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Low emission propulsion plants for urban and coastal transportation

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ABSTRACT: The problem of the pollution in the urban areas is increasingly conditioning our social life in many ways; the aim of this work is to give an outlook of some possible fields of application of alternative solutions having the goal of minimizing the environmental impact of the urban public transportation and of moving part of it at sea (when possible). Moreover, since in most cases load profiles present very particular characteristics from the point of view of their regularity, the evaluation of the use of alternative propulsion systems is opportune. In this work, the main aspects of the problem are examined while taking into account both conventional technical solutions and new solutions under development.

1 INTRODUCTION

Any present effort to improve the quality of the life in very inhabited zones must take into account alternative solutions for the urban transportation systems, both private and public.

Of course, the first problem to cope with is the environmental pollution due to the simultaneous presence in our streets of many ICEs that, in spite of the more and more stringent rules about emissions, produce a unacceptable level of air pollution.

As a partial answer to this situation, in our cities no traffic zones, limitation to private traffic or other traffic planning appeared with the aim of reducing the environmental impact of the urban traffic on the life of citizens; but, it seems clear that the situation in major cities will soon collapse if structural, and probably innovative, solutions will be not taken in the near future.

A possible solution is taking place for coastal cities: part of the transportation of people and goods can be operated via sea or internal water, when physical and geographic conditions allow it.

As well known, in some cities where there are inner navigable canals, the possibility of using them for marine transportation systems has been already exploited; of course, in most cases, the energy systems of boats are traditional and their use doesn't lead to a real reduction of the environmental impact of urban transportation but only to a displacement from the land to water. Sometimes, this improves the road urban traffic but not the overall pollution level in the areas where this kind of transportation is active; to reach the goal of the reduction of the environmental impact the only solution is to built alternative energy system working with a reduced level of pollution.

2 CHARACTERISTICS OF THE LOCAL PUBLIC TRANSPORTATION

There are many sites in the world where the application of maritime transportation is theoretically possible. But, at present, it rarely plays the role of main transportation system and, in most cases, it is only a marginally used alternative to road traffic.

Of course, the displacement of part of road traffic to waters does not imply a solution of all the logistic and environmental problems: in fact, together with the reduction of the environmental cost per unit, other problems may arise. One of them – mainly in restricted waters – is the wave formation which may create serious damages to the banks (washing) and other installations and ships.

The local routes are, in many cases, characterized by very frequent passenger stops; even the speed of the ship can be influenced very deeply by the navigation conditions in canals or coasts.

The above mentioned problems may determine mission profiles similar to those of the road vehicles, characterized by many stop and go and frequent changes of speed. A very significant (but limited) case is the public transportation in Venice: in the following figure the power release during an urban cycle of a "vaporetto" (public transportation boat) in the Grand Canal is shown. Data were logged during full scale tests carried out in regular service.

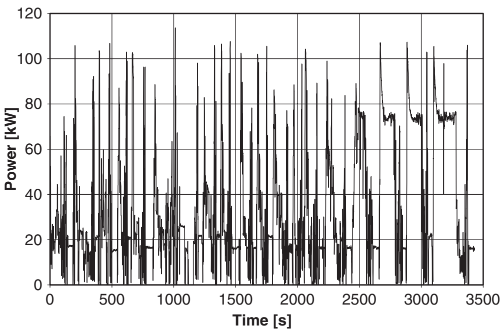

Figure 1. Typical mission profile.

Another typical aspect of propulsion plants powering boats destined to urban traffic (restricted waters) is that the maximum power is set to achieve a reduction of acceleration and deceleration times which reduces not only the overall running times, but always guaranties adequate security margins during maneuvers.

In conclusion, a mission profile for urban transportation is composed by a combination of steady and unsteady conditions:

– power close to its nominal value (steady);
– power lower than the maximum (steady);
– acceleration and deceleration (unsteady).

From the point of view of fuel consumption and exhaust emissions, steady conditions represent the best use of the power plant, while in unsteady conditions the power plant works far from its best.

A mission profile, where second and third conditions are predominant on the first, presents an irregularity degree in power release that may justify the study of alternative systems with the aim of improving the overall efficiency of the cycle.

Sometimes further constraints force the choice of alternative solutions as, for example, in zones with more stringent limitations for gas emissions in the air.

3 ANALYSIS OF SOLUTIONS BASED ON THE PRESENT TECHNOLOGY

The easiest – and cheapest – way to power a boat is to fit a diesel engine coupled to a propeller through a reduction gear (fig. 2); the overall efficiency of this solution for urban transportation is not the best if the mission profile is very irregular, in the sense mentioned above. In fact, when the diesel engine works far from its nominal conditions, both consumption and emissions level may raise dramatically.

Moreover, in unsteady conditions, not only does the efficiency worsen but also other undesirable phenomena may appear, such as the growing of smoke levels that depends basically on high loads delivered at low rpm.

Recent common rail diesel engines present a reduction of this problem; but there is a need of a strong reduction of the air pollution close to very inhabited zones.

A possible solution is to adopt energy systems where the prime mover works at fixed point thus allowing the optimization of its consumption and emissions, and taking into account that the two don't follow always the same trend.

These systems use energy buffers that store the surplus of energy when the load is low and supply energy when the required load is high; the energy buffers can be also pneumatic and mechanical but the most convenient and technologically mature way is adopting electric batteries in a hybrid diesel-electric application.

Two kind of hybrid plants can be considered: in parallel and in series.

In the parallel version (fig. 3), diesel engine is mechanically coupled with the propeller; on the same shaft a generator/motor is fitted, with the aim of supplying or deriving energy from a set of electric batteries.

The engine rpm is variable and must follow the propeller speed, while the torque delivered by diesel engine can be managed also by the control system which sets the current flow to the batteries.

The main advantage of this solution is that a large part of the energy involved in the working cycle doesn't undergo the double mechanical-electric-mechanical conversion.

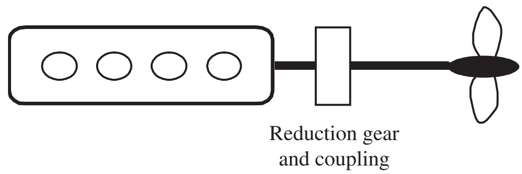

Figure 2. Conventional arrangement.

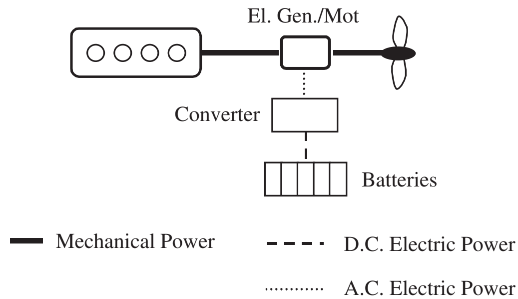

Figure 3. Parallel hybrid diesel-electric plant.

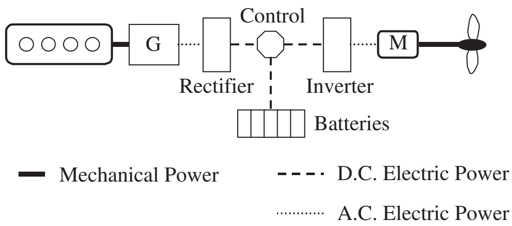

Figure 4. Series hybrid diesel-electric plant.

On the other side, the direct coupling with the propeller doesn't allow the operations at fixed point and makes this solution less attractive in terms of layout; furthermore, the power management needs a very sophisticated control system which involves a lot of plants complications and high costs.

The overall efficiency of such a system is a function of the percentage of energy flowing through the batteries; it can be represented as follows:

$\eta_t' = \eta_{eng} \cdot \eta_{rid} \cdot \eta_s$ valid for direct transmission
$\eta_t'' = \eta_{eng} \cdot \eta_{gen} \cdot \eta_{cc} \cdot \eta_{bat} \cdot \eta_{em}$ through batteries

See nomenclature for meanings of symbols.

It's worth pointing out that, in the value of the efficiency of batteries both the charge and discharge efficiencies are included.

In the series version (fig. 4), diesel engine drives an alternator which feeds batteries and/or the electric propulsion system through a rectifier; the overall energy is converted into electric and a part of it passes through batteries, according to the load profile on the propeller.

The prime engine is completely disengaged from the propeller and may work at fixed point; the difference between the power required by the propeller and the constant power rated by the diesel generator is supplied by batteries.

In this case the prime engine works at constant rating or at idle speed; consequently, it can be set to work at best in that point. But, on the other side, the efficiency of the plan after the diesel engine is lower than in the previous case because all the energy must be converted.

The efficiencies involved in the operations are:

$\eta_t'' = \eta_{eng} \cdot \eta_{gen} \cdot \eta_{cc} \cdot \eta_{em}$ not through batteries
$\eta_t'' = \eta_{eng} \cdot \eta_{gen} \cdot \eta_{cc} \cdot \eta_{bat} \cdot \eta_{em}$ through batteries

A possible variant of this system includes a switch that constitutes the so called electric shaft, connecting directly the alternator to the motor.

In order to evaluate the feasibility and the convenience of substituting a conventional propulsion system with a hybrid propulsion it's appropriate to consider a real case.

4 A CASE STUDY – A URBAN ROUTE IN GENOA

With reference to the route described in the paper [Caprio et al., 2005], we will try to verify if that ship, designed to work on a new metropolitan route – between Genoa Foce and Genoa Cornigliano – can be powered with a conventional propulsion system or if alternative solutions might make sense. Indeed, in that work the authors proposed two different routes: line one is characterized by long steps at constant speed, line two presents some of the aspects – such as the presence of a great number of stops and a certain number of stretches – with speed limits that may suggest the use of a new solution. For these reasons, some attention has been paid to line two as presented above.

The first step is to build a power release profile; it results from the sum of ideal profiles for acceleration, deceleration, steady condition – at high and low speed – and of the power requirements during berthing. The latter condition is due to the fact that, generally, in relatively small ships needing to reduce berthing time, the propeller gives thrust even if the ship is stopped at peer, in order to obtain a better position control.

To determine the power profile in accelerating and stopping period, we used a simulation program based on MatLab™ Simulink tool run with propeller characteristics and hull resistance data [Balsamo 1995a, Benvenuto 2000a, 2000b]. This model is simplified and doesn't include the dynamic of the engine; indeed, the control was made in terms of rpm and a time sequence of rpm was applied to a propeller-hull model capable to run the boat to the required distance.

The output of such model is made by speed and torque which was limited to take into account the possible rating by the engine. In the next future the model of the engine will be developed from the point of view of the dynamic of torque and power release and of exhaust emissions.

Note that the shown power profile is related to half the power required by the ship; therefore, all the following considerations will relate to only one of the two propulsion plants installed on each hull of the staggered catamaran presented in the above mentioned paper.

We will try and compare the fuel consumption on the route Genoa Foce – Genoa Cornigliano using a conventional power plant, a hybrid diesel electric parallel plant and a hybrid diesel electric series plant. For details about the route and positions of stops, see [Caprio et al., 2005].

4.1 *Conventional diesel engine power plant*

This is the simplest way to power the ship; in our simulation the nominal engine power was based on that required to obtain the maximum speed in full load conditions. Some times, for ships operating in restricted

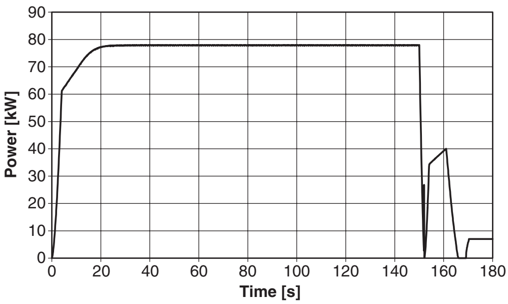

Figure 5. Power release between two stops.

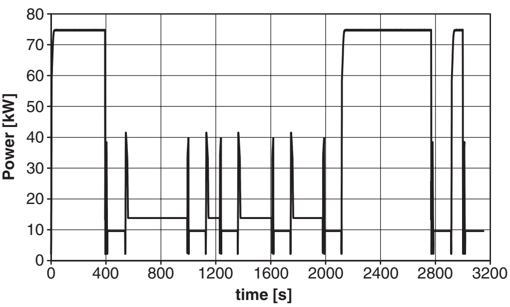

Figure 6. Mission profile between Foce and Cornigliano.

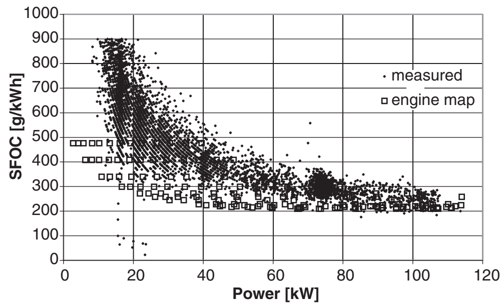

Figure 7. SFOC scatter diagram (full scale tests).

Table 1. Results of simulation for the conventional system.

Partial route	Mean speed (kn)	Energy to prop. (kJ)	Mean shaft power (kW)	Energy from DE (kJ)	Fuel cons. (kg)	SFOC (g/kWh)
Trip1	10.8	29500	72.1	30725	1.87	219
Trip2	4.8	22807	13.3	23760	2.34	355
Trip3	9.3	56624	63.0	58980	3.79	231
Total	7.0	108930	36.1	113465	8.00	253

waters, the engine has more power to guarantee, as said above, adequate maneuvering performance.

The steady parts of the power profile are easier to calculate from propeller and hull resistance curves. The power profile obtained thus is shown in figure 6.

At this point we need to determine the fuel amount to complete the route and could proceed in two ways: using a diesel engine model based on steady state curves or applying a more complete engine model. In this work, we have followed the first approach, which is easiest but will underestimate – as we know – fuel consumption during transients. To confirm that, the figure 7 shows measured specific fuel consumption during a very irregular mission profile [Balsamo et al., 1995b], compared with the values calculated by a simulation program based on steady state conditions engine map.

Remarkably, at low power and in unsteady conditions, there is a great difference between full scale data and those obtained from engine map; this is due to transient phenomena and to the presence of a hydraulic coupling between engine and reduction gear in the boat under exam. Moreover, while specific fuel consumption versus torque and engine speed maps are generally available for many diesel engines, obtaining curves for pollutants is not so easy. A detailed knowledge of fuel consumption and emissions in unsteady conditions would require a more complex engine model implying a great calculation power and time.

We calculated the SFOC in the points torque-rpm obtained from simulation; to do so, we used the fuel consumption engine map.

Mainly, the route is composed by three different conditions, each characterised by its speeds, energy and power released, etc. In table 1 these characteristics are reported; referring to the figure 6, trip 1 is the first high speed trip (approx. 0 – 400 s), trip 2 is the second, at low speed (up to 2100 s), and trip 3 is the third again at high speed.

Note that the efficiency of the transmission of energy from diesel to propeller has been assumed as 0.96; it also depends on the coupling characteristics and on its dynamic.

4.2 *Hybrid diesel electric parallel plant*

In a hybrid electric system, the main parameters to be appreciated are the power of the diesel engine, the power of the electric motor/generator, the overall charge of batteries.

The diesel engine power is based mainly on the mean power of the cycle, by taking into account the efficiencies involved in the power transformation; in our case, after some attempts, we choose a value of 48 kW. When the ship is at maximum speed, the power delivered by electric buffer is about 32 kW. The charge of batteries to be installed is determined not only by the maximum discharge energy requirements but also (and mainly) by the maximum charge current they can accept. However, the mission profile is characterized by a long time period where the power demand is lower than that delivered by the diesel engine and by relatively long trip at maximum speed involving a long phase of discharge of batteries. In our mission profile this phase occurs at the beginning and at the end of the route, therefore a given time of recharge is required to begin a new trip. A better energy management would be obtained if low speed trips were placed before and after the higher one.

The time required to complete the charge of battery is approx. 300 s.

As stated before, the power is delivered in two ways, with different efficiency; to optimize the diesel engine, which works at variable speed, it's important to control torque in order to choose the lowest specific fuel consumption – for that engine revolution speed – taking also into account the needs of storing power in batteries.

During charge, the energy exchanged with batteries suffers from the losses in the generator-rectifier and batteries; during the power release to shaft, in batteries and inverter-motor.

With present technology (AFE), the efficiency of a generator rectifier group is about 0.92 at rated power, while that of the inverter-electric motor is slightly lower, 0.89. The characteristics of these devices is that the efficiency is quite constant in a big part of the range; at low power it diminishes of about 3 ÷ 4 per cent.

The losses in the batteries are due mainly to internal resistance and self discharging; the first depends on the current, the other is quite constant. The parameters used in dimensioning batteries are the expected energy discharge and the charging current, so that the amount of batteries also influences the energy exchange efficiency. The current rate has an influence also on the expected battery life time, so that the propulsion energy control should take into account the effects of charge-discharge strategy on the battery duration.

In the transportation field, generally Ni-Cd batteries are used, mainly for weight reasons and because they accept higher charging current. A possible dimensioning criterion is to adopt a charging current up to 1.5 times the nominal discharge current, that is the current which perform a complete discharge in one hour.

In our simulation we choose a Ni-Cd element with nominal current 40 Ah at 238 V, which allows a charging power of 1.45 kW. Note that if the diesel releases 48 kW, due to losses in generator rectifier we have a maximum charge power of about 43 kW, requiring at least 30 battery elements, weighting about 1100 kg per each propulsion plant installed onboard. At this point, from table 2, we note that the maximum battery discharge is about 23 MJ, that corresponds to 17% of battery capacity, a value that allows a good life expectation for batteries.

The dimensioning of batteries quantity has a great influence on conversion efficiency (because the charge/discharge current determines internal losses) but also on costs.

Table 2. Results of simulation for the parallel hybrid.

Partial route	Mean speed (kn)	Energy to propeller (kJ)	Energy from buffer (kJ)	Energy to buffer (kJ)	Energy from DE (kJ)
Trip1	10.8	29500	12280	290	19540
Trip2	4.8	22807	0	11890	36690
Trip3	9.3	56624	22980	5000	43180
Final charge	0	0	0	18080	22420
Total	7.0	108930	35260	35260	121830

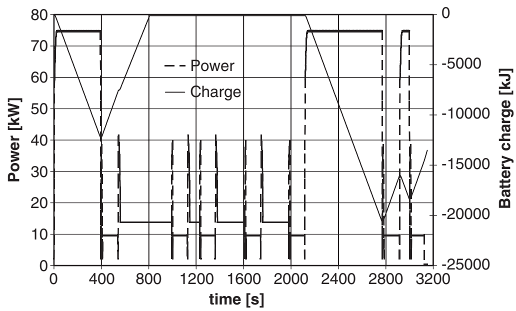

Figure 8. Battery charge/discharge cycle.

A reduction of the charging rate (in our case we have enough time to recharge batteries in the long trip at variable speed) may allow us to reduce the number of battery elements, thus obtaining a consistent reduction in weight and cost.

The following figure shows the battery charge/discharge cycle during the route.

The efficiency of energy conversion through electric devices is about 0.72, and the efficiency of conversion of the whole energy from diesel engine to shaft is 0.89, that is the cost of electric energy conversion.

The fuel needed to complete the route for each diesel engine, based on steady state engine conditions, is 8.5 kg, so that the overall efficiency is about 280 g/kWh. In this case, with the help of electric motor, the variations of diesel engine condition are really slight.

As regards pollutant emissions, a similar approach can be used; the problem is that operating maps of specific flow of pollutant specimen – as a function of engine speed and torque – are very difficult to obtain. As stated before, a complete simulation model of the diesel engine would give more information.

4.3 *Hybrid diesel electric series plant*

The difference with the previous hybrid system is that all the energy supplied by diesel engine is converted into electric.

This obviously involves a worse conversion efficiency from diesel to shaft, but the diesel engine works at the best condition, at fixed speed and power. To obtain a relatively small energy deficit at the end of the route, the rectifier must supply 45 kW; assuming an efficiency of 0.92 for the group generator-rectifier – as we did in the previous case – the nominal power of the diesel engine must be 49 kW. The maximum power shaft is about 75 kW; in order to consider a reasonable power margin, the nominal electric motor power is 83 kW.

The maximum charge rate is approximately the same as the previous case (45 kW), so the same quantity of batteries can be considered. The diesel engine works at nominal condition or is idle, when the batteries can't accept more charge. The managing of charge to batteries is one of the more complex aspects of this kind of plants. A little secondary battery buffer, with high current characteristics, could be applied to avoid current peak on the main package.

Figure 9 shows the battery charge/discharge cycle during the route.

Note that, in the field where the batteries are full, it's possible to use different charge/discharge strategies: the one shown in fig. 9 consists of slight discharges – when the engine is idle – followed by charges and discharges again. A more detailed exam may highlight a better energy strategy for this operating condition.

The energy data obtained from a simple simulation of the complete route are summarized by the following table.

As in the previous case, it's not possible to calculate the single trip efficiency, but only the overall.

In this case, the efficiency of the energy conversion from diesel engine to shaft is 0.70, sensibly lower than in the previous case. The difference is that the diesel engine works at the minimum fuel oil consumption nowadays obtainable for these kinds of engines: 200 g/kWh.

As regards the recharging time, the total fuel consumption for a complete route is 8.6 kg, little more than a parallel hybrid solution.

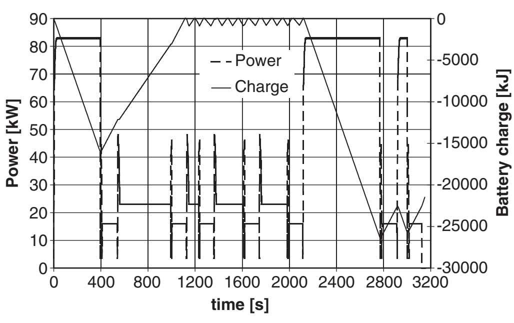

Figure 9. Battery charge/discharge cycle.

In this case it is easy to appreciate the amount of pollutant (NOx), because the specific emission is a data generally available for nominal condition; this can be easily done while keeping in mind that the current value for the present diesel engine specific emission of NOx is 10 g/kWh.

4.4 *Comparison*

In order to verify the effective convenience in adopting an alternative solution we can compare the results obtained from the simulations in the three cases.

The conventional system seems to be the best in terms of energy saving performance; but the related fuel consumption data are certainly affected by the initial assumption and by the method followed in our work. In fact, the mission profile in transient states was chosen as the best, that is the maneuvers are made by the helmsman with the minimum variations; this can be assessed by comparing a real power profile (fig. 1) with the ideal one we used for the simulation.

Moreover, as previously stated, the method for calculating diesel engine fuel consumption is based on steady state data, so the fuel consumption calculated for conventional plant and even for hybrid parallel plant could be underestimated. For the hybrid series solution the fuel consumption estimate is more precise.

Table 3. Results of simulation for the series hybrid.

Partial route	Mean speed (kn)	Energy to propeller (kJ)	Energy from buffer (kJ)	Energy to buffer (kJ)	Energy from DE (kJ)
Trip1	10.8	29500	15990	205	19710
Trip2	4.8	22807	11165	26980	59450
Trip3	9.3	56624	29580	4060	43970
Final charge	0	0	0	25490	31770
Total	7.0	108930	56735	56735	154900

Table 4. Comparison of various systems.

	Conventional	Hybrid parallel	Hybrid series
Energy to shaft [kJ]	108930	108930	108930
Energy from diesel engine [kJ]	113465	121830	154900
Energy through batteries [kJ]	–	35260	56735
Transmission efficiency	0.96	0.89	0.70
Fuel consumption [kg]	8.0	8.5	8.6
Overall SFOC [g/kWh]	253	280	284

5 FUTURE DEVELOPMENTS

While remembering that the first way to reduce the pollution is to reduce the fuel consumption, it is clear that hybrid solutions could be effective in certain cases but they don't represent a final solution to the problem.

Nowadays, the world of energy is studying the fuel cells as the energy system of the future, and their applications in various fields; some applications of fuel cells have been made also on ships.

On the other hand, the main problem related to fuel cells is the safety of life at sea; indeed, handling hydrogen on a boat gives evident problems of security which are not compatible with the severe rules of the field. At present, discussion on the application of fuel cells on boats predicts first applications of PEM with or without fuel reforming onboard. First experimental applications will have hydrogen tanks to be refilled in special stations to be built and connected to a network of hydrogen destined to feed all the users of this gas; evidently, this application is possible when a hydrogen net will be available and has the big advantage of using pure hydrogen already reformed so as to prevent the installation of complex (and dangerous) tools for the reforming onboard. But the problem of the "bunker" seems to be very hard to manage, since the occasional expansion of H_2 may cause the heating of the gas and its explosion, if flammable limits are exceeded; this means that the refilling operation will be very delicate while, normally, a public transportation company doesn't want any problem in this phase of its operations.

The reforming onboard simplify the operations of bunkering very much (it is predictable that the marine application of fuel cells will happen together with the achievement of a technology that will allow the reforming of fuels today commonly used in marine applications like gas oil, diesel oil, etc.). Even in this case, many problems are to be solved; the first will be related to the purity needed for a good working condition of the membrane inside the fuel cells.

Any other consideration – regulation of the power, suitability to a complicated load profile, economics, logistics onboard – seems to be postponed to a more mature technology in the field of fuel cells.

6 CONCLUSIONS

In marine urban/coastal traffic, the convenience of alternative solutions can be clearly assessed only after;

– an accurate mission profile characterization, eventually taking into account not only full load condition but also intermediate one, including the maneuvering requirements (power for starting and stopping);
– an accurate simulation of diesel engine performance and consumption in transient states, also in terms of pollutant emission (generally NOx and soot);
– an accurate modeling of the electric part of the system, with particular regard the battery model;
– an accurate choice of energy management control strategy, in order to maximize batteries performance.

Moreover, a boat "tuned" on a particular route generate also problems in terms of a flexible utilization on different trips.

Lastly, an unconventional boat involves higher initial costs and eventually higher maintenance costs, together with personnel training difficulties.

Even so, that could be the only solution to cope with pollution problems in restricted and very inhabited areas.

7 NOMENCLATURE

In the following, the efficiency definition of all the systems component are reported

η'_t	overall mechanical
η''_t	overall electric
η_{eng}	diesel engine
η_{rid}	coupling and reduction gear
η_s	shaft transmission
η_{gen}	electric generator
η_{cc}	electric energy conversion
η_{bat}	charge and discharge
η_{en}	electric motor

REFERENCES

Balsamo F. 1995a Studio di una propulsione ibrida diesel elettrica per la navigazione costiera *PhD. Thesis (in italian)*

Balsamo F., Brighenti A., Landri G., Paciolla A., Quaranta F. 1994 Sistema ibrido per vaporetti: studio di pre-fattibilità, *Napoli: Istituto Motori del CNR (paper n. 94RR822), 1994*

Balsamo F., Brighenti A., Landri G., Paciolla A., Quaranta F. 1995b The propulsion of coastal and inland water transportation vessels – Working data acquisition and preliminary design of innovative systems to reduce pollutant emissions, *CIMAC 21th International Congress on combustion engines, Interlaken, maggio 1995 – paper D75*

Benvenuto G., Campora U. 2002 Dynamic Behaviour Analysis of a Sequentially Turbocharged Marine Diesel Engine, *ISC 2002, St. Petersburg (Russia), Oct 8–10, 2002*

Benvenuto G., Campora U., Carrera G., Figari M. 2000a Simulation of Ship propulsion Plant Dynamics in Rough Sea *ICMES/SNAME 2000, New York (USA), May 22–23, 2000*

Benvenuto G., Campora U., Carrera G., Figari M. 2000b Ship Stopping Manouvre: Simulation of the Propulsion system Behaviour, *NAV 2000, Venice (Italy), Sept 19–22, 2000*

Caprio F., Migali A., Pensa C. 2005. Staggered Catamarans: Experimental Data and Feasibility Study for Low Pollution Service *IMAM 2005; Proc. intern. symp., Lisbon (in prep)*

Hansen J. F., Adkanes A. K., Fossen T. 2001 Mathematical Modelling of Diesel Electric Propulsion Systems for Marine Vessels *Mathematical and Computer Modelling of Dynamical Systems, 2001, Vol. 7, No. 1, pp.1–33*

Kyrtatos N. P., Theodossopoulos P., Theotokatos G. and Xiros N. I. 1999 Simulation of the Overall Ship Propulsion Plant for Performance Prediction and Control, *MarPower '99 Conference, Newcastle-upon-Tyne, UK, March 25–26, 1999*