The propulsion of coastal and inland water transportation vessels - Working data acquisition and preliminary design of innovative systems to reduce pollutant emissions

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Abstract

An unusual but rewarding partnership has involved both public (Dept. of Naval Engineering - Naples and CNR Istituto Motori - Naples) and private (Systems and Advanced Technologies Engineering - Venice) organisations in co-operation with the public transportation company of Venice (ACTV). The cue of this co-operation was the renewal, now in progress, of the fleet providing the public transportation in the Venetian lagoon; in this framework the study of *the operating conditions of a vessel destined to the service in inner waters* has taken place recently and has already given interesting and encouraging indications about the possible improvements in the energy systems of the ACTV vessels.

The first step of this research was the evaluation of the real operating conditions of a boat in service in inner waters by onboard measurements and theoretical analysis; this involved a campaign of measurements and the subsequent analysis and synthesis of the collected data.

The final goal is the design of an alternative energy system capable of improving the present working conditions and, in particular, fuel consumption and exhaust emissions. The importance of the screening of harmful emissions and the effort in reducing them come from the possibility that, in the near future, international laws and regulations limiting the emissions from marine engines will be set forth, especially for vessels operating in coastal and inner waters.

Hence, this paper will outline the state of the art and report the conclusions drawn from the data logging campaign. Particular attention has been paid to the analysis of the fuel consumption and emission reduction obtainable with an alternative energy management based on a hybrid diesel - electric system with an energy buffer provided by electric batteries.

Introduction

Rarely, in the field of marine power systems, are the working conditions such that the amount of the time spent in transient state largely overcomes the time in permanent state (as it happens, for example, in road traction, especially in the urban cycles).

But there is a very remarkable exception: *public transportation in the Venetian lagoon.* People and car transportation in this “Town of Water” is provided by some types of vessels (different in dimensions and missions) destined to lagoon service.

This creates the same well-known troubles as in road traction: the need of working at very different running states leads to oversizing of the propulsion engine, which, generally coupled directly to the final user (the propeller, in this case), must work, for most of its life, at rates and speeds lower than the nominal ones and, thus, with poor consumption and emissions.

The ACTV (the public transportation company in Venice) supplies service in the lagoon with six types of vessels. The transportation of cars and heavy vehicles is provided by ships and ferries with displacement from 200 to 600 tons working in large canals as the normal ships usually do, i.e. basically in permanent running state; the transportation of people in the canals and in the very centre of the town is granted by two types of boats: the water bus (“vaporetto” - M/B) and the motor craft (“motoscafo” - M/S). The fleet includes also a fully electric water bus that works, however, quite rarely, being a prototype; the main characteristics of these boats are reported in the table 1.

type	**n**	**D**	**grt**	**pass**	**v**	**lbp**	**P**
M/B	54	37.5	24	220	11	21	135
M/S	59	21.2	23	155	11.5	20.8	135
E/B	1	32	24	208	9	20.9	60

n - number of vessels
D - displacement [t]
grt - gross register tonn
pass - max number of passengers
v - speed of the vessel [kn]
lbp - length between perpendiculars [m]
P - MCR of main engine [kW]

Table 1 - Characteristics of the boats working in the Venetian lagoon

This study was performed on the most critical lines crossing the city of Venice, involving the M/B type vessel; indeed these boats run along the narrow canals of the lagoon, almost always in transient state and close to the most inhabited areas, thus amplifying the problem of releasing noxious substances and enhancing the pollution level in such areas. Table 2 shows the main characteristics of the boat taken into consideration.

M/B 54	
Lbp = 20.91 m	**Reduction-inversion gear**: Lohman GUS 200
Δ = 38.7 t (with no passengers)	mean reduction ratio = 4:1
v = 11 kn	**Propeller**: 3 blades (right)
max passenger number: 224	D = 1000 mm
Engine: IVECO ***aifo*** M821	p = 1000 mm
MCR: 162 kW @ 2200 rpm	hull conditions: limit of classification (very dirty)
nominal power according to the propeller law:	140 kW (at the engine shaft) @ 1800 engine rpm 120 kW (at the propeller shaft) @ 440 propeller rpm

Table 2 - Main characteristics of the M/B

Previous papers by the authors dealt with the analysis of the data acquired on board, in particular, those regarding torque, power and engine speed, focusing on the degree of irregularity of the service conditions of the present engine system. Preliminary conclusions showed that a significant reduction in fuel consumption and noxious emissions can be obtained by a diesel-electric hybrid system. This paper goes into more detail as concerns this analysis, and proposes a new energy system with a working cycle which should be particularly suitable for the application under exam.

The rules on exhaust emissions existing in the naval field

Since the '60s, the environmental pollution caused by propulsion engines has been considered and several regulations have been enacted so as to limit exhaust emissions from such engines. The marine field, however, did not receive the same attention due to the very different sizes, operations and characteristics of the naval engines.

Nevertheless, marine pollution can be very heavy in case of high concentrations of ships working in relatively restricted areas such as big ports where the simultaneous presence of many vessels may create a large release of noxious substances in the air and in the water. Probably, the contribution to pollution from marine engines is modest but, in order to decongest land traffic, there is a shift in the merchant activity from land to sea and, in general, to water traffic. Moreover, there are remarkable exceptions such as the "Towns of Water", where the people and car moving is supplied by marine systems which, working close to the coasts, may create big problems of concentration of harmful substances in the environment.

This is the reason why there are more local than international regulations universally valid; naturally, the problem of limiting exhaust emissions is more felt in areas largely involved in maritime trade. The first approach is the extension to the marine field of the regulations already valid for the road traction engines, although the working conditions of the engines are quite different in the two cases. The IMO, on the guideline of international boards like ISO, EPA, CIMAC, EUROMOT, is promoting some procedures for the limitation of exhaust (most of all NOx, although also CO, THC, CO_2 and, in the future, other substances will be taken into consideration).

An example of local regulation is that promoted by the CARB (Californian Air Resources Board) for the Long Beach - Los Angeles area; table 3 shows the limits proposed for the emissions from the main engine and from the auxiliaries:

	Engine	*NOx limit (ppm at 15% O2)*	*NOx limit (g/kWh at 15% O2)*
new ship	main engine	130	2
	auxiliary engine	600	10
in use ship	main engine	600	10
	auxiliary engine	750	12

Maximum bunker fuel sulphur content 0.05%

Table 3 - CARB limits to NOx emissions in the Long Beach - Los Angeles area

The IMO is also interested in the strategy of reduction of NOx and SOx using two different approaches (which are subject, of course, to discussion and different evaluations): the first is "the lower limits for the highest speed", i.e. it defines the limit of NOx emissions as inversely proportional to the engine speed thus favouring low speed engines. In figure 1 the IMO limits are reported as a function of the engine speed together with the field including the values of the NOx emissions from present marine engines (source: Ricardo Library Services - Worldwide exhaust emissions legislation summaries). Others, in the IMO context, consider it better to link the NOx maximum allowable emission to the specific consumption (BSFC) following a law shown in figure 2

As regards the proposed test method and measurement systems, the ISO 8178 project supplies some indications regarding the measure of gaseous emissions and particulate matter together with the mission profile suggested for marine engines.

Thus, although at present there are a few rules valid only in particular zones, probably, in the near future, general regulations will be promoted by the countries interested to coastal and inner water navigation. In such perspective, neglecting this aspect in the choice of propulsion plants today (by ship manufacturers and owners) could eventually bring some difficulties in respecting rules.

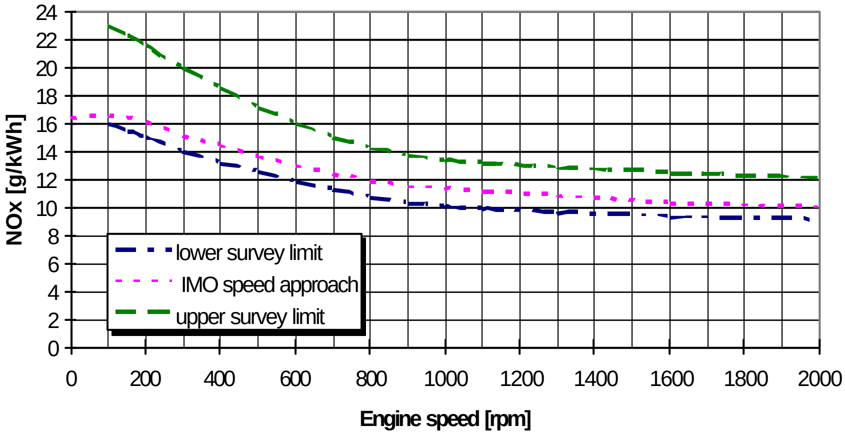

Fig 1 - IMO speed approach for the NOx emissions from large marine diesel engine

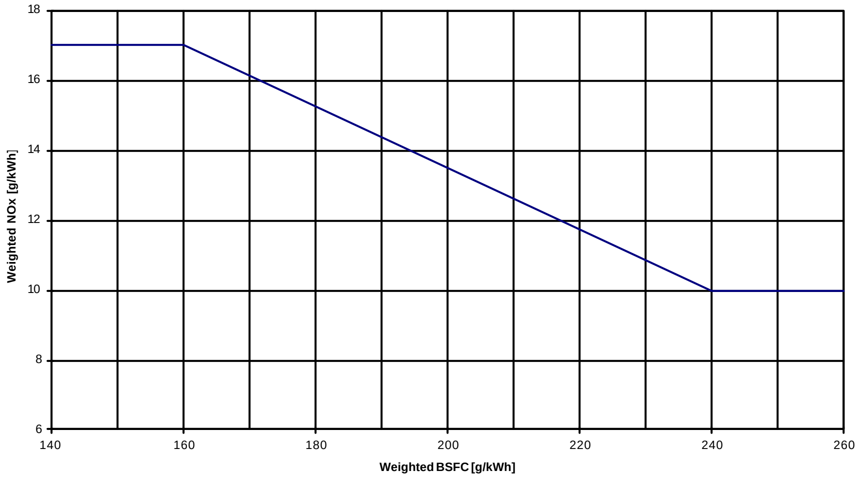

Fig 2 - IMO specific fuel consumption approach to NOx regulations

The load profile of the water bus

In order to appreciate the real working conditions of a water bus, a campaign of data logging was carried out on the vessel on bollard, in free water and in service in the various lines running through the centre of the town; among them, the research focused on route n.1 moving along the Grand Canal and having a large number of stops, with consequently a heavy sequence of stop-and-go transient conditions.

Torque, propeller and engine rpm (the transmission ratio varies due to a hydraulic coupling existing between the engine and the shaft line), water and air inlet and outlet temperatures were recorded continuously with a sampling rate of 2 Hz; fuel consumption and exhaust emissions were also logged in the various working conditions of the boat.

The results were processed and underwent a statistical analysis; this paper shows the results of the elaboration and the analysis of a whole trip (to the destination and back) along the Grand Canal which can be considered as a sample of the route 1 working conditions. Figures 3 to 5 show the load profile of the water bus in a trip (n. 30, in the sequential order) from P.le Roma to Lido together with the related statistical distribution of the power levels; figures 6 to 8 show the same in the return trip (n. 40: Lido - P.le Roma).

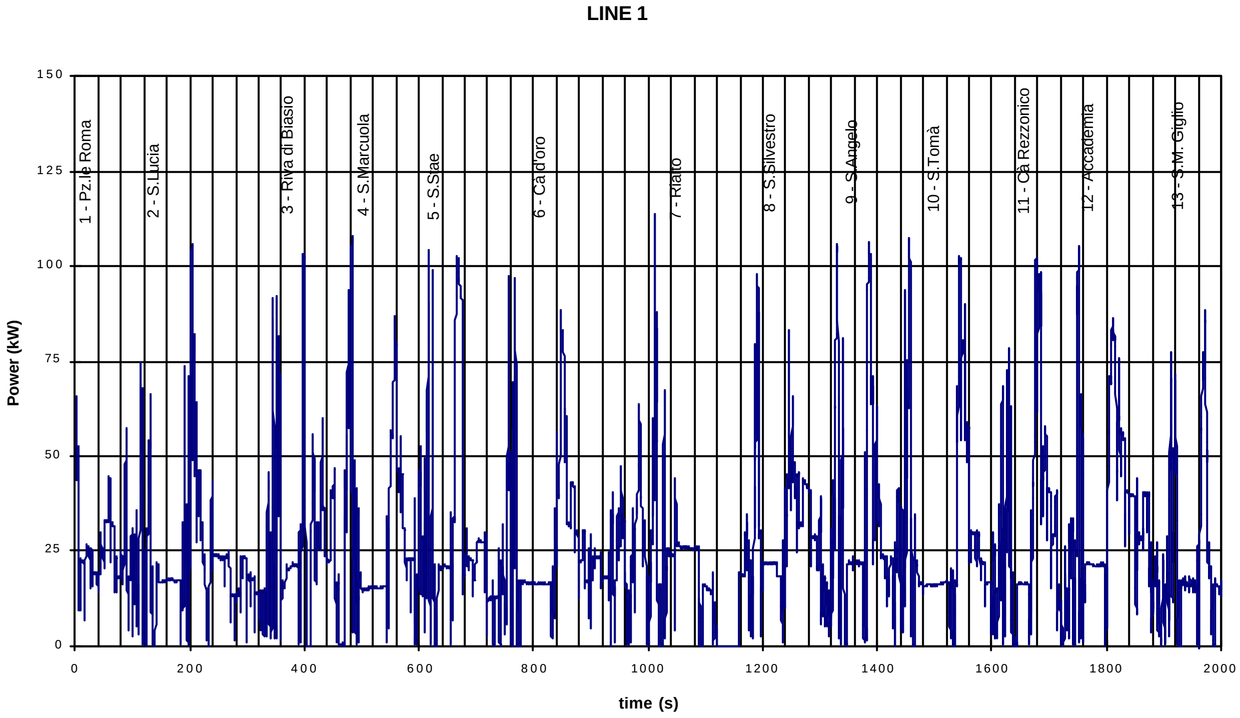

Fig 3 - Recorded propeller shaft power during the first half of the route 1 (P.le Roma - S. M. del Giglio)

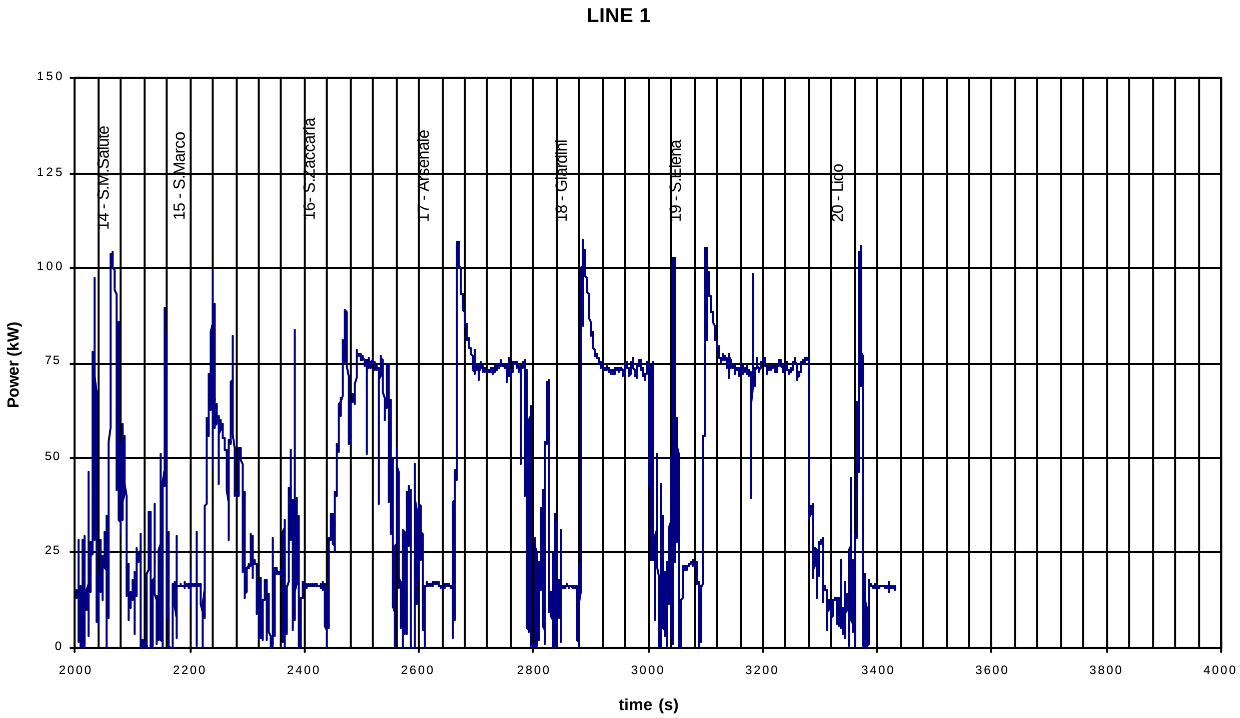

Fig 4 - Recorded propeller shaft power during the second half of the route 1 (S. M. Salute - Lido)

PROPELLER SHAFT POWER STATISTICAL ANALYSIS
Absolute Power (kW)

LINE	1 (Grand Canal)		
FILE	CR30E		
MAXIMUM	113.6		
MINIMUM	0.0		
AVERAGE	33.6		
VARIANCY	26.3		
MEDIAN	22.5		
	P1 (kW)	f (P<=P1)	f (P1<P<=P2)
DISTRIBUTION	0	0.000	0.083
	5	0.083	0.033
	10	0.116	0.080
	15	0.196	0.218
	20	0.414	0.135
	25	0.549	0.071
	30	0.620	0.045
	35	0.665	0.031
	40	0.696	0.036
	45	0.732	0.017
	50	0.749	0.017
	55	0.766	0.019
	60	0.785	0.014
	65	0.799	0.013
	70	0.812	0.092
	75	0.904	0.042
	80	0.946	0.013
	85	0.959	0.010
	90	0.969	0.008
	95	0.977	0.008
	100	0.985	0.011
	105	0.996	0.003
	110	0.999	0.001
	114	1.000	

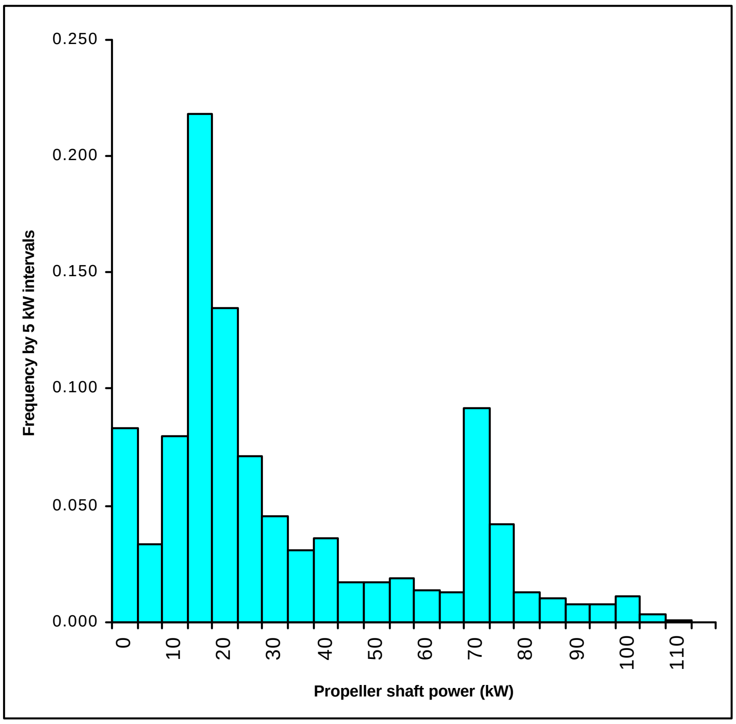

Fig 5 - Power distribution (route 1 - outbound trip)

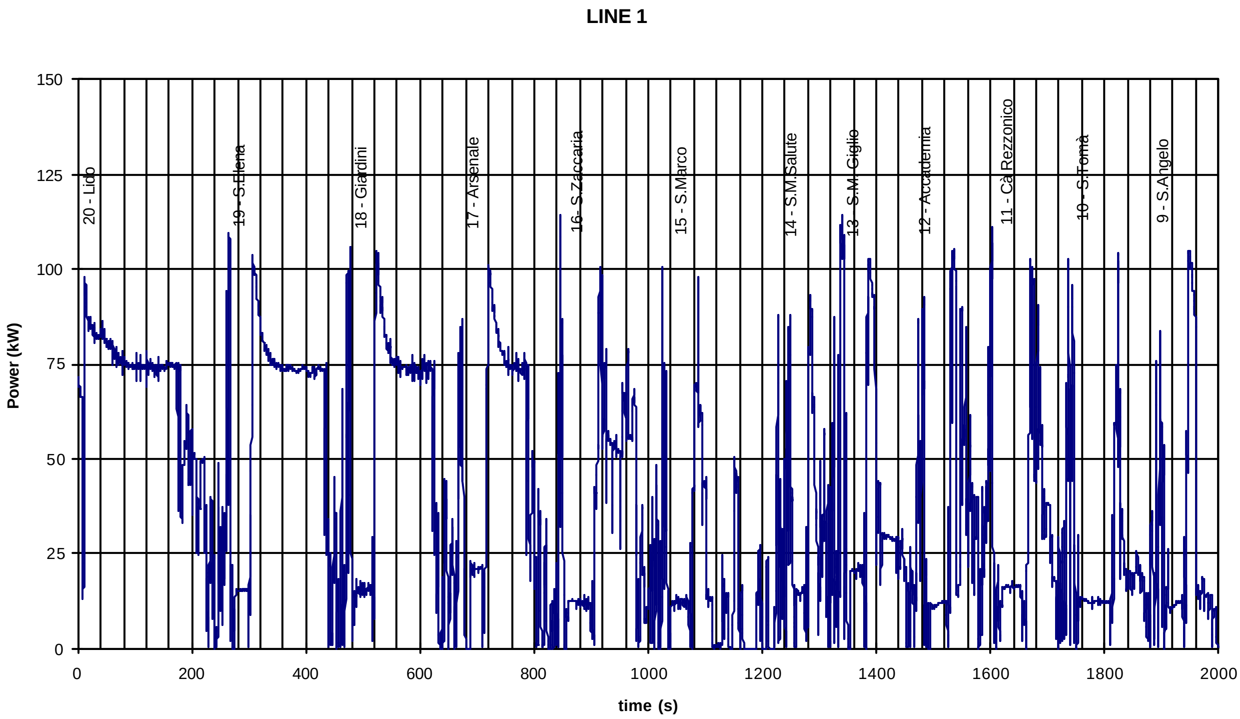

Fig 6 - Recorded propeller shaft power during the first half of the course 1 (Lido - S. Angelo)

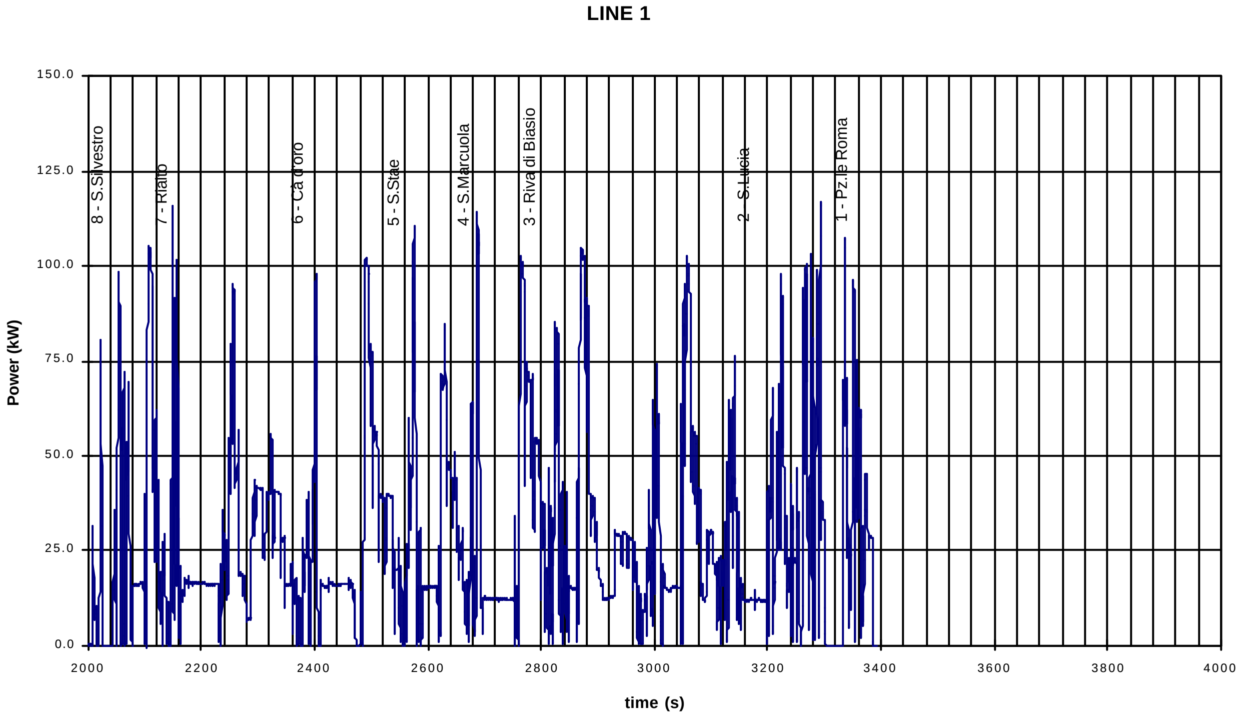

Fig 7 - Recorded propeller shaft power during the second half of the course 1 (S. Silvestro - P.le Roma)

PROPELLER SHAFT POWER STATISTICAL ANALYSIS

Absolute Power (kW)

LINE	1 (Grand Canal)		
FILE		CR40E	
MAXIMUM		116.1	
MINIMUM		0.0	
AVERAGE		35.0	
VARIANCY		29.3	
MEDIAN		22.5	
	P1 (kW)	f (P<=P1)	f (P1<P<=P2)
DISTRIBUTION	0	0.000	0.114
	5	0.114	0.045
	10	0.159	0.155
	15	0.314	0.142
	20	0.456	0.062
	25	0.518	0.059
	30	0.577	0.033
	35	0.610	0.040
	40	0.650	0.037
	45	0.687	0.023
	50	0.710	0.022
	55	0.732	0.024
	60	0.756	0.015
	65	0.771	0.017
	70	0.788	0.085
	75	0.873	0.039
	80	0.912	0.021
	85	0.933	0.014
	90	0.947	0.015
	95	0.962	0.015
	100	0.977	0.017
	105	0.994	0.004
	110	0.998	0.002
	116	1.000	

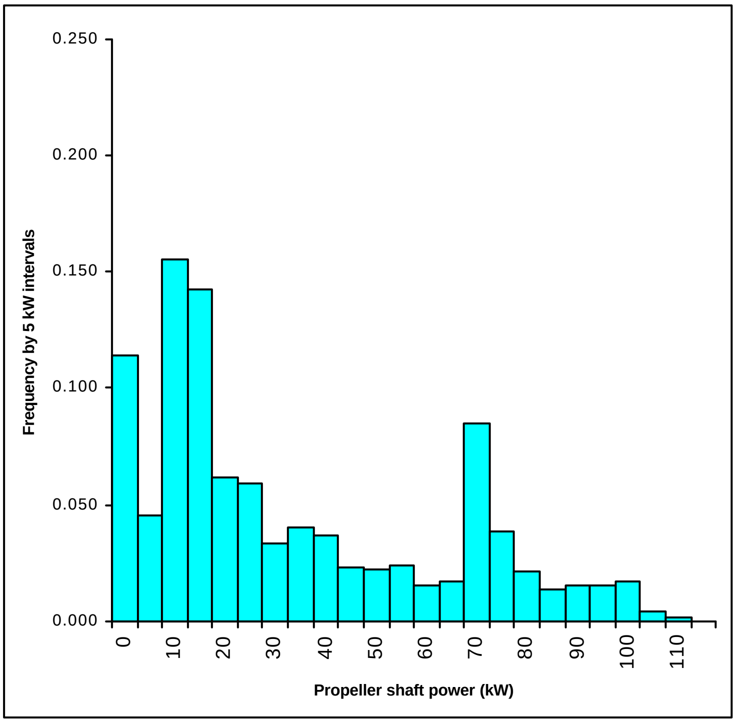

Fig 8 - Power distribution (line 1 - return trip)

It is worth pointing out that the above figures give the *propeller shaft power* (since the real point of measure was in the last part of the shaft line). For the following analysis, it is useful to estimate the *engine shaft power* which can be obtained dividing the useful propeller power by the shaft line efficiency (η = 0.856); consequently, the main statistical parameters of the engine power distribution are changed as in table 4 while the power frequency distribution diagrams are similar to the ones in figures 5 and 8 due to scaling up of the power levels.

trip	*minimum engine shaft power (kW)*	*average engine shaft power (kW)*	*maximum engine shaft power (kW)*
30	0	39.3	132.7
40	0	40.9	135.6

Table 4 - Engine shaft power statistic values

The analysis of these diagrams shows that the mean power used is much lower than the one installed on board (respectively 40 kW and 140 kW at the engine shaft) with a very strong degree of irregularity in the power supply. This underutilisation of the engine causes the poor operating conditions mentioned above and worsens fuel consumption and exhaust emissions. This can be minimised by reducing the ratio between the MCR of the engine installed on board and the value of the mean power used and, most of all, letting the engine work in better conditions (i.e. at as constant a speed as possible).

Fuel consumption and emissions

During the data logging campaign, the figures on fuel consumption were measured in each trip: the following table shows the fuel consumption read (trips n. 30 and 40).

trip	*course*	*total consumption (g)*	*consumption per hour (g/h)*	*mean specific consumption (g/kWh)*
30	1	12893	13651	348
40	1	13577	14722	360

Table 5 - Fuel consumption of the M/B 54 in the routes in the Grand Canal

During the data logging campaign, the exhaust emissions were also read on board: figures 9 and 10 show the present situation of the NOx emissions.

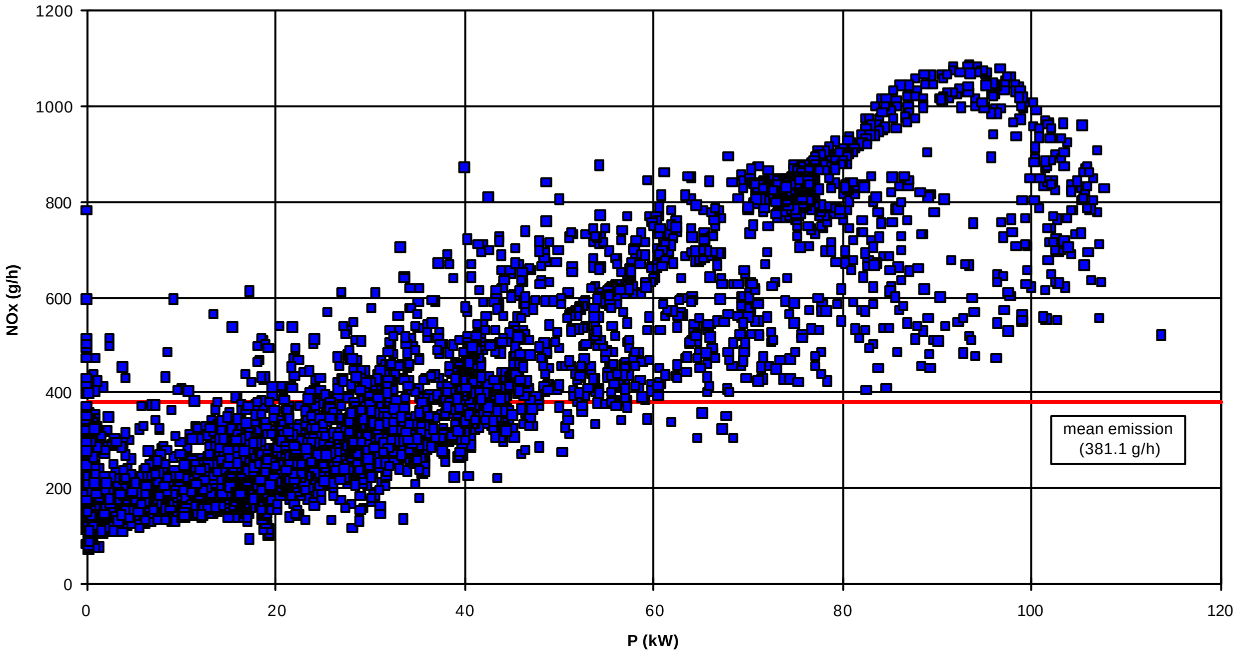

Fig 9 - NOx emission scatter diagram (course n. 30)

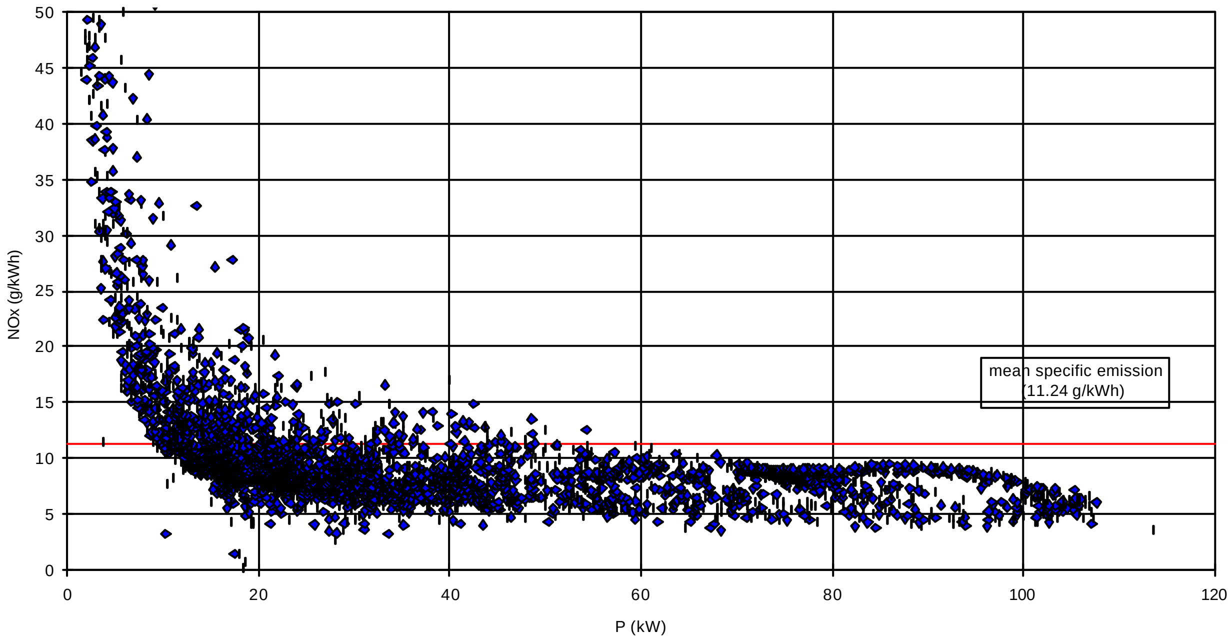

Fig 10 - NOx specific emission scatter diagram (course n. 30)

It is worth remarking that the mean value of NOx specific emission (~ 11 g/kWh) is higher than the present limit (8 g/kWh up to October '95 and 7 g/kWh thereafter) adopted by the ECE R49 rule for the limitation of exhaust emissions from road traction engines, which will probably be extended to the naval field.

Why should the hybrid system solve these problems ?

The load profile and the consumption and emissions read on board clearly say that*, it is very unlikely that a decisive improvement in the operating conditions of this kind of marine system can be obtained without experimenting with innovative energy management systems*. In particular, for the missions of the motor boats working in the lagoon, it is necessary to lower the degree of irregularity by providing the energy system with an energy buffer; indeed, it could either supply or store energy according to the requirements of the propulsion system of the boat thus letting the main engine work in permanent state for the most part of its operations.

Several kinds of alternative propulsion systems have been taken into consideration, from the simple reduction of the engine power rating to a fully electric system. The one which shows the best performance from the point of view of a compromise between the required characteristics (reduction of specific consumption and emissions, use of conventional and non-extreme technologies, suitability to technologically-improved components) seems to be the *diesel-electric hybrid system with energy buffer*. Moreover, especially if the energy buffer is composed of a battery package, this solution fits very well the marine application, thanks to the remarkable room available on board and the possibility of carrying relevant weights, maybe reducing the solid ballast needed.

Certainly, other systems can be applied but the hybrid seems to be the best compromise. In comparison with the fully electric system, it improves endurance (normally there is no need of battery charge and, consequently, of related substations) and energy management (when considering the whole cycle efficiency of the transformation of the primary energy and its transportation from the power station to the boat). In comparison with the traditional system, the hybrid shows better energy management and, consequently, better consumption and emissions.

On the other hand, several important manufacturers of road traction systems are studying hybrid applications (with various solutions) in extreme conditions, for example, when there is not much room for the energy buffer tools. In the field of public transportation, some busses moved by I.C.E. - electric hybrid systems are already in service (for instance, the public transportation company of Stockholm regularly uses two hybrid busses for urban service) showing that this solution fits perfectly the local transportation needs. In Italy also some hybrid busses are running and will be delivered this year for regular service.

The hybrid system proposed

After the evaluation of several possible settings and considering some features as pre-eminent, two solutions for the layout of a new energy system were conceived: figures 11 and 12 show the hybrid system schemes proposed and table 6 summarises their main characteristics.

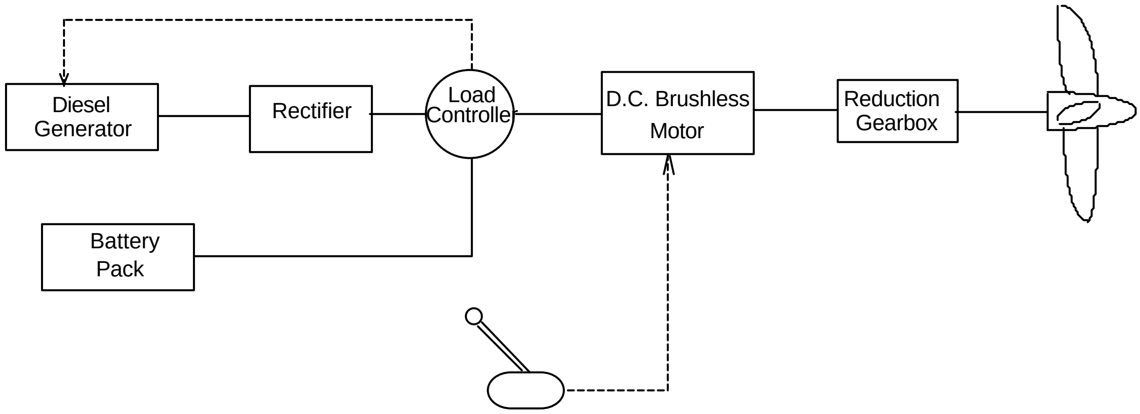

Fig 11 - Scheme of the hybrid diesel - layout with D. C. brushless engine

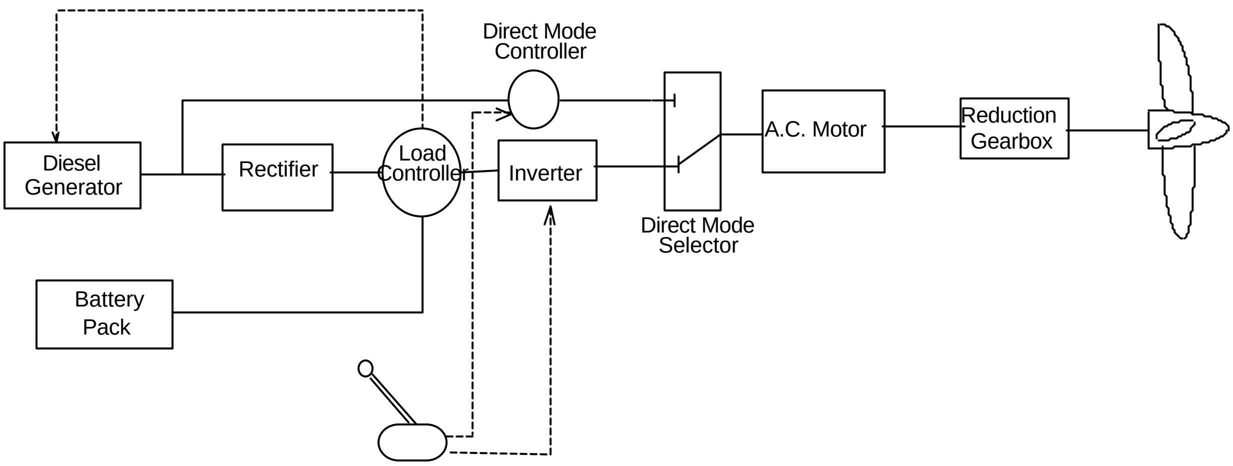

Fig 12 - Scheme of the hybrid diesel - layout with A. C. asynchronous engine

electric generator driven by the diesel engine
rectifier
buffer of electric batteries
battery charge regulation system
electric set cooling system
CC/CA inverter with voltage and frequency variable output
reduction gear
brushless engine with variable speed (D. C. solution)
three-phase asynchronous engine (A. C. solution)

Table 6 - Main elements in the layout of the hybrid system

For each working condition of the hybrid, the final efficiency varies as a function of the efficiency of each element involved; table 7 sums up the expected power conversion efficiencies in the possible working conditions of the system and compares them with the present ones.

	(with charge and discharge)	(without charge and discharge)	(direct)	(present system)
alternator	0.880	0.880	0.880	-
rectifier	0.980	0.980	-	-
batteries	0.850	-	-	-
inverter	0.970	0.970	-	-
motor	0.880	0.880	0.880	-
azimuthal propeller	0.980	0.980	0.980	-
hydraulic coupling	-	-	-	0.900
reduction gear	-	-	-	0.970
transmission and bearings	-	-	-	0.980
global efficiency	**0.613**	**0.721**	**0.759**	**0.856**

Table 7 - Comparison among the various solutions for the propulsion of the boat

The main effect of such systems would be:

- a diesel engine with a maximum rating lower than the present one would work closer to the mean power required by the load profile;
- it is possible to operate the engine in an optimised range of working conditions since the power requirement does not depend anymore on the instantaneous propeller demand.

As regards the working cycle of this system, the load profile can be chosen in a wide range; for the moment, after several tests, an operation mode with two power levels of the I.C.E. has been preferred. This procedure leads to four working conditions of the system; table 8 outlines the foreseen operating conditions giving the variables on the interface at which powers are referred:

	a case	**b case**	**g case**	**d case**
	$P < P_B$	$P_B < P < P_{med}$	$P_{med} < P < P_A$	$P > P_A$
P_m	$P/\eta_1 + (P_B - P)/\eta_2$	P_B/η_1	$P/\eta_1 + (P_A - P)/\eta_2$	P_A/η_1
P_d		$P - P_B$		$P - P_A$
P_c	$P_B - P$		$P_A - P$	
phase	charge	discharge	charge	discharge

Table 8 - Operational modes of the hybrid system

P	power demand at the propeller shaft
P_m	power released by the diesel engine at the engine shaft
P_b	battery power (in discharge when supplied, in charge when absorbed) at the propeller shaft
P_c	charge power (power absorbed by batteries during the charge phase) at the propeller shaft
P_d	discharge power (power delivered by batteries during the discharge phase) at the propeller shaft
P_A	first power threshold at the propeller shaft
P_B	second power threshold at the propeller shaft
P_{med}	mean value between P_A and P_B
η_1	global conversion efficiency from engine to propeller shaft (excluding the charge-discharge efficiency) = 0.72
η_2	global conversion efficiency from engine to propeller shaft (including the charge-discharge efficiency) = 0.61

For each working condition, the engine operates *at constant speed*; the following values were proposed for the power thresholds and rpm:

P_A = 75 kW P_B = 25 kW $P_{c(max)}$ = 25 kW n = cost = 1800 rpm

In order to test the suitability of the proposed solution, a simulation was carried out where the same load profile logged on board (trips n. 30 and n.40) was applied to the new system with an engine whose power and rpm are suitable for the new working conditions. Figures 13 to 18 report power and energy profiles obtained for these routes together with the power statistic distributions.

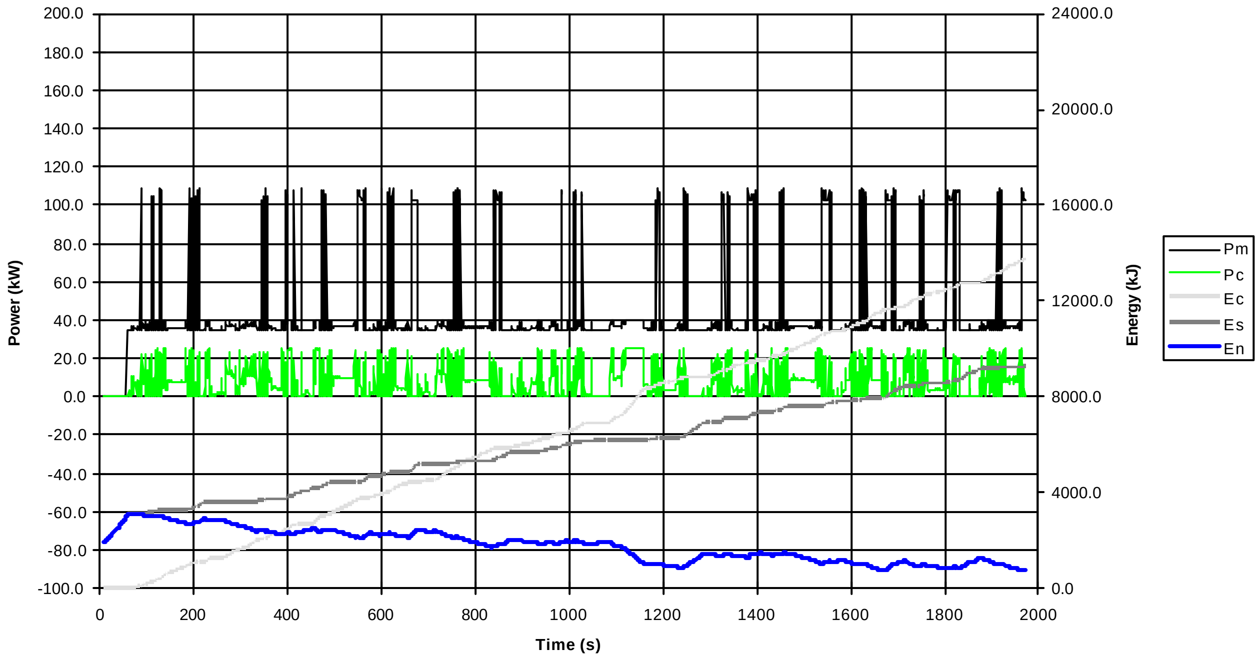

Fig 13 - Energy and power profiles during the first half of the outbound trip n.30 (line 1)

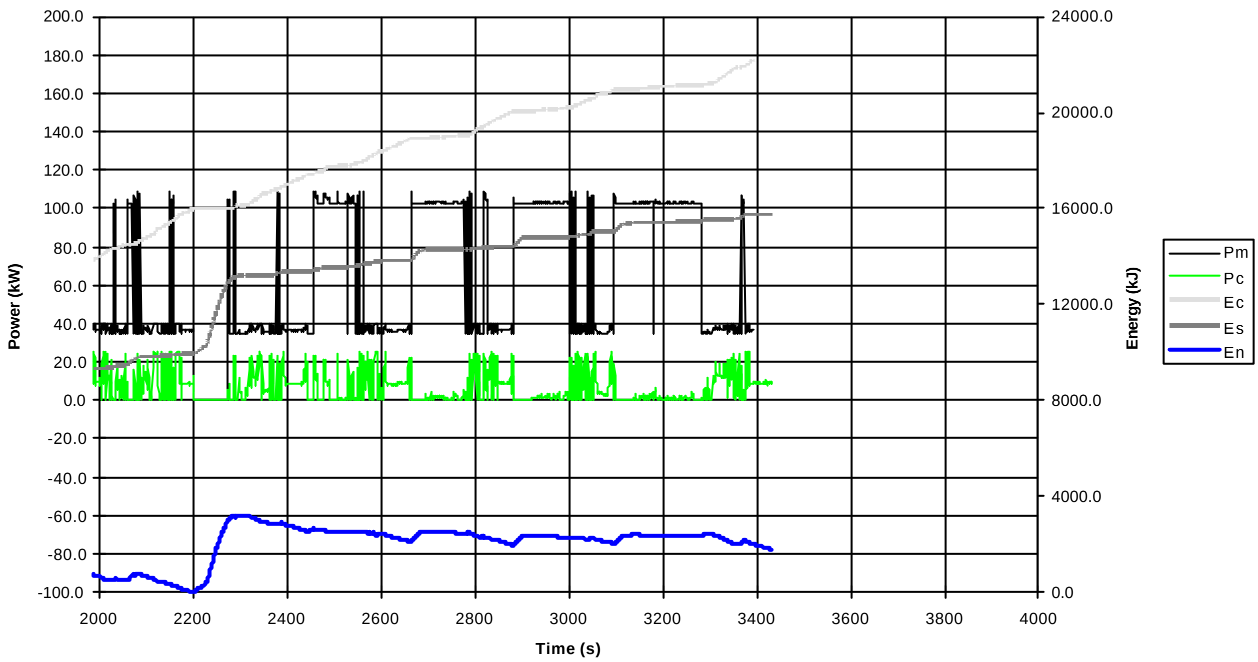

Fig 14 - Energy and power profiles during the second half of the outbound trip n.30 (line 1)

ENGINE SHAFT POWER STATISTICAL ANALYSIS - HYBRID SYSTEM

Absolute Power (kW)

LINE	1 (Grand Canal)		
FILE	CR30ENE3		
MAXIMUM	108.8		
MINIMUM	0.0		
AVERAGE	51.2		
VARIANCY	30.5		
MEDIAN	36.4		
	P1 (kW)	f (P<=P1)	f (P1<P<=P2)
DISTRIBUTION	0	0.000	0.035
	5	0.035	0.000
	10	0.035	0.000
	15	0.035	0.000
	20	0.035	0.000
	25	0.035	0.000
	30	0.035	0.263
	35	0.298	0.402
	40	0.699	0.058
	45	0.757	0.000
	50	0.757	0.000
	55	0.757	0.000
	60	0.757	0.000
	65	0.758	0.000
	70	0.758	0.000
	75	0.758	0.000
	80	0.758	0.000
	85	0.758	0.000
	90	0.758	0.000
	95	0.758	0.000
	100	0.758	0.197
	105	0.955	0.045
	108.8	1.000	

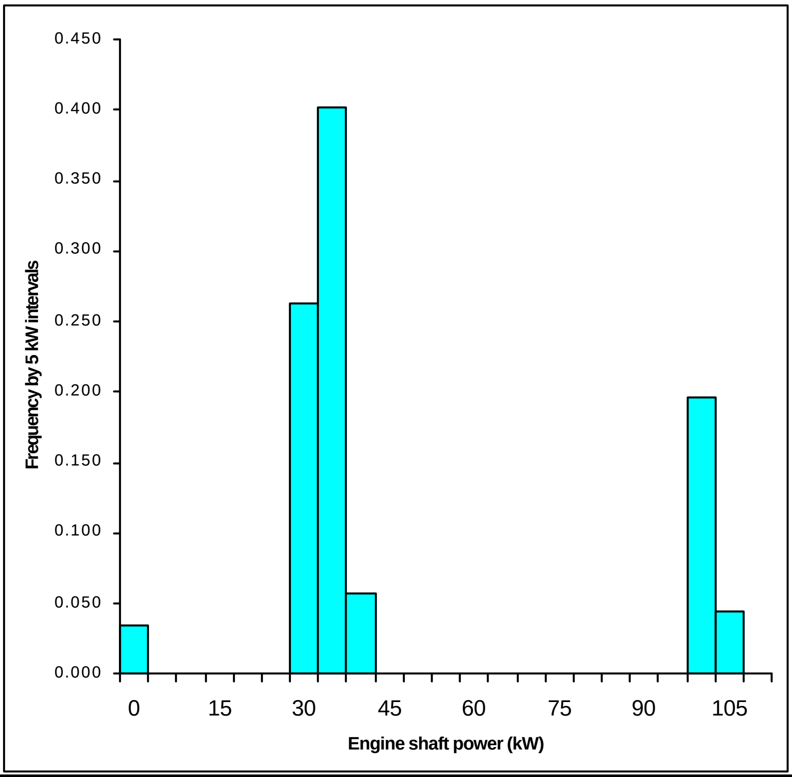

Fig 15 - Power distribution with the hybrid system (line 1 - outbound trip)

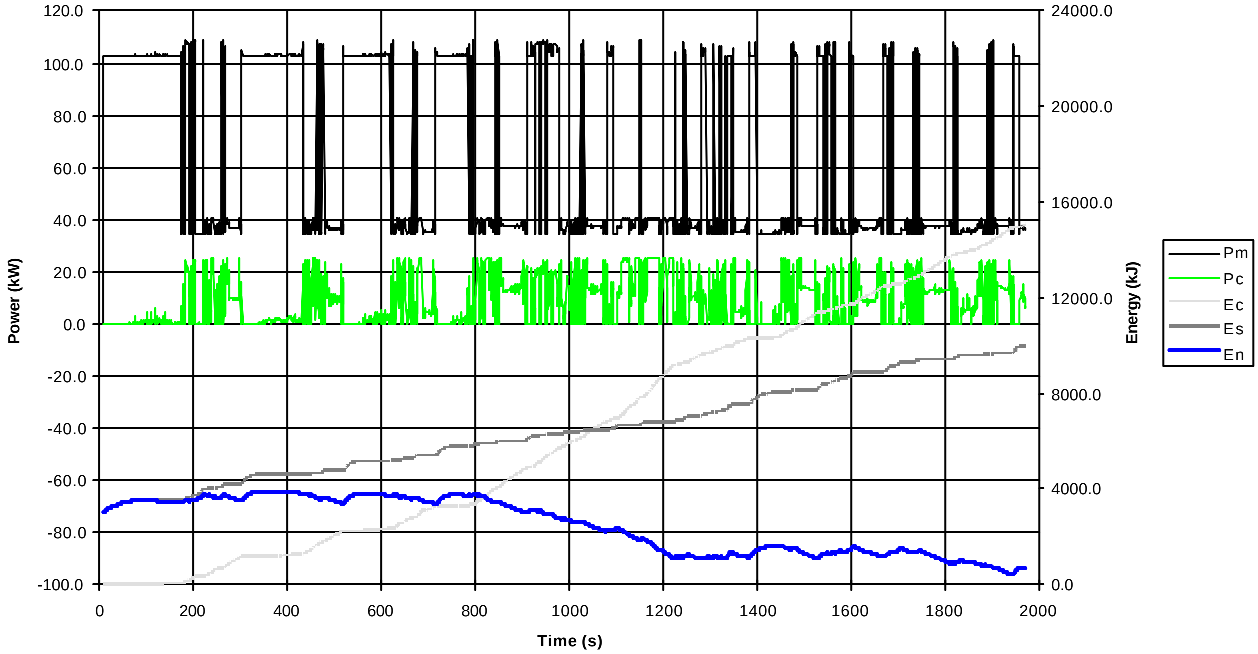

Fig 16 - Energy and power profiles during the first half of the return trip n.40 (line 1)

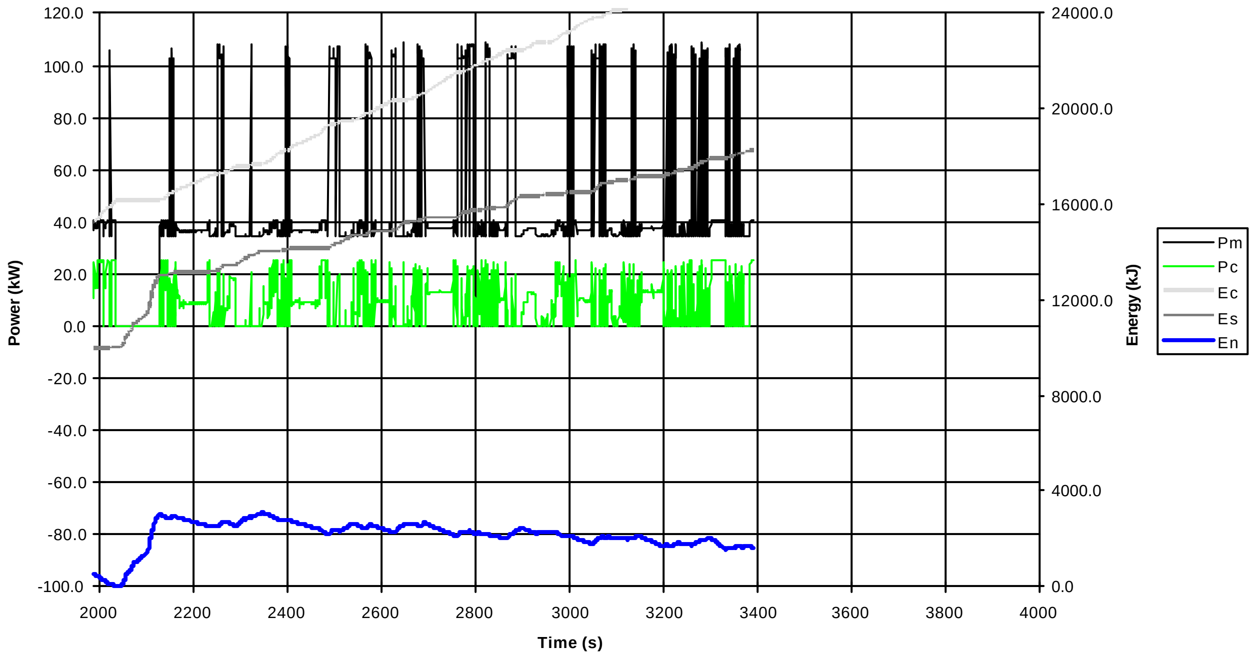

Fig 17 - Energy and power profiles during the second half of the return trip n.40 (line 1)

ENGINE SHAFT POWER STATISTICAL ANALYSIS - HYBRID SYSTEM
Absolute Power (kW)

LINE	1 (Grand Canal)		
FILE	CR40ENE4		
MAXIMUM	108.8		
MINIMUM	0.0		
AVERAGE	54.4		
VARIANCY	31.5		
MEDIAN	37.4		
	P1 (kW)	f (P<=P1)	f (P1<P<=P2)
DISTRIBUTION	0	0.000	0.028
	5	0.028	0.000
	10	0.028	0.000
	15	0.028	0.000
	20	0.028	0.000
	25	0.028	0.000
	30	0.028	0.214
	35	0.242	0.395
	40	0.637	0.082
	45	0.719	0.000
	50	0.719	0.000
	55	0.719	0.000
	60	0.719	0.000
	65	0.719	0.000
	70	0.719	0.000
	75	0.719	0.000
	80	0.719	0.000
	85	0.719	0.000
	90	0.719	0.000
	95	0.719	0.000
	100	0.719	0.221
	105	0.940	0.060
	108.8	1.000	

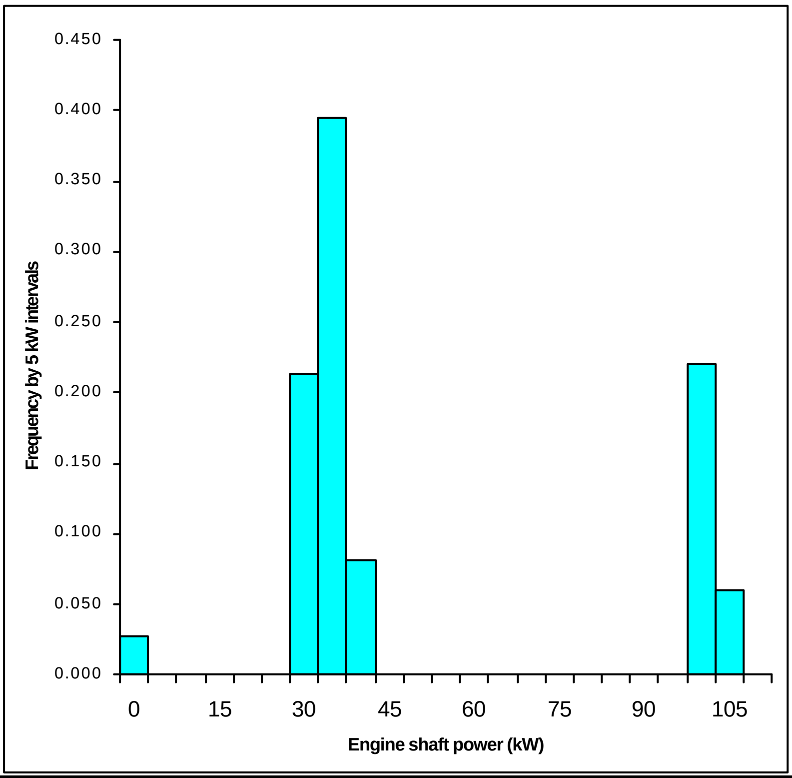

Fig 18 - Power distribution with the hybrid system (line 1 - return trip)

The figures show clearly that:

- the engine is used only in very narrow range of power which gives the possibility of fine tuning of its parts to optimise fuel consumption and exhaust emissions;
- the chosen operational profile satisfies the energy budget of the mission of the water bus; in other words, with the chosen power levels, the generator can provide all the electric energy required by the system. In particular, it satisfies the battery charge - discharge cycle by duly considering the further energy loss due to its partial storage.

The value of $P_{c(max)}$ is the maximum charge at the batteries and it was chosen as equal to 25 kW, approx. corresponding to a discharge power of 75 kW (the assumed ratio P_c/P_d is about 1/3); E_c is the charge energy (in kJ at the propeller shaft), E_s is the discharge energy and E_n is the net energy (the last two, in kJ at the propeller shaft), while the relation among these variables is:

$$E_n = E_s - \eta_2 E_c$$

Naturally, the value of E_n must be the same at the beginning and at the end of the mission so for the vessel to be energetically independent from external sources; this condition is verified in both trips covered by the proposed hybrid.

In order to obtain a reasonable comparison between the alternative system proposed and the present one, in the first phase of the elaboration, a commercial engine was chosen for the analysis of the hybrid power system; this engine is similar to the present one but its power and speed characteristics are more suitable for the new application. The values of the fuel consumption thus obtained are given in table 9 as compared to the values measured on board of the present system.

The remarkable reduction in the hourly fuel consumption, for the same useful power, (about 20%) shows that, from the energetic point of view, the adopted solution fits very well the application in the Grand Canal, where the high degree of irregularity is to be considered the major problem for the operation of the main engine and, consequently, the source of the higher fuel consumption. In other words, this result confirms that, although the hybrid system introduces new energy losses (due to the efficiencies of the new elements in series), these are offset by the better operation of the engine closer to its nominal conditions, so as to improve the overall energy transformation process.

course	*total consumption (g)*		*consumption per hour (g/h)*		*mean specific consumption (at the engine shaft - g/kWh)*	
	hybrid	traditional	hybrid	traditional	hybrid	traditional
30	10410	12893	11022	13651	214	348
40	10980	13577	11689	14722	214	360
the hybrid was supposed as powered by a diesel engine with the following characteristics: MCR = 147 kW @ 2700 rpm BSFC @ 1800 RPM; 110 kW = 206 g/kWh (when the propeller power demand is higher than P_{med}) BSFC @ 1800 RPM; 60 kW = 225 g/kWh (when the propeller power demand is lower than P_{med})						

Table 9 - Comparison between the fuel consumption of the M/B 54 powered both by the proposed system and the traditional one, in the routes along the Grand Canal

From the point of view of emissions, it must be highlighted that no direct reduction of the NOx emission can be foreseen with the described working cycle of the hybrid system. The data elaboration on the hybrid system confirms this result: while running the most part of the mission at relatively high power, the engine emits more or less the same NOx than before. On the other hand, the constant speed of the engine allows the application of catalysts which, in these conditions (i. e. at constant engine speed), are very efficient and can cut the NOx emission almost completely. Again an improvement can be obtained by a systems approach.

In order to preliminarily show the potential improvement of exhaust emissions which can be obtained with the hybrid system, the Authors compared the results of a complete mission simulated with two commercial engines (see “Experimentation and measurements on the propulsion plant of a water bus in service on the ’Canal Grande’ in Venice”) both powering the traditional and the innovative hybrid propulsion systems. The results of such a comparison were very encouraging: although the NOx emission is practically the same, for the other substances a very remarkable reduction can be foreseen. As shown in figure 10, the NOx specific emission has a relatively flat constant pattern vs. power whereas the CO and HC showed, from preliminary evaluations and previous tests on different engines, a more pronounced decrease of their value as a function of power. Future experimentation (at test bench and in water) will improve the confidence in this conclusion.

However, to clarify the real reduction in CO, particulate matter and THCs (total hydrocarbons), specific laboratory tests are going to be carried out on the same engine which powered the M/B 54 during the tests on board. The results of these tests will highlight the actual emission pattern of the engine emissions of the engine powering the boat. Due to the almost constant operating conditions of the hybrid system, a remarkable reduction in CO and particulate matter is expected.

Finally, in order to improve the global efficiency of the hybrid system (and, consequently, the fuel consumption and the exhaust emissions) and to increase the operative flexibility of the vessel, the developments in the design of the system should be:

- direct drive in permanent state conditions: by linking directly the alternator and the electric motor, the intermediate elements (rectifier, inverter, regulation kit, batteries) can be by-passed, thus improving the overall efficiency of the whole system;
- optimisation of the hybrid working cycle in order to match the need of power release of the courses in which the boat will be used;
- optimisation of the parameters involved in the powering system (power of the I.C.E., battery charge, electric motor);
- study of the use of different kinds of energy buffers (i.e. mechanic flywheels);
- use of advanced-control logic to have the engine work with better fuel consumption and emissions;

- possibility of following particular working conditions (i.e. silent running in the Grand Canal).

Conclusions

This is the present state of this investigation on an alternative energy management system destined to the M/B in service on the Venetian lagoon; the elaboration above must be considered as a step of pre-feasibility of a project whose future is in the hands of the involved local Authorities. Thus, the level reached in this elaboration, although certainly liable to further developments, appears to the Authors as sufficient to show the advantages of the proposed system and start the demonstration phase.

However, the elaboration on the marine application of the hybrid diesel-electric system showed remarkable improvements in the propulsion plant of the water bus like those in service in the Venetian lagoon; together with the (always desirable) improvement of the internal and external acoustic comfort, the constant running of the main engine allows an appreciable reduction of consumption and emissions.

Although the diesel-electric system introduces further losses in the energy conversion, not all the energy involved in the propulsion must be stored in the battery pack (so as it happens in the case of the full electric boat) and, consequently, the overall efficiency is encouraging in comparison with other possible versions of the propulsion plant of the water bus.

Further developments are also possible: the control logic may help in the management of the propulsion plant and can sensibly reduce the consumption and emission of noxious and greenhouse gases (CO_2) from the engine.

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