

# Gas turbine prime movers fuelled by LNG as a future alternative for sustainable power in marine propulsion: current emission policy assessment and exhaust quality evaluation

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**Abstract.** In recent years, climate change has dramatically shown its effects in terms of fluctuations of temperatures because of increased global warming due to greenhouse gas emissions. Pollution control is strongly linked to atmospheric acidification and contaminants in combustion exhausts. In such a contest, marine propulsion is actually a key player that is accounting for a substantial contribution to pollution. Kyoto protocol's obligations established decarbonisation as a compulsory commitment and contaminant constraints are defined by current emission policy and regulations both on a global and on a regional basis. In this paper, a study is carried out in order to develop a framework for current emission policy and assessment of exhausts due to constraints imposed on fuel choice. Gas fuelled marine propulsion, implemented through state-of-the-art GT areoderivative prime movers, powered by LNG, is analysed from the environmental point of view. The pollutant emissions from various size GT models are evaluated through both GT datasheets and commercial (as well as self-coded) software, in order to assess the validity of LNG as an alternative fuel option for future sustainable marine applications.

## 1 Introduction

Greenhouse gas emissions (GHG) are being recently considered responsible for an undisputable trend in global warming. Thus, pollution control is usually strongly recommended and lately established by law.

The transport sector is a key player for such a problem: its powering is one of the energy conversion processes responsible for the above pollutant injections into the atmosphere and its contribution is dependent on conventional fuels. In the transport sector, marine propulsion is certainly accounting for a substantial contribution to pollution, especially in coastal zones, main marine routes, and harbour towns, as well as in a global world framework relating to sustainable energy policies. For this reason, marine propulsion is considered a keystone to sustainable power generation and innovative systems.

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Reduction of CO<sub>2</sub> from combustion is established by Kyoto protocol's obligations: decarbonisation may be met by gradually substituting traditional fuels (diesel and variable-weight marine gas oils) with alternative fuels marked out by a more propitious hydrogen-to-carbon ratio (natural gas). Contaminant constraints are established by current emission policy and regulations issued on a global and on a regional basis. For these reasons, abatement needs are actually forcing naval companies to consider either fuel substitution or the installation on board of expensive, as well as heavy, abatement device equipment. Gas fuelled propulsion can be implemented through GT prime movers, whose elected fuel for marine applications shows LNG (Liquified Natural Gas) to be one of the best candidate in a naval context [1].

In this paper a study is carried out in order to develop a framework for current emission policy and assessment of exhausts. The regulatory policy for emission control is discussed and its impact is taken into account. Since intercontinental naval routes span different geographical regions, focus is got on the legislative context and its evolution with regard to standards and regulations on a global basis. Emissions from different GT models are evaluated through GT manufacturer's datasheets and simulated by commercial as well as self-coded software, in order to assess the validity of LNG as a sustainable alternative fuel option for marine propulsion.

## **2 Marine propulsion**

Marine propulsion has been generally characterized by large internal combustion engines (2 strokes/4 strokes slow/medium speed diesel), powered by MGO (marine gas oil), MDO (marine diesel oil), IFO (intermediate fuel oil), HFO (heavy fuel oil), as common fuelling resources. Recently, due to environmental attention, a new interest has been aroused for innovative fuel sources, such as natural gas and liquefied gas (gas-fuelled engines). Similarly, interest has been aroused towards innovative propulsion systems, such as combined gas/steam cycles: COGAS (combined gas and steam), where propulsion is directly driven by the turbine shaft, and COGES (combined gas turbine electric and steam), where propulsion is driven by electrical power generated by the turbine shaft. For these systems GTs are ideal innovative prime movers [1, 2, 3, 4].

As compared with the Diesel counterpart, the gas turbine, which is characterized by smaller spaces for the engine and auxiliaries (especially for a power range above 20-30 MW [5]), reduced vibrations, and greater speed in the loading variation, nevertheless, it involves a higher cost on fuel and a lower efficiency. It is, however, appreciated above all for its reliability and reduced maintenance needs, both in terms of personnel and time required [6]. The first applications on commercial ships for freight and passenger transport date back to the 1970s with the GTS Finnjet [7]. Generally, a gas turbine requires about 50% less auxiliary equipment than a traditional ship engine and 75% less space on board once installed, including the engine and auxiliaries [2]. Maintenance is lowered to a maximum of 24 hours [2, 6, 8] using specific diagnostic software. In order to overcome the drawbacks associated with the lower efficiencies, as compared with the low speed Diesel engines actually installed on board, gas/steam combined cycle layouts, widely adopted in terrestrial applications, are in the last years being considered also for naval applications. The use of combined gas/steam cycles (in the aforementioned COGAS or COGES arrangements) allows on the one hand to exploit the advantages associated with the gas turbines just listed and on the other to maximize the efficiency of the plant thanks to the heat recovery from exhausts [1].

## **3 Environmental framework**

Naval transport is accounting for 5-10% of anthropic world SO<sub>2</sub> emissions [9] and for 80 times the SO<sub>x</sub> amount out of the aviation transport [10]. So a limiting regulation will obviously impact on cost increase for new designed ships (from 20% to 85%, depending on

speed, fuel price and ship tonnage) [11]. A similar consideration is valid for any different regulated pollutant.

IMO regulations have identified multiple international controlled areas (tab. 1). Harder constraints may be present on a regional or on a local basis (such as EC regulations [12] and related discretion in establishing additional limit values left to EC member states).

**Table 1.** Currently IMO controlled areas.

Geographical zone	Pollutant	Adoption	In force
Caribbean Sea (USA)	NO <sub>x</sub> , SO <sub>x</sub> , PM	26/07/11	01/01/14
North America	NO <sub>x</sub> , SO <sub>x</sub> , PM	23/03/10	01/08/12
North Sea	SO <sub>x</sub>	22/05/05	22/11/07
Baltic Sea	SO <sub>x</sub>	26/09/97	19/05/06

MARPOL Convention 73/78 has been an international panel aimed at reducing marine pollution originated from both ordinary ship operations and ship extreme events (e.g. hydrocarbon leakage to sea). *Annex VI* of MARPOL Convention (resolution of 1997, in force since 2005) concerns air pollution. It is applied to ships whose flag-country ratified the 1997 agreement as well as to ships whose flag-country did not, but that are anyhow operating into adherent countries' seas. *Annex VI* concerns 1) NO<sub>x</sub> and SO<sub>x</sub> in exhausts from internal combustion engines; 2) Volatile Organic Compound (VOC) out of shipload zone of cargo tanks. *Regulation 13* of *Annex VI* is relevant to NO<sub>x</sub> emissions, *Regulation 14* is relevant to SO<sub>x</sub> emissions. Details will be discussed in the following sections.

## 4 Emission regulation

### 4.1 NO<sub>x</sub> emissions

*Annex VI (Reg. 13)* [13] from MARPOL Convention 73/78 and *NO<sub>x</sub> Technical Code* [14] are regulations governing test, certification and control over NO<sub>x</sub> emissions from ordinary ship propulsion powered by internal combustion engines. NO<sub>x</sub> emission values are stated increasingly over years (application periods are called *Tiers*) for ships built from 2000, 2011 and 2016 (tab. 2). Since 01/01/16 all new built ships must comply with *Tier III* (3,4 - 2,0 g/kWh NO<sub>x</sub> limit).

*Reg. 13 - part. 1* [13] deals with engines above the 130 kW level and a distinction is drawn between an engine built before 2000 and after 2000. The latter must grant reduced emissions compared with the former one. NECA areas (*NO<sub>x</sub> Emission Control Areas*) are established, where NO<sub>x</sub> emission values must drop below 3,4 - 2,0 g/kWh, starting from January 2016. *Reg.13 - part. 2* [13] specifically deals with engines built before 2000 (1/1/90-31/12/99) exceeding the 5000 kW level. *Tier I* is in such a case applied when the engine matches additional environmental certification and technical-economical features.

As of today, a ship built after 01/01/16 must comply with *Tier III*: 1) 3,4 gNO<sub>x</sub>/kWh (engine speed lower than 130 rpm); 2)  $9 \cdot n^{-0.2}$  gNO<sub>x</sub>/kWh (engine speed ranging between 130-2000 rpm); 3) 2,0 gNO<sub>x</sub>/kWh (engine speed higher than 2000 rpm) (tab. 3).

**Table 2.** Application cases.

Engine type	Power	Commentary
Any diesel	≥ 130 kW	Ship built on or after 01/01/2000
Any diesel	≥ 130 kW	Engine subject to important reconversion at 01/01/2000
<b>Tiers</b>		
Tier I		Engine powering a ship built on or after 01/01/00
Tier II		Engine powering a ship built on or after 01/01/11
Tier III		Engine powering a ship built on or after 01/01/16

**Table 3.** NO<sub>x</sub> emission limits.

Tier	Ship building	Limit [g/kWh]	Limit [g/kWh]	Limit [g/kWh]
		n ≤ 130	130 < n < 2000	n ≥ 2000
I	01/01/00	17,0	$45 \cdot n^{-0,2}$	9,8
II	01/01/11	14,4	$44 \cdot n^{-0,23}$	7,7
III	01/01/16	3,4	$9 \cdot n^{-0,2}$	2,0

## 4.2 SO<sub>x</sub> emissions

Geographical areas subjected to SO<sub>x</sub> emission control are listed in *Annex VI (Reg. 14)*, *Annex I (Reg. 1)*, *Annex V (Reg. 1)* [13] of MARPOL Convention 73/78. Those areas are included in geographical zones reported in tab. 1.

*Annex VI* introduces limitations to the sulphur content allowed for the marine fuel (tab. 4): 1) a global limit has been established (sulphur content from 4,50% to 3,50%, in force since 2012, with an additional drop to 0,50% by 2020 and again a further undefined drop is scheduled by 2025); 2) a specific limit for SECA areas (*Sulphur Emission Control Areas*), where limitations are even far demanding (sulphur content is set at 1,00% as of 2012 and at 0,10% as of 2020).

**Table 4.** Fuel sulphur content.

Outside SECA areas		SECA areas	
Sulphur content [% m/m]	Time range	Sulphur content [% m/m]	Time range
4,50	before 01/01/12	1,50	before 01/07/10
3,50	from 01/01/12 to 31/12/19	1,00	from 01/07/10 to 01/01/15
0,50	from 01/01/20	0,10	from 01/01/15

According to *Annex VI*, ships inside a SECA area must comply with one of the following: 1) fuel sulphur content is lower than 1,5% m/m; 2) an exhaust scrubbing system maybe alternatively employed, providing at least a 6,0 gSO<sub>x</sub>/kWh abatement limit; 3) an alternative technological system, capable of granting a similar abatement, is at any rate employed.

As the rule concerns sulphur content inside the fuel, in order to match sulphur content inside the exhaust to appropriate values, IMO has introduced a simplified procedure [15]. The sulphur content is verified on the exhausts and an emission ratio is calculated. A comparison table has been regressively issued to match the calculated emission ratio against an equivalent deduced sulphur content in the fuel. A subsequent update [16] ratifies the existing limitations and specifies conditions in order to equivalently match *Annex VI Reg. 14.1* and *Reg. 14.4* (tab. 5) [16].

**Table 5.** Tab. 1 from Resolution MEPC. 259 (68) [16].

Marine fuel sulphur content [% m/m]	Emission ratio SO <sub>2</sub> (ppm)/CO <sub>2</sub> [% v/v]
4,50	195,0
3,50	151,7
1,50	65,0
1,00	43,3
0,50	21,7
0,10	4,3

*Reg. 14*, due to its stringent limitations, let adherent states to allow on their territory the use of technologies and fuels able to meet *Annex VI* requirements. EC regulations [12] are similarly promoting both the usage of a fuel whose sulphur content is within approved limits, as well as any alternative technology substituting approvable on-limit fuels.

### 4.3 CO emissions

At the best knowledge of the authors, IMO has never issued any international CO emission regulation. National regulations, such as U.S. EPA’s directives, may represent a valid reference [17]. EPA’s *Tiers II* set CO emission at a 5,0 gCO/kWh limit for large marine engines.

### 4.4 CO<sub>2</sub> emissions

CO<sub>2</sub> emissions are not subject to established limits yet, however they will be in the next future. IMO has introduced an *Energy Efficiency Design Index* (EEDI) [18], applied to the vessel design phase, and an *Energy Efficiency Operational Indicator* (EEOI) [19], applied to the vessel operational life. Those indexes give information about the ratio of environmental costs over social benefits and efficiency performance over time, during day-to-day vessel operations.

In the EC framework, CO<sub>2</sub> quotas authorization in the naval sector [20, 21] has recently became an obligation, hence CO<sub>2</sub> emission evaluation is progressively affecting the marine sector.

## 5 Propulsion and fuel characteristics for the study

For the present study three GTs have been selected as possible candidate prime movers and on board service power engines for marine applications, to empower COGES propulsion technology, through gas/steam combined cycles, with particular reference to intercontinental cruise shipping. GTs’ technical specs are reported in tab. 6 from the vendor datasheets at ISO conditions [22, 23, 24]. All models are not intended to use steam or water injection for NO<sub>x</sub> mitigation.

**Table 6.** GT prime movers.

GT Model	Power Output [MW]	Heat Rate [kJ/kWh]	Pressure Ratio	RPM	Exh. Flow [kg/s]	Exh. Temp. [°C]	NO <sub>x</sub> [ppm 15% O <sub>2</sub> ]	CO [ppm 15% O <sub>2</sub> ]
GE LM2500+	31,0	9796	22,8	3600	89,4	486	25	25
Siemens SGT A30	27,2	9904	20,6	3600	90,1	501	25	25
Solar Taurus 70	8,2	10470	16,5	3600	26,4	515	9	15

Depending on geographical extraction gas fields, LNG shows large composition variability. Simulations have been based on LNG mean composition (3 mixtures) from literature [4, 25] and sulphur contaminant tolerance from regulations [26, 27, 28], as reported in tabs. 7 and 8. The maximum sulphur value has been precautionarily adopted to test performance against the most unfavourable conditions (100 ppm - 0,01% vol).

**Table 7.** LNG mixture composition.

Mixture	CH <sub>4</sub> [% vol]	C <sub>2</sub> H <sub>6</sub> [% vol]	C <sub>3</sub> H <sub>8</sub> [% vol]	C <sub>4</sub> H <sub>10</sub> [% vol]	C <sub>5</sub> H <sub>12</sub> [% vol]	C <sub>6</sub> H <sub>14</sub> [% vol]	N <sub>2</sub> [% vol]
LNG light	98,60	1,18	0,10	0,02	0,00	0,00	0,10
LNG medium	92,30	5,00	1,50	0,60	0,10	0,00	0,50
LNG heavy	85,87	8,40	3,00	1,20	0,23	0,00	0,50

**Table 8.** LNG sulphur tolerance.

Contaminant	EASEE gas specs	ISO 15403:2006	OLT S.p.A.
	[mg/Sm <sup>3</sup> ]	[mg/Sm <sup>3</sup> ]	[mg/Sm <sup>3</sup> ]
RSH	6	15	15,5
H <sub>2</sub> S	5	5	6,6
S	30	120	150

## 6 Results

### 6.1 Methodology

GTs have been simulated through the THERMOFLEX® process-scheme design environment, granting full control (on fuel and air properties, GT engine, etc.). The fuel flow and the outlet temperature are calculated on the assumption that the fuel is oxidized in full measure and its lower heating value is fully exploited to produce the combustor exit temperature.

Emissions of CO<sub>2</sub> and of SO<sub>x</sub> are estimated on the assumption that all of the fuel's consumed carbon and sulphur are fully oxidized. Other pollutants (CO, NO<sub>x</sub>) in the exhaust are estimated through data from manufacturers' datasheets or through the procedure hereafter described.

Closed mass and chemical balances around the gas turbine are therefore calculated, as well as exhaust composition and enthalpy, providing the core quantities required for an overall heat balance check.

### 6.2 Discussion

The performance of the three selected gas turbines has been simulated under design and off-design conditions, through THERMOFLEX® by Thermoflow Inc [29]. SO<sub>x</sub> and CO emissions have been directly taken as a result of the Thermoflex simulations.

SO<sub>x</sub> emissions, plotted below in the shape of SO<sub>2</sub> emission ratio, as prescribed by the regulations, show an appreciable dependence on LNG composition and a quite constant trend with GT load. They are, however, way beyond the 4,3 SO<sub>2</sub> (ppm)/CO<sub>2</sub> [% v/v] indicating a fuel sulphur content lower than 0,10% m/m (fig. 1).

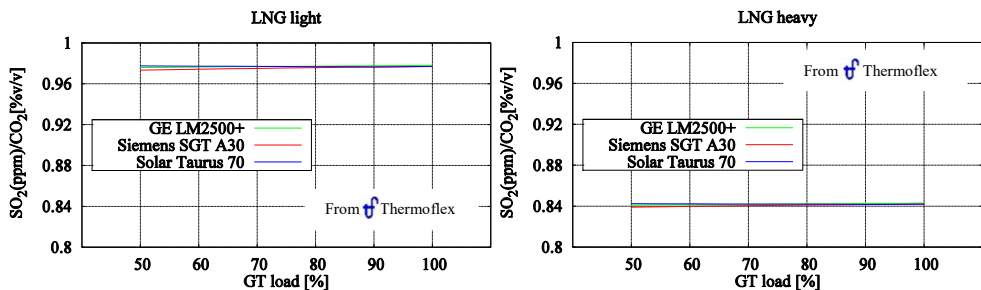


Fig. 1. SO<sub>x</sub> emissions from GTs for LNG light (on the left) and LNG heavy (on the right).

CO emissions show poor dependence on LNG composition. The value is way beyond the limit of 5,0 g/kWh stated by EPA Tier II (fig. 2).

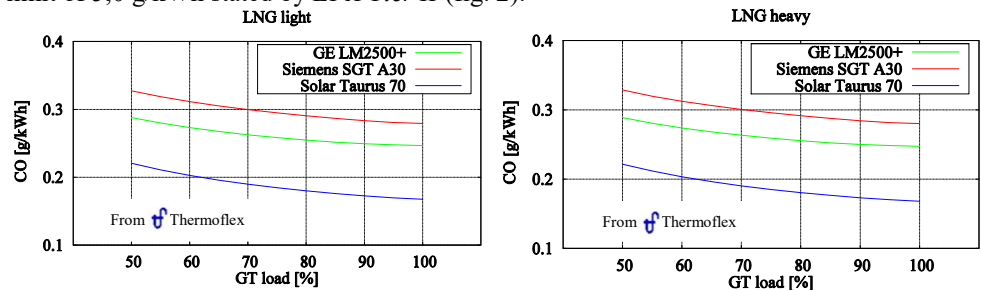


Fig. 2. CO emissions from GTs for LNG light (on the left) and LNG heavy (on the right).

For the above reported cases, results concerning LNG medium mixture, here not plotted for brevity, always show an intermediate trend between LNG light and LNG heavy mixtures.

To evaluate the thermal  $\text{NO}_x$  emissions, a different procedure, based on the classical theory, has been followed. This calculation, being simplified, has some limitations, based above all on the impossibility of using fuel mixtures. For this reason, pure methane has been simulated, which is a viable approximation for all three LNG mixtures. The calculation involves two phases. A first step consists in determining the adiabatic flame temperature and the concentration of the combustion products at equilibrium, once known the chemical composition of the fuel and the equivalence ratio. The calculation model is based on the use of the codes provided by Turns [30], based in turn on the routine of Olikara & Borman [31]. During the second phase, the values calculated at the previous step are used as input to determine the  $\text{NO}_x$  emissions, according to the extended Zeldovich mechanism [32]. The limitation of this procedure is related to the possibility of evaluating only thermal  $\text{NO}_x$  formation mechanism, related to adiabatic flame temperature value, which strongly reduces for partial load conditions. However, since usually in gas turbines the contribution from other (prompt and  $\text{N}_2\text{O}$  intermediate) formation mechanisms represent the 5-10% of the total amount of  $\text{NO}_x$  production, the neglected contributions should be small.

The result of the calculation for the different off-design conditions is shown both in terms of ppm made non dimensional by the value obtained under on-design conditions (fig. 3, on the left), and in terms of  $\text{gNO}_x/\text{kWh}$  (fig. 3, on the right), to allow the comparison with the limits imposed by regulations. The  $\text{NO}_x$  value is way beyond the limit of 2,0  $\text{g/kWh}$  stated by EPA Tier III, for all of the operating conditions.

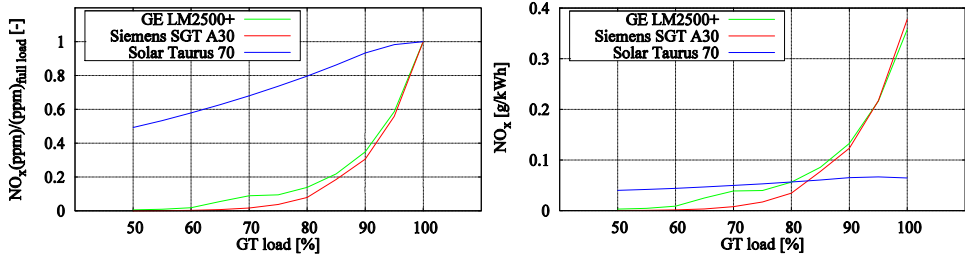


Fig. 3. Thermal  $\text{NO}_x$  emissions from GTs for LNG light

As no  $\text{CO}_2$  regulation at present forces the establishing of compulsory values (see Section 4.4), this emission component is not relevant from any existing emission regulation compliance. Anyway, for completeness a comparison has been performed between results obtained from the three analysed turbines for light and heavy LNG compositions. Results are shown in terms of both  $\text{gCO}_2/\text{kWh}$  and  $\text{kgCO}_2/\text{kgfuel}$  in figs. 4-5.

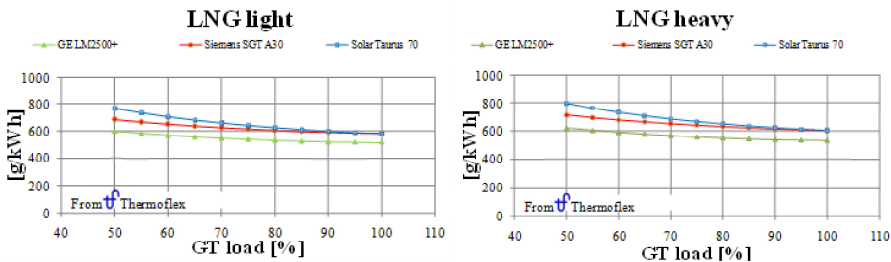
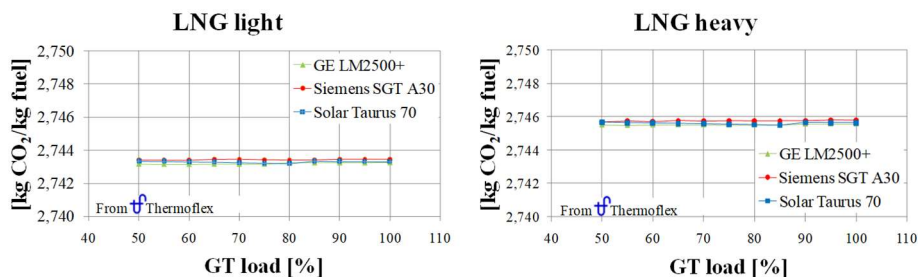


Fig. 4.  $\text{CO}_2$  emissions from GTs for LNG light (left) and LNG heavy (right).



**Fig. 5.** CO<sub>2</sub> emissions vs. fuel consumption from GTs for LNG light (left) and LNG heavy (right).

As expected, the gCO<sub>2</sub>/kWh values present a decreasing trend when the load increases, and the lowest are generated by the LM2500+ gas turbine. On the contrary, the kgCO<sub>2</sub>/kgfuel appear to be only slightly affected by the LNG composition.

## 7 Conclusions

Data contained in vendor datasheets and results obtained from software simulations show that present and future limits established for marine emissions are well compliant with the global regulation in force.

The advantage of introducing GTs in marine propulsion is backed up out of several considerations. The goal of a combined cycle is to achieve an increased work output for a given fuel supply. On account of such combined cycle designs, efficiencies are comparable to 2S/4S diesel engines' ones. Large reciprocating engines furthermore suffer from large weight and dimensions; on the contrary, GTs prime movers are smaller and lighter, and the global weight of propulsion, including combined cycle components, is reduced [1, 5-6]. Dual fuel reciprocating engines (fuelled by oil derivate and/or gas) benefit from high efficiencies, low sulphur emission, but increased amount of equipment, high installation and maintenance costs are a major concern.

The extremely poor content in sulphur contaminants, due to the liquefaction production process and contaminant abatement LNG is subjected to, grants the option of an alternative fuel virtually SO<sub>2</sub>/SO<sub>3</sub> free, capable of matching compulsory obligations. Furthermore, the GT combustion technology, with steady-state and controlled flame temperature grants heavy reduction in NO<sub>x</sub> emission, easily matching nitrogen regulations for current marine engines.

Finally, due to the fact that CO<sub>2</sub> emission evaluation is becoming a key factor in marine propulsion [20, 21], as well as in the vessel design operational stage (EEDI/ EEOI indexes), the choice of LNG (with an environmental advantageous C to H ratio, when compared to usual diesel or heavy oils) is an undoubtedly innovative step from the environmental protection and GHG reduction point of view.

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