their analysis confirmed that a coordinated strategy leveraging these pathways could reduce annual GHG emissions by up to 70 % compared to 2008 levels, aligning with IMO 2050 targets. More specifically, Akman [19] conducted a benchmark study on 57 Bodrum Gulets powered by MDO to evaluate their energy efficiency using actual hull form and propulsion data. According to the results, the installed power of many gulets does not align with the propulsion power requirements derived from numerical analyses, leading to higher environmental impacts. As reviewed, the adoption of low-emission alternative marine fuels, such as liquefied natural gas (LNG) and methanol (MeOH), presents a promising pathway to improve the environmental performance of yachts and support the broader decarbonization goals of marine tourism. Despite the absence of regulatory mandates on carbon emissions for vessels under 400 GT, this regulatory gap should not be construed as a rationale for exempting yachts operating along environmentally sensitive coastal routes from emission reduction efforts. On the contrary, enhancing the energy efficiency of these vessels—and where technically and economically feasible, converting them to low- or zero-emission propulsion systems—is of critical importance. However, the transition to alternative fuels in yachts requires a holistic assessment of their environmental performance in relation to fundamental design parameters, including hull form, stability, propulsion, and operational profiles.

Gulets, the iconic yachts of the Blue Voyage routes in the Aegean and Mediterranean seas, remain heavily dependent on conventional diesel engines due to their operational reliability and accessibility. Nevertheless, their widespread use and regional significance make them ideal candidates for pioneering the transition toward cleaner propulsion technologies in leisure maritime transport. Currently, a clear research gap exists regarding the feasibility and implications of integrating alternative fuels—specifically LNG and methanol—into gulet design and operation. Although numerous studies have investigated the environmental performance of alternative marine fuels through life cycle assessment and techno-economic analyses, the existing literature primarily focuses on large-scale merchant ships, ferries, or cruise vessels. Research addressing small displacement crafts—particularly traditional gulets—remains very limited. Furthermore, previous gulet-related studies have mainly concentrated on hull form optimization or conventional diesel propulsion performance, without integrating hydrodynamic and environmental evaluations within a unified framework. Consequently, there is a lack of research that simultaneously examines the hydrodynamic characteristics, power requirements, and fuel-specific environmental impacts of gulets operating in coastal tourism routes. The present study aims to bridge this gap by combining Computational Fluid Dynamics (CFD)-based resistance analysis with voyage-level energy and emission assessments for gulets using marine diesel oil, liquefied natural gas, and methanol as propulsion fuels. This study also contributes to the United Nations Sustainable Development Goals, particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action), by promoting energy-efficient ship design and strategies for decarbonizing maritime transport. Therefore, in this study, the hydrodynamic behavior and environmental performance of two Bodrum Gulet-type yacht hulls with overall lengths of 24 meters and 33.8 meters are investigated by employing Computational Fluid Dynamics (CFD) simulations. The hulls' hydrostatic properties are analyzed, and key performance metrics such as flow patterns, total resistance, and propulsion power demand are evaluated. Additionally, a representative Blue Voyage route is used as a case study to explore the environmental effects of gulets powered by marine diesel oil (MDO), liquefied natural gas (LNG), and methanol (MeOH). The Emission Ratio (*ER*) and Energy Efficiency Index (*EEI*) are determined under environmental impact analysis. Finally, the design remarks regarding alternative fuel-powered gulets are revealed.

2. Gulet-type sailing yachts

Gulet-type sailing yachts, known for their historical significance and unique design, have long been considered one of the icons of maritime heritage [20]. These vessels trace their origins back to the 1800s, with the earliest gulet believed to have been constructed in Italy. Derived from the Italian word "Goletta"—and referred to as a schooner in English—these yachts typically feature two masts of equal height or a shorter foremast [21]. Originally designed for fishing and cargo transport, gulets have evolved into comfortable, motor-sailing yachts equipped with modern amenities to cater to leisure cruising. Besides, Bodrum Gulets are wooden sailing yachts that have become iconic vessels for the Blue Voyage, a popular form of coastal tourism along the Aegean and Mediterranean shores of Türkiye. As a symbol of sustainable maritime tourism, gulets continue to play a central role in preserving the traditional character and environmental values of the Blue Voyage, which emphasizes low-speed cruising between bays and anchorage points, aligning well with the operational profile of gulets, which typically operate between 8 and 12 knots [20].

Gulets, on the other hand, traditionally powered by diesel engines, rely on conventional propulsion systems consisting of a single or twin engine, gearbox, shaft, propeller, and rudder configuration. Diesel propulsion remains the dominant choice due to its reliability, widespread availability, and long-distance cruising [22]. Generally, two auxiliary service engines are installed onboard based on the power requirements. The main engine brake power of Bodrum gulets with overall lengths between 18 m and 50 m is reported to range from 200 kW to 1500 kW [19]. Besides, these yachts have single or twin-screw configurations which is usually used above 24 m overall length [19]. In twin-screw configurations, shafts are supported by brackets welded to the underwater portion of the hull. Figure 1 shows a typical arrangement plan for a round stern Bodrum Gulet with an overall length of 24 m and a twin-screw propulsion. The engine room is positioned between frame numbers 8 and 16, with a frame spacing 50 cm. The breadth of the engine room deck is about 6 m. Besides, as shown in Figure 1, these hulls generally have a keel angle of around 2°, with the engine-shaft assembly installed at an inclination of 2° to 7° from the baseline. The keel is usually constructed from steel and integrated into the hull as an additional weight and is also referred to as the "ballast keel" [20, 23]. These yachts are equipped with large freshwater and fuel storage capacities, as well as onboard systems to enhance both comfort and safety.

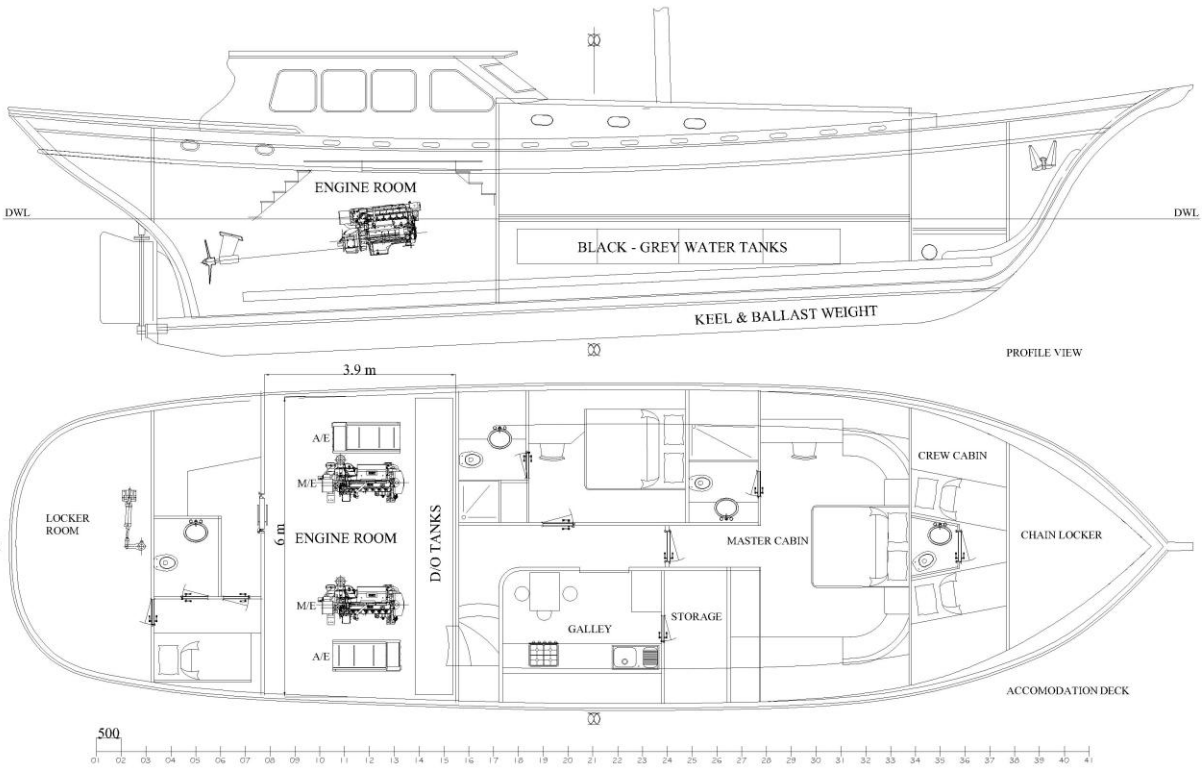

Fig. 1. General arrangement of a typical gulet with an overall length of 24 m

3. Methodology

3.1 Hull form modelling and characteristics

The modelling of gulet hulls plays a substantial role in preserving their cultural heritage while enhancing performance characteristics such as hydrodynamic efficiency, stability, and maneuverability. Unlike modern yacht designs, gulets often feature broad beams, rounded or transom sterns, and pronounced sheer lines, which contribute to their spacious interiors and smooth motion at sea [22]. To investigate the resistance and powering performance, two hulls of Bodrum Gulets commonly found in service [19, 21], with overall lengths of 24 m (M1) and 33.8 m (M2), are modelled as shown in Figure 2. The line plans of these gulets, used for hull form modelling, are obtained from the authors' previous studies [19, 20]. After the modelling process, the hydrostatic characteristics are determined for CFD-based analysis as shown in Table 1. According to the hydrostatics, the two gulets, with an overall of 24 m (M1) and 33.8 m (M2), exhibit notable differences in their hydrostatic properties, reflecting the scale and design adaptations associated with larger vessels. The prismatic coefficient (C_P) remains similar, suggesting comparable longitudinal volume distribution. However, M2 has higher block and midship section coefficients, indicating a fuller and more voluminous hull form amidships. Waterplane area coefficients (C_{WP}) are close, with M2 showing a slightly higher value, reflecting minor differences in deck fullness.

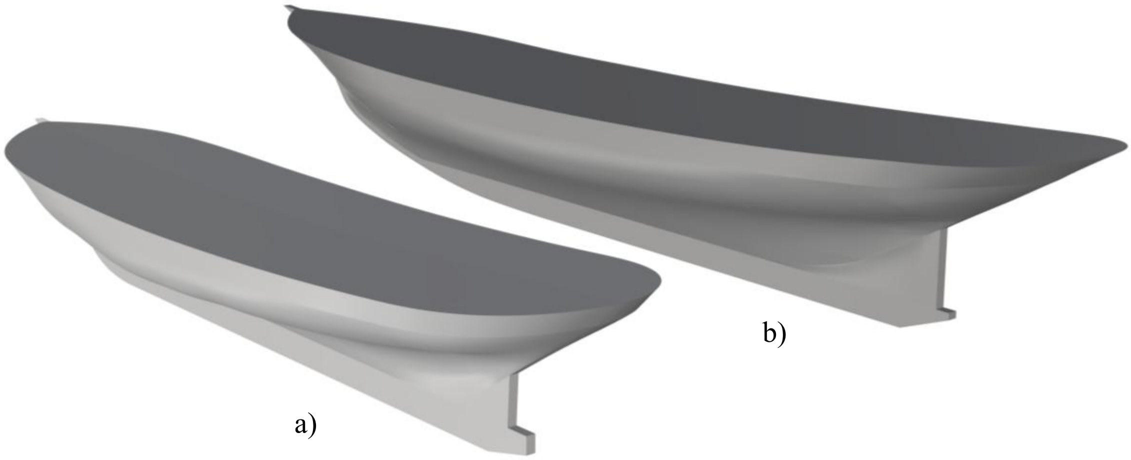

Fig. 2. Hull forms of gulets: M1: L_{OA}= 24 m (a), M2: L_{OA}= 33.8 m (b)

Table 1 Hydrostatic characteristics of the investigated gulets

Parameter	**M1: L_{OA}=24 m**	**M2: L_{OA}=33.8 m**	**Unit**
Displacement tonnage	51.54	131.9	ton
Gros tonnage	100	224	GT
Draught (amidships)	2.5	3.306	m
Waterline length (L_{WL})	19.41	26.50	m
Waterline breadth (B_{WL})	5.906	7.045	m
Wetted surface area (WSA)	128.86	211.51	m^2
Waterplane area (WPA)	82.73	136.04	m^2
Prismatic coefficient (C_P)	0.651	0.642	
Block coefficient (C_B)	0.175	0.209	
Midship section coefficient (C_M)	0.32	0.371	
Waterplane area coefficient (C_{WP})	0.721	0.729	
Longitudinal center of buoyancy (LCB)	9.408	11.863	m
Longitudinal center of floatation (LCF)	9.4	11.902	m
Vertical center of buoyancy (KB)	1.994	2.571	m
1 cm sinkage tonnage (TPc)	0.848	1.394	ton/cm
1 cm trim moment (MTc)	0.894	1.978	ton.m

3.2 Resistance and power prediction

In the present analysis, both physical and numerical assumptions are carefully defined to establish a consistent computational framework. The flow is modelled as steady, incompressible, isothermal, and

Newtonian, with seawater properties represented by constant density and viscosity values. To capture the water–air interface and free-surface elevation, the Volume of Fluid (VOF) method is applied, while gravity is included to represent the hydrostatic pressure field. The hull geometry is treated as a rigid body fixed in position, consistent with calm-water conditions. The analysis focuses on the bare-hull configuration, aiming to evaluate the fundamental viscous and pressure resistance characteristics of the hull. These modelling choices follow the ITTC recommended procedures [24,25] for CFD-based ship resistance prediction and ensure the physical consistency of the simulation setup.

Under these assumptions, Computational Fluid Dynamics uses numerical methods to solve the continuity, momentum, and energy equations, considering specific initial and boundary conditions. For steady and laminar flow of viscous, incompressible Newtonian fluids without free-surface effects, the relevant equations are the continuity equation (1) and the Navier-Stokes equations (2), which describe momentum across the domain. In the case of steady, incompressible, and turbulent flows, the Reynolds-Averaged Navier-Stokes (RANS) equations are used, as shown in equation (3):

$$\vec{\nabla} \cdot \vec{V} = 0 \tag{1}$$

$$(\vec{\nabla} \cdot \vec{\nabla})\vec{V} = -\frac{1}{\rho}\vec{\nabla}P' + v\nabla^2\vec{V} \tag{2}$$

$$(\vec{\nabla} \cdot \vec{\nabla})\vec{V} = -\frac{1}{\rho}\vec{\nabla}P' + \vec{V}\nabla^2\vec{V} + \vec{\nabla}.(\tau_{ij}) \tag{3}$$

In the closed-form equations, $\vec{V}$ denotes the flow velocity, v is the kinematic viscosity, P' represents the modified pressure, and τ_{ij} is the Reynolds stress tensor. Modeling the flow field around a Gullet hull presents significant challenges due to its turbulent and complex nature. Therefore, selecting a suitable turbulence model for physical configuration is a key aspect of numerical analysis. To balance computational accuracy and cost, the *k-ω* SST turbulence model based on unsteady RANS is used for predicting hull resistance [26,27].

The *k–ω* SST model [28] solves two additional transport equations for the turbulent kinetic energy (k) and the specific dissipation rate (ω), which can be expressed as follows:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_j)}{\partial x_j} = P_k - \beta^*\rho k\omega + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_k\mu_t)\frac{\partial k}{\partial x_j}\right] \tag{4}$$

$$\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial(\rho\omega u_j)}{\partial x_j} = \sigma\frac{\omega}{k}P_k - \beta\rho\omega^2 + \frac{\partial}{\partial x_j}\left[(\mu + \sigma_\omega\mu_t)\frac{\partial\omega}{\partial x_j}\right] \tag{5}$$

where P_k denotes the production rate of turbulent kinetic energy, μ_t is the eddy viscosity, and σ, β, β^*, σ_k and σ_ω are empirical model constants [28].

The turbulent viscosity is defined as:

$$\mu_t = -\frac{\rho a_1 k}{max(a_1\omega, SF_2)} \tag{6}$$

Here, S represents the mean strain rate and F_2 is the blending function ensuring smooth transition between the near-wall k–ω and outer k–ε formulations. This model blends the near-wall accuracy of the k–ω approach with the robustness of the k–ε model in the free-stream region, providing reliable predictions for ship hydrodynamics, especially under adverse pressure gradients and flow separation conditions [28, 29].

The numerical simulations are performed using a pressure-based segregated solver that applies the finite volume method for discretizing the governing equations. The SIMPLE algorithm is employed for pressure–velocity coupling, and an algebraic multigrid method is used to enhance convergence. The convective and diffusive terms are discretized using a second-order upwind scheme, while the transient terms are treated with a first-order implicit scheme to maintain numerical stability. The simulations are conducted with a constant time-step of 0.001 seconds and 10 inner iterations, which is appropriate according to ITTC's recommended procedure for Reynolds stress turbulence models [24, 25]. The construction of the computational mesh plays a crucial role in determining both the accuracy and the convergence behavior of CFD simulations. The mesh is generated using the trimmed hexahedral mesher technique with local refinements near the hull, bow, stern, and wake regions to improve resolution in high-gradient areas. The near-wall region is resolved with 10 prism layers and a growth ratio of 1.2, ensuring that $y^+ < 1.0$ across the wetted surface in accordance with ITTC guidelines [24, 25]. To resolve the boundary layer around the hull, the mesh structure is refined based on local flow gradients and geometric curvature. Several mesh configurations, ranging from approximately 2 to 6 million cells depending on hull geometry, are evaluated in mesh-independence and sensitivity analyses to identify the optimal grid structure that balances computational cost and numerical accuracy.

The computational domain is also defined based on ITTC recommendations: $4\times L_{OA}$ upstream of the bow and approximately $8\times L_{OA}$ downstream of the stern along the *x*-axis; $3\times L_{OA}$ from the centerline in the transverse direction (*y*-axis); $2\times L_{OA}$ below the keel and $1\times L_{OA}$ above the hull in the vertical direction (*z*-axis), as shown in Figure 3. Moreover, boundary conditions are set as follows: a velocity inlet at the domain entrance, a pressure outlet at the exit, symmetry conditions at the side boundaries, and a no-slip wall condition on the hull surface. It should be noted that the CFD analyses are performed under calm-water conditions without considering external environmental factors such as wind and waves. These effects can considerably influence the total resistance and propulsion performance under realistic sea conditions.

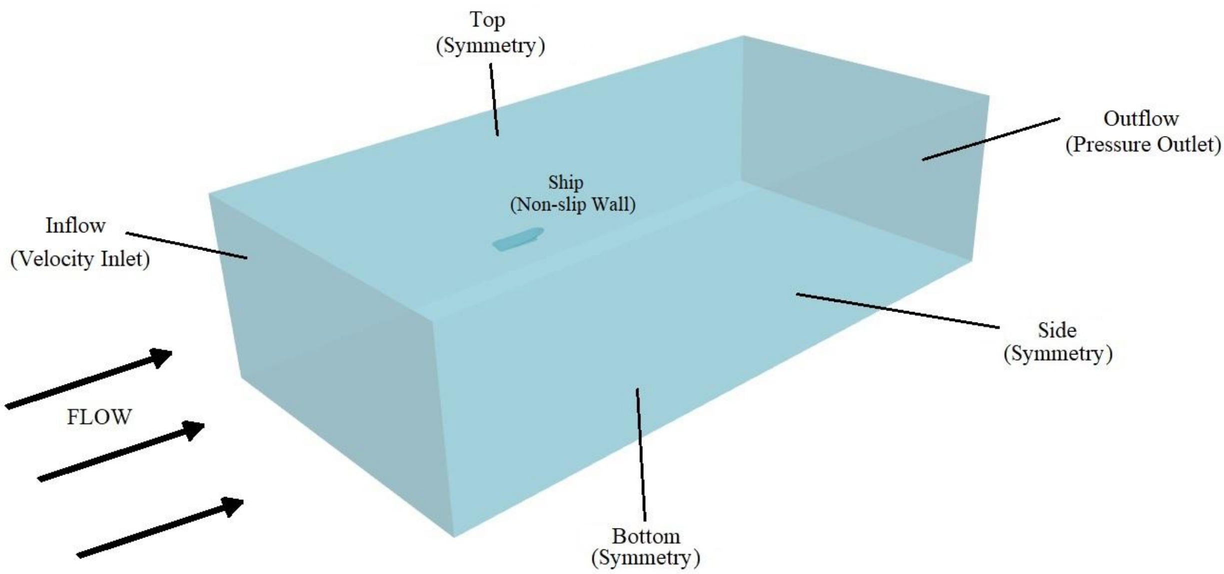

Fig. 3. The computational domain for the CFD simulations of gulet hull forms

After obtaining the total resistance by CFD simulations, the effective power (P_e) is calculated using the corresponding speed as follows:

$$P_e = R_T V \tag{7}$$

Once the effective powers of gulet hull forms are determined, choosing a propulsion system capable of delivering the necessary thrust becomes a crucial aspect of design, energy efficiency, and emission control. In this study, the conventional propulsion configuration of engine-shaft-propeller is considered as shown in Figure 1. Besides, effective power does not represent the engine brake power (P_{ME}) based on energy losses in the propulsion and transmission system; therefore, total propulsive efficiency (η_T) is used for determining the brake engine power of the main engine as follows [29]:

$$P_{ME} = P_e/\eta_T \tag{8}$$

The total propulsive efficiency was assumed to be 0.5 for determining the engine brake power of Bodrum Gulets [20, 30], as this value is typical for traditional Gulet-type vessels operating at low Froude numbers.

3.3 Environmental impact analysis

The voyage-based, tank-to-wake Emission Ratio for gulets (ER_g) is calculated to evaluate the environmental impacts of modelled gulets depending on the total fuel consumption (FC), emission factor of CO_2 for the corresponding fuel (C_F) and distance (D) as follows:

$$ER_g = \frac{\sum FC_{i,j} \times C_{F,j}}{\sum D} \quad (9)$$

The subscript i represents the engine number, while the superscript j indicates the fuel type. During emission ratio calculations, total fuel consumption is determined using fuel usage during cruising and anchorage operations. Fuel consumption while at port is excluded from the calculations, as gulets usually use shore power during these periods. Table 2 presents the emission factors, energy density, lower calorific values, and greenhouse gas (GHG) data for MDO, LNG, and methanol (MeOH), along with their global warming potential (GWP) values over a 100-year time horizon [31] which is a key indicator for comparing the climate impact of various GHGs. As shown in Table 2, carbon dioxide (CO_2) serves as the reference point with a GWP of 1. Methane (CH_4), although it remains in the atmosphere for a shorter duration, has a GWP of 28, reflecting its much stronger heat-trapping capability compared to CO_2. Nitrous oxide (N_2O) is even more influential, with a GWP of 265. However, the emissions of CH_4 and N_2O from MDO- and MeOH-powered engines are relatively low compared to the released CO_2. In contrast, LNG-fueled dual-fuel engines are associated with methane slip, a significant challenge that increases their climate impact [31].

Table 2 Fuels' lower calorific value (*LCV*), GHG emission factors (C_F) and GWP100 [7, 31]

Fuel type	***LCV*** (kJ/kg)	**Energy density** (kJ/L)	**CO_2 - C_F** (gCO_2/g_{fuel})	**CH_4 - C_F** (gCH_4/g_{fuel})	**N_2O - C_F** (gN_2O/g_{fuel})
MDO	42700	35800	3.206	0.00005	0.00018
LNG	48000	21200	2.750	0	0.00011
MeOH	19900	14900	1.375	-	-
GWP_{100y}	-	-	1	28	265

The Blue Voyage on the southwest coasts of Türkiye, characterized by its tranquil bays, crystal-clear waters, and historical coastal towns, is ideally suited to the slow and scenic cruising style of gulets [32]. Ecological concerns surrounding the Blue Voyage are increasing, making alternative fuels a promising option for gulets to reduce emissions. The environmental impact of using alternative fuels on gulets is evaluated through a case study conducted along one of the most common Blue Voyage routes—Bodrum–Hisarönü–Bodrum—as shown in Figure 4. The total distance of the route is 142.7 nm, comprising 9 anchorage stations, with individual segments ranging from at least 5.4 to 32.3 nm. The cruising speed is 10 kn, the engine load factor at cruising and anchorage is 75 % MCR and 50 % MCR, respectively. The specific fuel consumption of engines using MDO, LNG, and MeOH is 200 g/kWh, 165 g/kWh and 375 g/kWh, respectively [19, 33].

Besides, to evaluate the energy efficiency of the modelled gulet-type yachts, the Energy Efficiency Index for gulets (EEI_g) is calculated inspiring *EEDI* regulation [34]. The EEI_g is based on the total CO_2 emitted by the main and auxiliary engines, the contribution of energy-efficient devices that reduce fuel consumption, the vessel's gross tonnage, and its reference speed:

$$EEI_g = \frac{\left(\sum_{i=1}^{n,ME} P_{ME_i}{}^{j} \cdot C_{F_{ME_i}}{}^{j} \cdot SFC_{ME_i}{}^{j} + P_{ME_i}{}^{j} \cdot C_{F_{ME_i}}{}^{j} \cdot SPOC_{ME_i}{}^{j}\right) + \left(\sum_{i=1}^{n,AE} P_{AE_i}{}^{j} \cdot C_{F_{AE_i}}{}^{j} \cdot SFC_{AE_i}{}^{j}\right) - f_{eff} \cdot P_{eff} \cdot C_{F_{ME}}{}^{j} \cdot SFC_{ME}{}^{j}}{GT \cdot V_{ref}} \quad (10)$$

where SFC is the specific fuel consumption (g/kW-h) at 75 % MCR and $SPOC$ is the specific pilot oil consumption (g/kW-h) at given main engine (P_{ME}) and auxiliary engine brake powers (P_{AE}). The subscript i and the superscript j denote the total number of engines and the type of fuel, respectively. Marine Diesel Oil is used as pilot fuel in LNG and MeOH-fueled engines to prevent knocking and misfiring [35]. The amount of $SPOC$ is assumed to be 2 % of the total fuel consumption for LNG-fueled engines and 3 % for methanol-fueled engines [36, 37]. The P_{eff} is the power supply of the energy efficiency device, f_{eff} represents the efficiency factor taken as 1 and V_{ref} is the reference speed determined as 10 knots according to the $EEDI$ Resolution [34]. In EEI_g equation, the numerical contribution of sail usage is not included in the energy efficiency calculations. Additionally, the formulation is designed to apply only to yachts with an overall length exceeding 24 meters and a gross tonnage below 400 GT [19].

Fig. 4. The Blue Voyage Route, environmentally analyzed in the case study

4. Results and discussions

4.1 Resistance and power

The distributions of skin friction coefficients around the hull forms of M1 and M2 at 10 knots service speed are shown in Figure 5, respectively. The skin friction coefficient (C_f) over the gulet hulls shows a typical pattern of a displacement hull with a relatively full form. The local skin friction coefficient (C_f) is defined as:

$$C_f = \frac{\tau_w}{0.5\rho V^2} \tag{11}$$

where τ_w denotes the wall shear stress, ρ is the fluid density, and V is the local flow velocity near the hull surface. Higher C_f values, generally in the range of 0.003-0.004, are observed in the mid-bottom region of the hulls. This is consistent with the fully developed turbulent boundary layer that forms as the flow progresses longitudinally along the hulls. The forward and aft ends of the hulls exhibit lower C_f values, due to either developing flow at the bow or flow deceleration at the stern. The color map indicates that most of the wetted surface is experiencing attached flow with increasing wall shear stress from bow to midship. Low C_f regions near the transom point to partial separation or a thickening boundary layer, but no drastic discontinuities are apparent.

The pressure distributions reveal expected hydrodynamic behaviour over the hulls as shown in Figure 6. In this study, the hydrostatic pressure is subtracted from the total pressure, and the results are presented in a dimensionless form as the C_P coefficient. At the bow region, model M1 exhibits a high-pressure zone near the waterline, consistent with flow stagnation, followed below by a low-pressure band indicating localized flow acceleration around the lower bow region. In contrast, model M2 presents a more uniform, slightly positive pressure distribution, implying smoother, more gradual flow deflection with weaker stagnation and acceleration. Moving aft along the hull, both models exhibit predominantly negative pressure coefficients, consistent with flow acceleration over the curved hull surfaces as predicted by Bernoulli's principle. Through the hulls' midsections, the C_P remains moderately negative or close to zero, implying a relatively stable pressure field and favorable pressure gradients. This contributes to smooth flow and low-pressure resistance, which is especially important for displacement hulls like Gullets that prioritize comfort and fuel economy. Towards the stern, both models show a region of pressure recovery, where the pressure becomes positive again as the tapering hull form allows the flow to decelerate. For model M1, a small area of negative pressure remains near the transom and propeller region, which may be associated with local flow acceleration or partial separation due to geometric curvature. It is also noted that the pressure and skin friction coefficient distributions of M2 are smoother than those of M1, suggesting that M1 experiences higher energy loss due to increased flow separation and turbulence along the wetted surface.

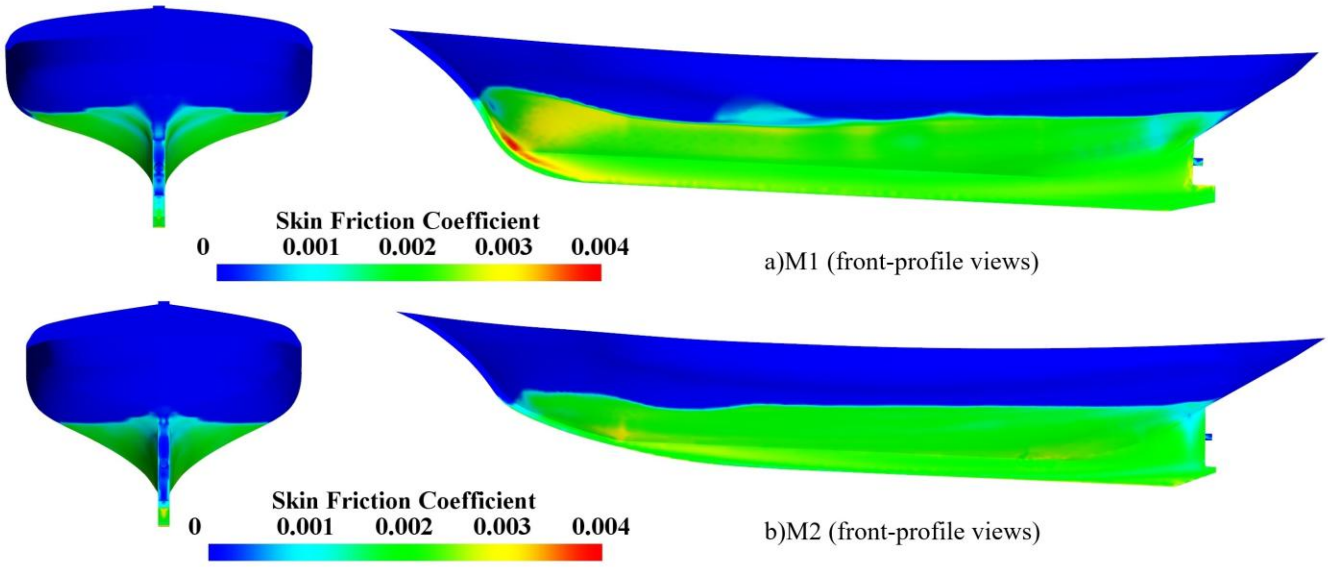

Fig. 5. Distribution of skin friction coefficient around the hull forms: M1 (a), M2 (b)

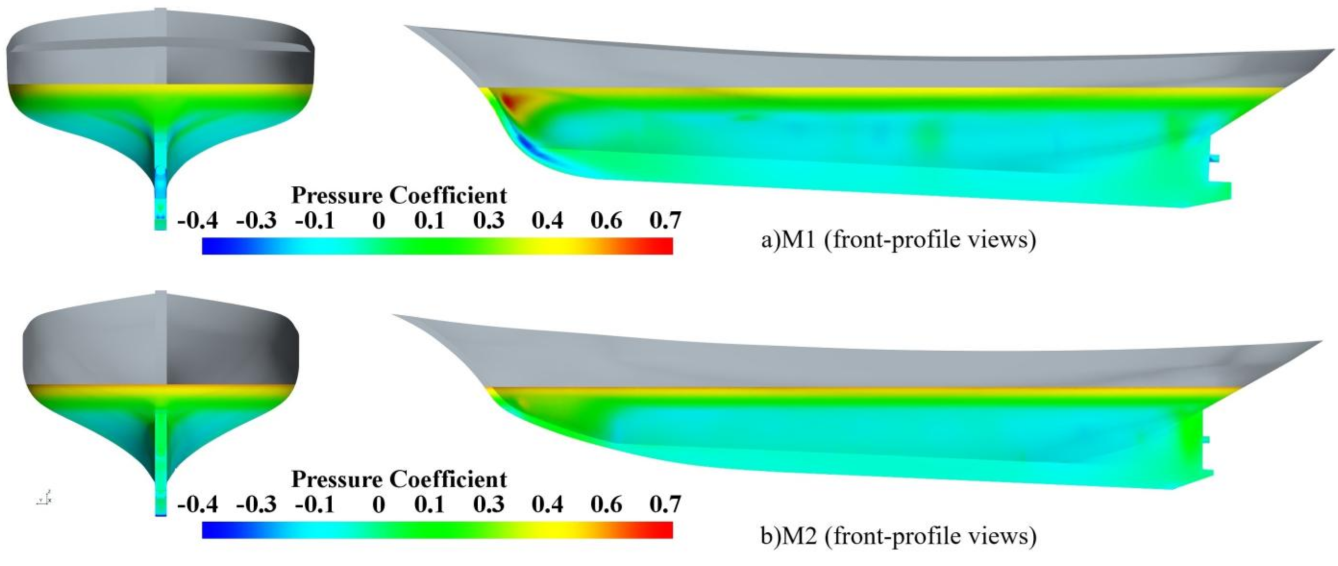

Fig. 6. Distribution of pressure coefficient around the hull forms: M1 (a), M2 (b)

The total resistance (R_T) values at 10 knots service speed for M1 and M2 are calculated to be 12.6 kN and 15.78 kN, respectively. The shares of pressure and frictional resistance are 7.56 kN and 5.04 kN for M1; 9.22 kN and 6.56 kN for M2, respectively. At the design speed of 12 knots, the total resistance values of M1 and M2 increase to 23.94 kN and 31.42 kN, respectively. The corresponding effective power values (P_E) at

12 kn are 147.8 kW and 193.9 kW, respectively. Assuming the sea and engine margins total 15 % [20], the total main engine power requirements for M1 and M2 are calculated to be 350 kW and 450 kW, respectively.

The validation study utilizes the experimental data provided by Kükner et al. [38], which involve resistance tests on traditional Bodrum Gulets as detailed in Table 3. The physical model used for testing was built at a 1:11 scale, with a loaded displacement of 93.05 kg, corresponding to a full-scale displacement of 123.85 metric tons. The numerical simulation is configured using the identical hull form of M1 and matching hydrostatic characteristics. As shown in Table 3, the numerical and experimental results show good agreement, with a maximum discrepancy of 4.73 %.

The distribution of wall shear stress along the hulls is presented in Figure 7. Wall shear stress serves as a key indicator of local flow behavior, particularly for identifying separation zones, which occur when the shear stress approaches zero or becomes negative, indicating flow reversal or detachment from the surface. In model M1, regions of low or negative wall shear stress are observed, especially near the stern and along certain curved sections, suggesting localized flow separation. This condition can increase pressure drag and contribute to higher overall resistance. In contrast, model M2 exhibits a more uniform distribution with fewer negative zones, indicating that the flow remains attached over most of the hull surface and thereby reducing skin-friction resistance. These findings are consistent with resistance and power analysis, as flow separation directly influences the skin-friction coefficient and overall hydrodynamic efficiency.

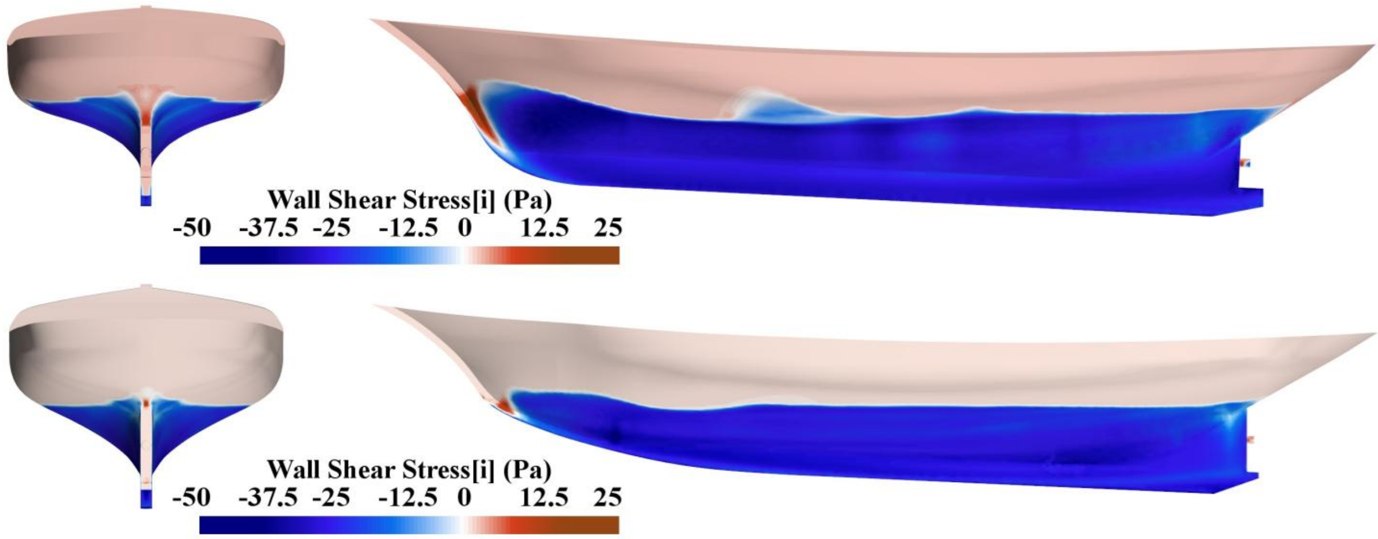

Fig. 7. Distribution of wall shear stress (*x*-direction) around the hull forms: M1 (a), M2 (b)

Table 3 Comparison of the CFD-based total resistance of M1 with model test results

Total Resistance	CFD	Model Tests	Deviation (%) CFD / Experiment
$R_{T@10\ kn}$ (kN)	15.78	16.34	3.43
$R_{T@12\ kn}$ (kN)	31.42	32.98	4.73

On the other hand, the Grid Convergence Index (*GCI*) method [39] is used to evaluate discretization errors and determine an appropriate mesh structure. The root mean square (RMS) value of the total resistance coefficient (C_T) is used as the reference parameter for assessing these errors. Table 4 presents the *GCI* values calculated for coarse (1.5 million), medium (2.2 million), and fine (3.2 million) meshes applied to the M2 form. Successive mesh refinements lead to a decrease in the *GCI*, satisfying the requirement $\left(GCI_{fine}^{21} < GCI_{med}^{32}\right)$. The reduction in GCI values from coarser to finer meshes indicates that the solution is nearly mesh-independent. Based on the grid convergence analysis, the mesh consisting of approximately 2.2 million cells is selected for numerical analyses, as it offers a balance between accuracy and computational cost. The relationship between mesh resolution and the total resistance coefficient is illustrated in Figure 8, which demonstrates that excessive grid refinement does not lead to significant improvements.

Table 4 The results of the mesh-independence study applied to M2 (r_{21}=r_{32}=1.46)

Parameter	***Fn*=0.32**
N_1, N_2, N_3(x10^{-6})	3.2, 2.2, 1.5
$G1$, $G2$, G_3(x10^3)	5.892, 5.836, 5.681
φ_{ext}^{21}(%)	0.59
e_a^{21} (%)	0.95
e_{ext}^{21} (%)	0.54
GCI_{fine}^{21} (%)	0.68
GCI_{med}^{32} (%)	1.89

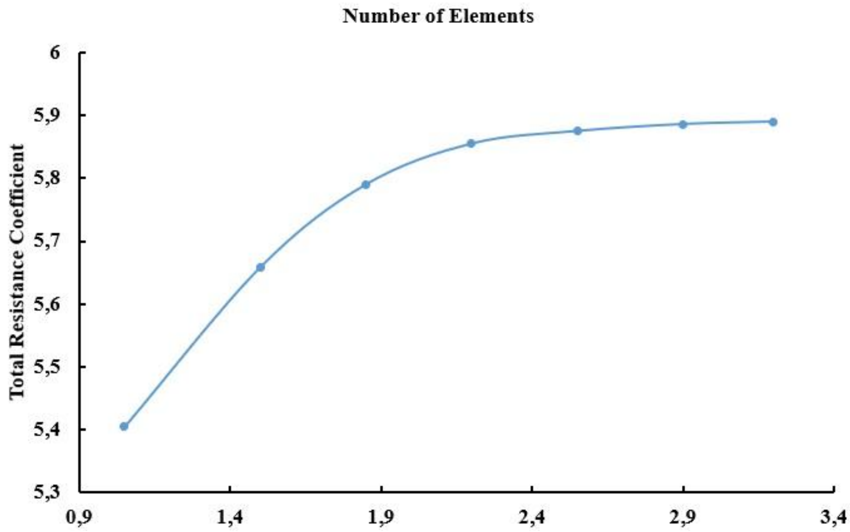

Fig. 8. Mesh Sensitivity Study Graph

4.2 Environmental impact evaluation

Transitioning to cleaner fuel technologies supports environmental conservation and enhances the Blue Voyage's appeal as an eco-friendly sailing experience. Figure 9 shows the CO_2 emissions of the Blue Voyage route of M1 based on different fuel types - Marine Diesel Oil, Liquefied Natural Gas, and Methanol - considering cruising and anchorage phases. The comparison highlights the potential environmental benefits of transitioning from conventional MDO to alternative fuels, as LNG and MeOH exhibit significantly lower emission levels. According to the results, the total CO_2 emissions per voyage are calculated as 5.11 tons for MDO, 4.61 tons for LNG, and 4.3 tons for the MeOH-powered M1-gulet, based on a total of 14.2 hours of cruising and 216 hours (24 hours/station) at anchorage. These values for M2-gulet at the same operating hours are 6.95 ton-CO_2, 6.26 ton-CO_2, and 5.84 ton-CO_2, respectively. Cruising-based CO_2 emissions are calculated as 2.68 tons, 2.46 tons, and 2.35 tons for M1-gulet powered by MDO, LNG, and MeOH, respectively. For the M2-gulet powered by MDO, LNG, and MeOH, the emission values are 3.48 tons, 3.19 tons, and 3.05 tons, respectively. Despite its higher fuel consumption, methanol has the lowest tank-to-wake environmental impact among other fuels. It is also noteworthy that the majority of the CO_2 emissions are sourced by the cruising phase, underscoring the importance of fuel type during active navigation. The use of alternative fuels, LNG and MeOH, leads to a significant reduction in emissions, not only during cruising but also during prolonged anchorage periods at bays, where auxiliary energy consumption contributes significantly to CO_2 emissions. It is notable that compared to MDO, both LNG and MeOH ALSO offer reductions of approximately 90 % in particulate matter (PM), 50 % in nitrogen oxides (NO_X), and 90 % in sulfur oxides (SO_X) [7].

Energy Efficiency Index (*EEI*) and voyage-based Emission Ratio (*ER*) of modelled gulets powered by different fuels are presented in Figure 10. According to the results, alternative fuels remarkably decrease the Energy Efficiency Index, contributing to the energy-efficient design of gulets. M2-gulet shows a significantly better energy efficiency compared to M1 across all fuel types, likely due to design or operational advantages. Methanol yields the lowest *EEI* values for both gulets, indicating its potential for enhancing energy efficiency.

It is noteworthy that, although the M2 gulet exhibits a lower Energy Efficiency Index compared to the M1, its Emission Ratio is notably higher. This is based on the larger gross tonnage of M2 (224 GT) compared to M1 (100 GT). Additionally, M2 has six cabins, whereas M1 has four, indicating a higher passenger capacity for M2. However, when the M2 gulet operates with a low passenger load, its higher *ER* value results in increased CO_2 emissions per passenger, thereby leading to a greater environmental impact relative to M1. This highlights the significance of maintaining high occupancy rates, particularly for larger vessels, to achieve environmentally sustainable maritime tourism operations.

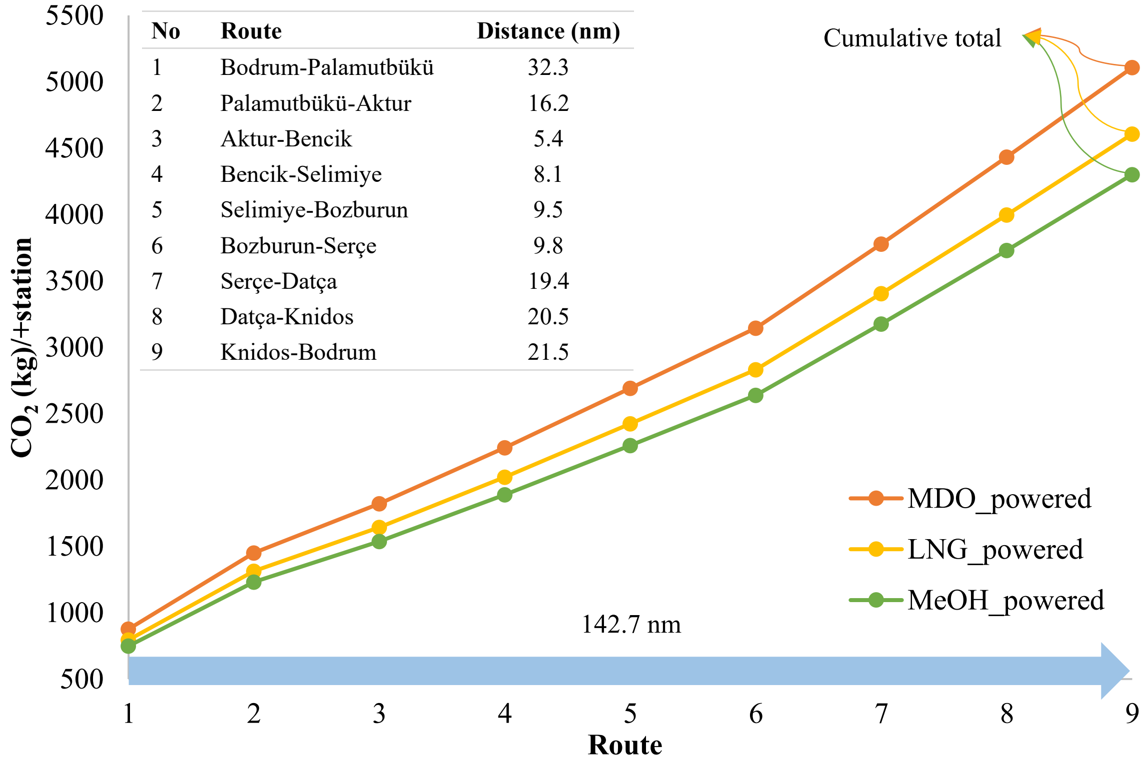

Fig. 9. Cumulative total CO_2 emission (cruising + anchorage) for the Blue Voyage case

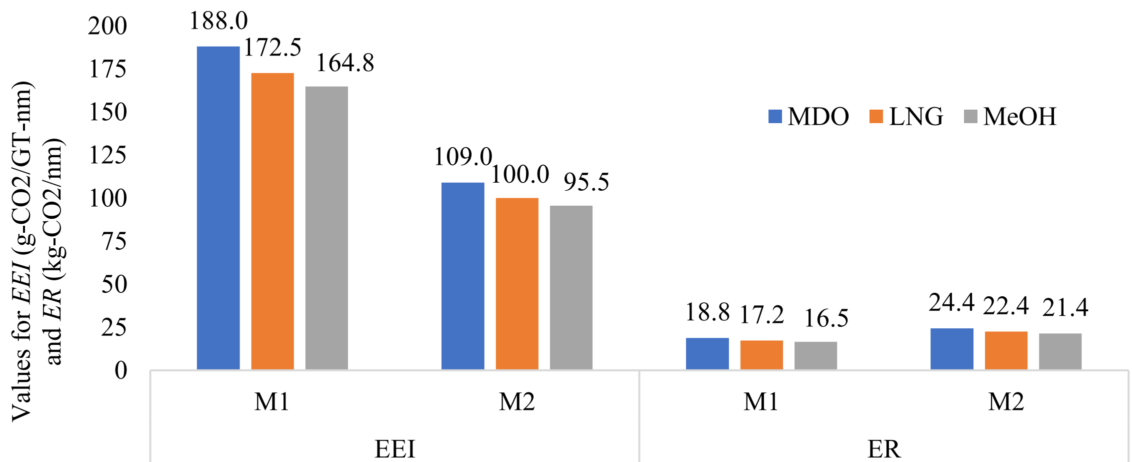

Fig. 10. Energy Efficiency Index (*EEI*) and Emission Ratio (*ER*) of the modelled gulets

4.3 Design remarks on using alternative fuels

The integration of alternative fuels into gulet design requires careful consideration of storage systems, safety protocols, and spatial configurations as detailed in Table 5. Compared to conventional MDO, both LNG and MeOH have lower energy densities, necessitating larger fuel storage volumes, which directly impact the internal layout and usable guest space—an important factor in touristic gulet operations. LNG, in particular, requires complex cryogenic storage at −162°C and poses higher safety and ventilation demands, making it more suitable for new builds rather than retrofitting existing vessels [7]. Methanol, on the other hand, is stored as a liquid at ambient conditions, allowing for simpler integration into existing tank spaces, although it requires corrosion-resistant materials and enhanced fire safety systems [40].

Table 5 Design remarks on using alternative fuels in powering gulets [19, 36, 40, 41, 42, 43]

Category	Marine Diesel Oil	Liquefied Natural Gas	Methanol
Storage	High energy density, stored in conventional tanks	Requires cryogenic (-162°C), vacuum-insulated tanks – large volume & weight	Storage at ambient temperature; requires corrosion-resistant or lined tanks
Space Requirement	Minimal impact on layout (reference)	~2.5x larger tank volume than MDO; extension of engine room by 2-4 m	~2x larger tank volume than MDO; easier to integrate than LNG; extension of engine room by 2-4 m
Safety Requirements	Standard marine safety systems	High: gas detection, double-walled tanks, ventilation systems	Moderate: Requires ventilation, fire suppression (for invisible fire), and toxicity control
Engine Compatibility	Widely available; mature technology	Requires spark-ignited or dual-fuel engines; No retrofitting option for existing diesel engines	Requires spark-ignited or dual-fuel engines; No retrofitting option for existing diesel engines
Fuel Availability	Widely available; Extensive infrastructure for Blue Voyage	Available; however, infrastructure remains limited for Blue Voyage region	Very limited adoption and no available infrastructure for Blue Voyage region
Retrofitting Feasibility	Easily retrofitted; existing systems used	Complex and space-demanding; limited feasibility for older gulets	Moderately feasible; better suited for retrofits than LNG
Regulatory Compliance	May not comply with future IMO/ECA limits	Compliant with IMO Tier II/III (SCR integrated) and ECA	Compliant with IMO Tier II/III (SCR integrated) and ECA; potential for green fuel credits
Operational Complexity	Well-understood; minimal training	High: requires cryogenic handling, specialized crew training	Moderate: training for safe handling and monitoring
Maintenance	Conventional maintenance routines	High-tech systems require specialized maintenance	Slightly more complex than diesel, material corrosion requires attention
Weight & Stability	Favorable for traditional gulet hulls	Affects the center of gravity; the keel with ballast weight can be reduced	Affects the center of gravity; the keel with ballast weight can be reduced
Suitability for Gulets	Traditionally used in all gulets	Limited to new builds or major reconstructions	Promising for both retrofitted and newly designed gulet

Besides, MDO remains the most compact and operationally simple option, but offers little future compliance margin with tightening emission limits. Both LNG and methanol require new or dual-fuel engines, yet methanol's simpler storage and lower integration demands seem to make it more adaptable for existing gulets. Stability effects are minor but necessitate renewed weight and trim checks. Overall, methanol and LNG appear to be the most balanced near-term alternatives for gulets; however, novel designs and infrastructure investments are required along the Blue Voyage route.

5. Conclusions

In this study, two gulet hull forms, with overall lengths of 24 m and 33.8 m, are modeled, and their hydrostatic characteristics are determined. Computational Fluid Dynamics analyses are performed to evaluate the flow behavior, total resistance, and power requirements of the modeled hulls. The environmental impacts of operating these gulets with marine diesel oil, liquefied natural gas, and methanol are evaluated through a Blue Voyage case study. Voyage-based Emission Ratio and Energy Efficiency Index are calculated to provide quantitative insights into the use of alternative fuels for gulets. Finally, design considerations for MDO-, LNG-and MeOH-powered gulets are discussed and compared. Based on the findings, the following conclusions are drawn:

- The CFD analysis shows that the modelled hulls based on the current gulet forms can be optimized to reduce total resistance, contributing to the transition of alternative fuels as the primary fuel sources for gulets.
- Environmental assessments reveal that utilizing LNG or MeOH as the primary fuel can reduce total CO_2 emissions by up to 9.8 % and 15.8 %, respectively. However, these reductions must be considered in the context of specific operational profiles of gulets.
- The Energy Efficiency Index (*EEI*) of gulet models powered by LNG and MeOH is approximately 8.3 % and 12.3 % lower, respectively, compared to the gulet model powered by conventional marine diesel oil (MDO).
- For gulets with larger gross tonnage and cabin capacity, such as M2-type vessels, the environmental benefits of alternative fuels become more significant, particularly when operating at high occupancy levels.
- The adoption of alternative fuels should be approached as part of an integrated design strategy that balances emissions reduction, vessel stability, safety compliance, and user experience. Even though the alternative fuels are promising choices for eco-friendly gulets and sustainable marine tourism, major modifications are required on both existing and newly designed gulets.
- The outcomes of this study extend beyond gulet applications and contribute to the wider transition toward sustainable maritime operations. By demonstrating the technical and environmental feasibility of methanol and LNG in small displacement crafts, the findings provide a framework that can guide future design, retrofitting, and policy initiatives aimed at low-emission marine tourism. The integration of CFD-based hydrodynamic optimization with alternative fuel assessment establishes a methodological foundation applicable to other categories of small vessels below 400 GT, which are currently outside the IMO's direct regulatory scope. Hence, this research supports the broader decarbonization agenda of the maritime industry and highlights the role of yacht and coastal tourism sectors as early adopters of cleaner propulsion technologies.
- The present study combines CFD-based hydrodynamic analyses with voyage-level environmental and energy efficiency assessments for gulets—a methodology rarely applied to small displacement crafts. The approach provides a quantitative foundation for evaluating alternative fuels within realistic operational contexts. However, the study is limited by its assumption of calm-water conditions and a fixed propulsive efficiency, without accounting for the influence of waves, wind, and self-propulsion effects. Additionally, infrastructure constraints and economic factors were not analyzed in detail. Despite these limitations, the methodology and findings offer a robust framework that can be expanded in future research through experimental validation, unsteady sea-state simulations, and techno-economic assessments of alternative fuel integration

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