Inland Waterway Gas-Fueled Vessels: CASM-Based Electrification of a Pushboat for the European Network

Vittorio Bucci, Alberto Marinò, Daniele Bosich, *Member, IEEE*, and Giorgio Sulligoi, *Senior Member, IEEE*

***Abstract*— The peculiarities of the European inland waterway transport are analyzed, and a novel design of a pushboat for barges convoys is proposed and optimized for the Rhine-Danube corridor. To this aim, a hybrid parallel electric propulsion system is adopted with the perspective to define an eco-friendly vessel. This paper is to be intended as the early stage in the proof of concept for commercial technologies useful for the electrification of pushboats employed in inland waterway navigation. Specifically, the optimal design solution is highlighted by evaluating proper attribute weights, which determine the degree of closeness among possible solution and the design target. In particular, computer-aided synthesis modeling methodology to minimize capital expenditures and operating expenses of a pushboat is adopted.**

***Index Terms*— Computer-aided synthesis modelling (CASM), hybrid electric propulsion, inland waterway transport (IWT), low emission ship, low-voltage ac-dc power system, pushboat.**

I. Introduction

INLAND navigation can contribute to make transport more sustainable, particularly where it substitutes for road transport, even if the inland shipping, together with the works for the development and the maintenance of the waterways, can have considerable environmental impacts [1]. In general, inland navigation is a slow mode that gets its strength in the high payloads of vessels. Inland waterway transport (IWT) is suitable for all kinds of mass goods, both liquid and dry bulk. In particular, it is advantageous for hazardous goods, since this mode of transport is very safe. Owing to these characteristics, the most volumes carried by IWT are bulk goods like ores, metal wastes, mineral products (both solid and liquid), and building materials. The backbone of IWT is essentially represented by navigable rivers, supplemented by manmade canals in order to form a useful network. At present, the total length of classified rivers and canals forming the inland waterways in the European Union is 29 500 km, which becomes 36 500 km if the Eastern European region (Russia, Ukraine, etc.) is considered. Compared with the existing railway lines in the same areas, inland waterways are less than one-fifth. In a part of the areas concerned, railway lines run parallel to waterways. The current European network, however, in some case does not follow major cargo flows. Therefore, road or rail haulage is required to fill such gaps, and freight storage and consignees centers are to be located far from the waterways [2].

From the economic point of view, IWT is a low-cost mode as well. The maintenance and operating costs of infrastructure are comparatively lower than alternative modes. In addition, emissions of ships per tonne kilometer are very low. Thus, it is possible to state that, for decades, IWT has unquestionably been the most environmentally friendly mode within the inland transport. However, this advantage is steadily eroding due to the rapid reduction of emissions from other transport modes. In particular, the road haulage sector must comply with stricter emission standards, which are, however, supported by strong incentives for road haulage operators (e.g., environmental zoning and differentiated infrastructure charges). Moreover, unlike the road haulage sector, the replacement rate of engines used in inland waterway vessels is very low, and anyway the imposed emission standards for new marine engines are much less strict regarding NO_x and particulate matter (PM) [3], [4]. As a consequence, IWT for certain routes, cargo types, and vessel sizes has higher air pollutant emission levels than road transport per tonne kilometer. Therefore, without specific actions on the legacy fleet, the traditional environmental advantages of IWT will further deteriorate in the future [5]. However, a continuous investment process needs to be maintained in order to revive a competitive advantage. The existing regulations have only a limited effect on the fleet modernization since they are only applicable to new engines.

The active motorized European cargo fleet counts about 11 500 vessels [6]. Rhine-Danube corridor is the greatest European waterway, with the biggest fleet, and it complies with nautical standards higher than other waterways in Europe. The strong economy of the region and, correspondingly, the large transport demand, as well as much more favorable nautical conditions, have influenced the development of an appropriate fleet. Specifically, the composition of the Rhine-Danube corridor fleet is shown in Table I.

In 2000, the mean age of the self-propelled dry-cargo ships, as the more numerous ship-type sailing on the Rhine-Danube corridor, was about 46 years. In particular, German and Dutch ships were on an average 50 and 47 years old, respectively. The second more numerous self-propelled fleet segment, the tankers, is generally 33 years old, while the pushboats are on

Manuscript accepted August 17, 2016. This work was supported by the Research Program Progettazione Navale Integrata of the University of Trieste, Italy, funded by Regione Autonoma Friuli Venezia Giulia.

The authors are with the Department of Engineering and Architecture, University of Trieste, 34127 Trieste, Italy (e-mail: vbucci@units.it; marino@units.it; dbosich@units.it; gsulligoi@units.it).

TABLE I

COMPOSITION OF THE RHINE-DANUBE CORRIDOR FLEET

Ship type	Number of ships	Total deadweight [t]
Self-propelled dry-cargo ship	6,700	5,968,916
Dry-cargo push barges	2,495	3,137,881
Dry-cargo towing barges	229	200,734
Self-propelled tanker ship	1,299	1,461,156
Tank towing barges	21	6,429
Tank push barges	162	235,985
River tugs	733	-
River pushboats	1,090	-
River passenger ships	1,994	253,529 (people)

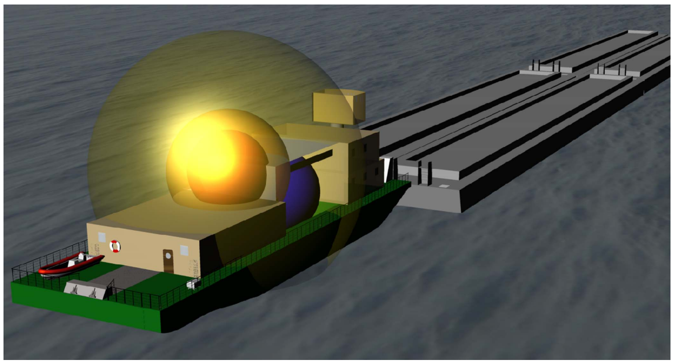


Fig. 1. Pushboat-barges convoy.

an average about 40 years old (the Dutch units are the oldest with 46 years). Because of the Dutch pushboats represent about 50% of the entire pushboat fleet of the Rhine-Danube corridor, their age significantly influences the statistics. In general, all vessels are subjected to emission requirements, which means that if an existing vessel is equipped with a new engine, such an engine must comply with the current emission standards. However, since 2003, only 17% of these vessels have been equipped with new engines. The reduction of emission levels of IWT is stagnating in comparison with other modes of transportation, because the renewal rate of engines of inland vessels is lower, due to their longer lifetime (ranging from 30 000 to over 200 000 h, depending on the engine type), so that breakthrough and large-scale innovations are introduced at a relatively slow pace. The aim of this paper is mainly addressed to develop a new concept design of a ship able to give a contribution to boost the economy of the IWT. Obviously, the new concept design must take into account various restrictions imposed by the normative related both to ship design and to emission control. The key point is the reduction of first costs and shipping times to be attained also through an efficient supply chain. It is worth noting that most barge convoys operating on inland waterways are owned by the masters themselves, who in many cases are quite reluctant to invest for the renewal of their fleet. Therefore, the new ship project has been conceived to operate the vessels till 50 years, but at the same time, it is also able to give an economic return in the short term. On these premises, the improvement of a pushboat/barges convoy has been considered (Fig. 1). In this case, the first costs are high for the pushboat, but they are very low for the barges. The study has been based on the research of efficient solutions for the pushboat as regards optimal speed, cargo capacity, number of pushed barges, and type of propulsion. The pushboat has been designed in accordance with the main rules and regulations for the construction of inland waterway vessels. All the boundary conditions previously identified have been collected and considered as inputs in a computer-aided synthesis model (CASM), in order to determine, among the countless hulls generated, the ones more suitable. The best combination of the variables of the problem has been obtained by advanced decision-making methods based on the concept of concurrent engineering. The final solution becomes the optimal compromise among technical matters, rules and regulations, and economic aspects. This way of setting up a concept design of a pushboat is a novelty herein performed for the first time, also for what concerns an easy estimation of the electric balance. In other terms, a proven technique has been applied for the very first time to the design of a pushboat in order to quickly/automatically develop novel solutions in a 3-D parametric environment, evaluating series of weight attributes. Thus, the CASM-based methodology has been used in the early-stage design to provide the proof of concept (POC) related to commercial technologies for the electrification of vessels in the IWT.

II. New Technologies for Inland Vessel Propulsion

A. LNG Engine

The criteria to choose a technical measure to achieve certain emission limits are different for new or existing vessels. Installation of Liquefied Natural Gas (LNG) fuel facilities in a new vessel may be considered without peculiar complications, while for existing ships, there could be some problems due to the available space on board. Anyway, the feasibility of installing LNG engines is strongly affected by the incidence of the fuel cost within the overall operational costs, as well as by the possibility to place the LNG tank on board. Moreover, fuel consumption is a crucial matter, because it has an influence on the payback time needed to recoup the high investment costs [7]. The pushboats have a high number of operational hours and consequently a high fuel consumption. Thus, the LNG engines turn out convenient. However, existing pushboats in general do not have room to place an LNG tank, and then they cannot adopt such an engine type. Therefore, the only solution is to replace existing pushboats with new pushboats expressly designed to run on LNG. Finally, the LNG vessels need bunkering stations for the refuelling. By means of a high number of bunkering stations regularly located along the waterway, smaller LNG fuel tank could be installed, thus solving the problems due to scarce availability of space on board.

B. Hybrid Propulsion System

The hybrid propulsion concept consists on the possibility to run the propeller with both thermic engine and electric motor [8], [9]. Thus, the main components of a hybrid propulsion system are essentially a propeller, a gearbox with an additional power take in/power take out (PTI/PTO), a thermic engine, an electrical machine, and an energy storage system.

The advantages of the hybrid propulsion are mainly inherent to the integration of different sources of energy, which can be exploited through motors running each one at regimes with high efficiency. In this manner, the global efficiency of the propulsion system becomes high at the different power demands of the propeller. Such a result is obtained with the modest increase in weight and complexity of the plant. Another advantageous peculiarity of this propulsive solution is given by the electrical machine that can work as electric motor or also as shaft generator to produce electric energy to be immediately used or stored in batteries. The key element in a hybrid plant is the power management system, i.e., a control unit capable of automatically choosing among the various energy sources the most convenient in terms of performance, fuel consumptions, and emission reductions. Moreover, if a parallel hybrid configuration is adopted, there is the possibility to boost the thermic engine when the vessel sails upstream or in shallow waters, whereas in slow steaming in harbor or in narrow sections of canals, the electric propulsion is more favorable. In addition, by employing the batteries as source for electric propulsion, a significantly noise reduction inside and outside the ship is ensured.

C. Microturbines

Microturbines represent a solution to produce electric energy at moderate costs with near-zero emissions profile. Compared with traditional diesel generator sets, they have extreme low NO_x emissions and produce a very negligible amount of PM. In hybrid solutions, microturbines operate in conjunction with the on-board battery pack (BP) to provide electrical power. The application to LNG system is simple and favorable. The clean-and-green microturbines can easily meet strict emission regulations without additional exhaust treatment. Moreover, the exhaust can be captured in a heat exchanger to heat water useful for the LNG vaporizer, from which draw gaseous fuel out for the microturbines themselves and for the main propulsion engines.

III. Computer-Aided Synthesis Model

CASM [10], [11] can be considered the most innovative tool by which tackle the early-design stages of a ship [12]–[15]. The results obtained may concern design, operation, or costs. In general, CASM is used for quite complex ships. In this paper, for the first time, it has been used for a pushboat, a relatively simple vessel but with numerous and different operating profiles that greatly affect the energy requirements on board. The main objective of the CASM is to determine the technical characteristics of a pushboat (in terms of size of the vessel and energy on-board management) to be exploited on a certain inland waterway. In particular, a detailed analysis of the transportation costs, in terms of capital expenditures (CAPEX) and operating expenses (OPEX), is carried out, taking into account the environmental peculiarities present along a given course, the configuration of the pushboat-barges convoy, as well as the operating modes performed.

As well known, CAPEX and OPEX represent two basic categories of business expenses. They differ in the nature of the subjects considered and for the tax treatment. CAPEX are the funds that a company uses to purchase major physical goods or services to expand its abilities in generating profits. These purchases can include real estates, hardware, vehicles to transport goods, and so on. Obviously, the cost items concerning CAPEX are strictly connected with the kind of industry involved. The asset purchased may be a new one or something else that improves the productive life of a previously purchased asset. If the useful life of the asset extends more than one year, then the company must capitalize the relevant expense, considering depreciation to spread the cost of the asset over its designated useful life, as imposed by tax regulations. Usually, CAPEX are depreciated over a five- to ten-year period, but may also be considered a longer period till or more than two decades, as in the case of ship owners managing inland vessels, which generally have an useful life up to 50 years. OPEX result from the ongoing costs a company pays to run its basic business. In contrast to CAPEX, OPEX are fully tax deductible in the year they are met. Since OPEX make up the bulk of a company's regular costs, management examines how to reduce them without causing a critical drop of quality or production. Sometimes, an asset that could ordinarily be obtained through CAPEX can be addressed toward OPEX when it is leased rather than purchased. This operation may be a financially attractive option if the company has limited cash flow and wants to tax deduct the total item cost for that year. Since CAPEX are referred to major purchases, the costs of which can be recovered over time only through depreciation, companies ordinarily budget these purchases apart from the operational budget.

In the CASM, for a given course, the values of a number of the input parameters [11] have been systematically varied, because it is not known *a priori* how they could affect CAPEX and OPEX, the sum of which determines the final cost of the transportation. The result attained through the model is the best combination of consistent design parameters that provides the lowest global cost (CAPEX + OPEX) along the considered course. In Fig. 2, the flowchart of the implemented CASM is represented. The first data to be input in the CASM concern information about the course along which the ship must be operated, in other terms, the ports of departure and arrival (block ①). Consequently, the intermediate ports with their relevant facilities, as well as the environmental constraints present along the selected inland waterway, are automatically drawn from a precompiled database (block ②). In fact, among the environmental constraints, there are, for instance, water depths (the presence of significant shallow waters [16]), air draught (due to the presence of bridges crossing the waterway), locks, waterway width, bends, direction of the current (downstream or upstream), and LNG bunkering stations (usually located in the harbors). Besides, other inputs more strictly connected to the unit for performing the transportation service must be given in block ③. The composition of the pushboat-barges convoy must be defined (that is number and formation of the barges to be pushed), which must comply with the class of the considered navigable waterway. With regard to the pushboat, the main characteristics of the hull (length, breadth, draught, and air drought) as well as the number of propellers should

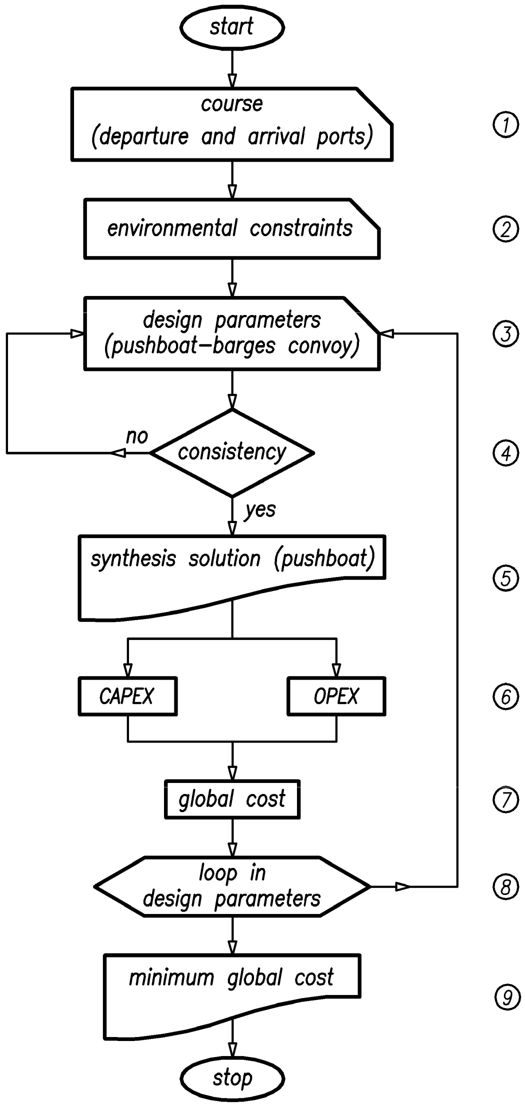


Fig. 2. Flowchart of the computer aided synthesis model.

be established. Thus, a check of the consistency between the environmental and the design parameters is done (block ④). If the check is not verified, then it is prompted to reinput new design parameters. Otherwise, taking into account both environmental and design inputs, a synthesis solution is generated on the basis of proper algorithms (block ⑤), and then a displacement (weight) results as the sum of the following components: hull structures [17], machinery and systems, out-fittings, LNG fuel, and cargo. Clearly, in the machinery item, there is also the hybrid propulsion system, the size of which depends on the powering required to reach a given speed [18], [19]. The powering in turn depends on the resistance of the entire pushboat-barges convoy [20]. Therefore, an iterative evaluation must be carried out. In general, for an inland convoy, a minimum value of the design speed equal to 13 km/h is established [21]. If a standard speed of 13 km/h is taken, the service speed could result in the range 10–16 km/h due to the sailing mode in upstream or downstream, being the current velocity between 3 and 4 km/h.

TABLE II
ATTRIBUTE WEIGHTS FOR THE DEGREE OF CLOSENESS

Attribute	Relative weight
LNG tank volume	0.35
Hydrodynamic resistance	0.10
Hourly LNG fuel consumption	0.05
Lightship weight	0.20
First cost	0.12
Average annual cost	0.18

Once propulsion engines and electric energy generators are sized, the range can be determined on the basis of the average specific fuel consumption and the fuel stored on board. Consequently, for the previously assigned course, the number of LNG bunkering can be calculated, keeping in mind the harbors properly equipped along the course. With reference to both the length of the pushboat alone and the convoy composition, a minimum number of crew members are imposed by the inland waterway navigation authorities [21]. In this manner, different weights related to the crew (accommodations, commodities, lifesaving appliances, etc.) are determined [22]. The above-outlined calculations ensure a rough evaluation of the costs for purchasing the vessel and also for operating it. In other terms, useful information to determine CAPEX [23] and OPEX [24] have been obtained as outputs of block ⑥, whereas block ⑦ provides the global cost (i.e., CAPEX + OPEX). By means of the CASM, a computational loop in design parameters randomly chosen can be run (block ⑧), so collecting a very high number of consistent solutions among which to identify the most convenient (block ⑨).

The decision among millions of processed solutions is carried out by means of the evaluation of the performance attributes (properly weighted according to the best designer practice) [25], which determines the degree of closeness of the examined solution, as shown in Table II. From Table II, it can also be observed that the LNG tank volume and the lightship weight have been assigned to prior importance, because they directly influence the feasibility of a design solution and the overall costs, both CAPEX and OPEX. Fig. 3 gives a graphical representation of the database reporting all the processed design solutions developed by the CASM. On the line of intersection between the surface of the CAPEX and the OPEX one, the design solutions that provide an appropriate balance between CAPEX and OPEX can be identified. Among them, the optimal solution has been chosen as the one that also has the best combination of the technical design parameters above described.

IV. NEW CONCEPT DESIGN

A case study has been performed considering in the Rhine-Danube corridor two courses from Rotterdam to Mannheim and from Rotterdam to the Black Sea. In particular, in the former, there are six LNG bunkering harbors, whereas in the latter, 23 (but among these, only 17 harbors have been considered because the other ones have not adequate

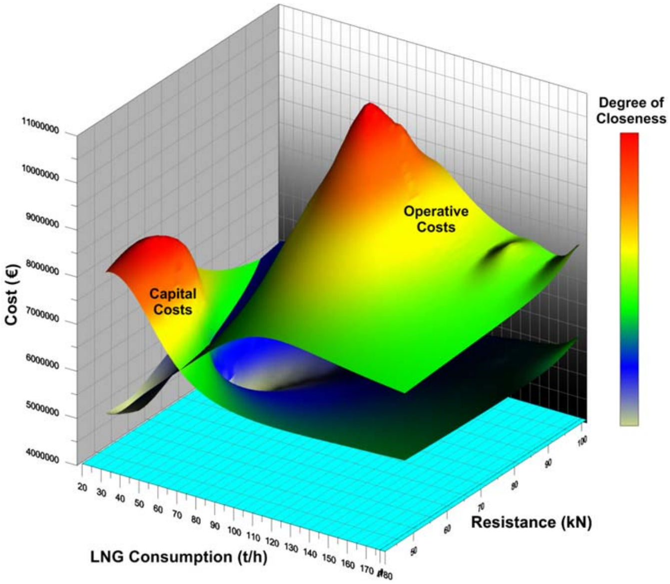
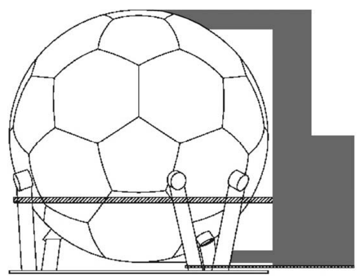


Fig. 3. Output of the CASM in terms of degree of closeness.



Leg height	2.45	m
Tank outer diameter	6.80	m
Volume	129	m^3
Net dry weight	92	t

Fig. 4. Spherical LNG storage tank.

TABLE III

MAIN FEATURES

Length overall	L_{OA}	=	37.70	m
Waterline length	L_{WL}	=	36.68	m
Breadth	B	=	11.35	m
Depth	D	=	2.90	m
Design draught	T	=	1.90	m
Displacement at design draught	Δ	≈	490	t
Full load speed, upstream		=	12.0	km/h
Full load speed, downstream		=	14.0	km/h
Speed without barges, upstream		=	16.0	km/h
Speed without barges, downstream			18.0	km/h

logistic services). The number of solutions drawn from the computational procedure has been in the order of millions. The concept design for an innovative pushboat optimized to operate along the course Rotterdam-Mannheim is shown in Fig. 4. The main features of the vessel are offered in Table III.

The hull form (Fig. 5) has been developed in order to optimize both hydrodynamic performance and construction. The three-propeller hull form has been preferred in respect of the four-propeller hull because it allows minimizing both first costs and maintenance costs. A hybrid-electric architecture has been selected for the propulsion system and the generation plant. Three dual-fueled engines supplied by LNG have been chosen. The most convenient shape for the LNG tank has resulted the spherical one, because offers more than double capacity in comparison with a cylindrical tank with the same overall dimensions. in Fig. 6, the LNG spherical storage tank considered is depicted together with its main dimensions.

V. SHIPBOARD POWER SYSTEM

An innovative shipboard power system has been proposed (Fig. 7) in order to properly satisfy the energy requirements for the operational profiles. In particular, all the specific needs related to efficiency, operational costs, and eco-friendliness has been taken into account for designing such a complex architecture endowed with a double distribution system [26]: a low-voltage ac bus (three-phase, 400 V, 50 Hz) has been conceived for supplying the shipboard loads, whereas a low-voltage dc bus (650 V) has been envisaged with the aim of interfacing the parallel hybrid propelling machinery with the upstream components [27]. In the following sections, such a power system will be discussed in detail together with some considerations about the energy management. Particular attention will be paid to the single elements depicted in Fig. 7 (right side), whose function is explained in the legend (left side). In order to simplify the comprehension of such a figure, the switches to configure the power system's operation are not shown, except those intended to manage the recharging of BPs.

A. Low-Voltage AC Distribution System

The proposed shipboard power system presents an ac bus, on which some components are connected as depicted in the highest section of Fig. 7. Particularly, the controlled ac generator G1 coupled with the micro gas turbine GT in the same sound shield is aimed at providing a power of 30 kW, while the shore connection SC may be used for supplying the power system during berthing. Talking about ac loads, it is possible to observe the electric motor M, the ac switchboard, and the LNG auxiliaries. The first one is an induction motor integrated into the rim-driven bow thruster (propeller diameter 1000 mm) that is capable of furnishing the notable power of 315 kW. The ac switchboard supplies different loads for a total power of about 300 kW: 400 V ac loads are directly supplied by the main switchboard bus, while the 220 V ac and 24 V dc users receive energy through various distribution boards. Thus, LNG auxiliaries' tag is used to represent the fuel-gas handling system to be installed in LNG fueled like the proposed pushboat. Considering the relevant importance of this system, it can be supplied (arrow) either by the ac bus or by the dc bus. In Table IV of the Appendix, the complete power balance of the optimized pushboat is presented.

B. Interface Power Converters

Several interface power converters (numbers from 1 to 4) are highlighted in the middle section of Fig. 7. They are

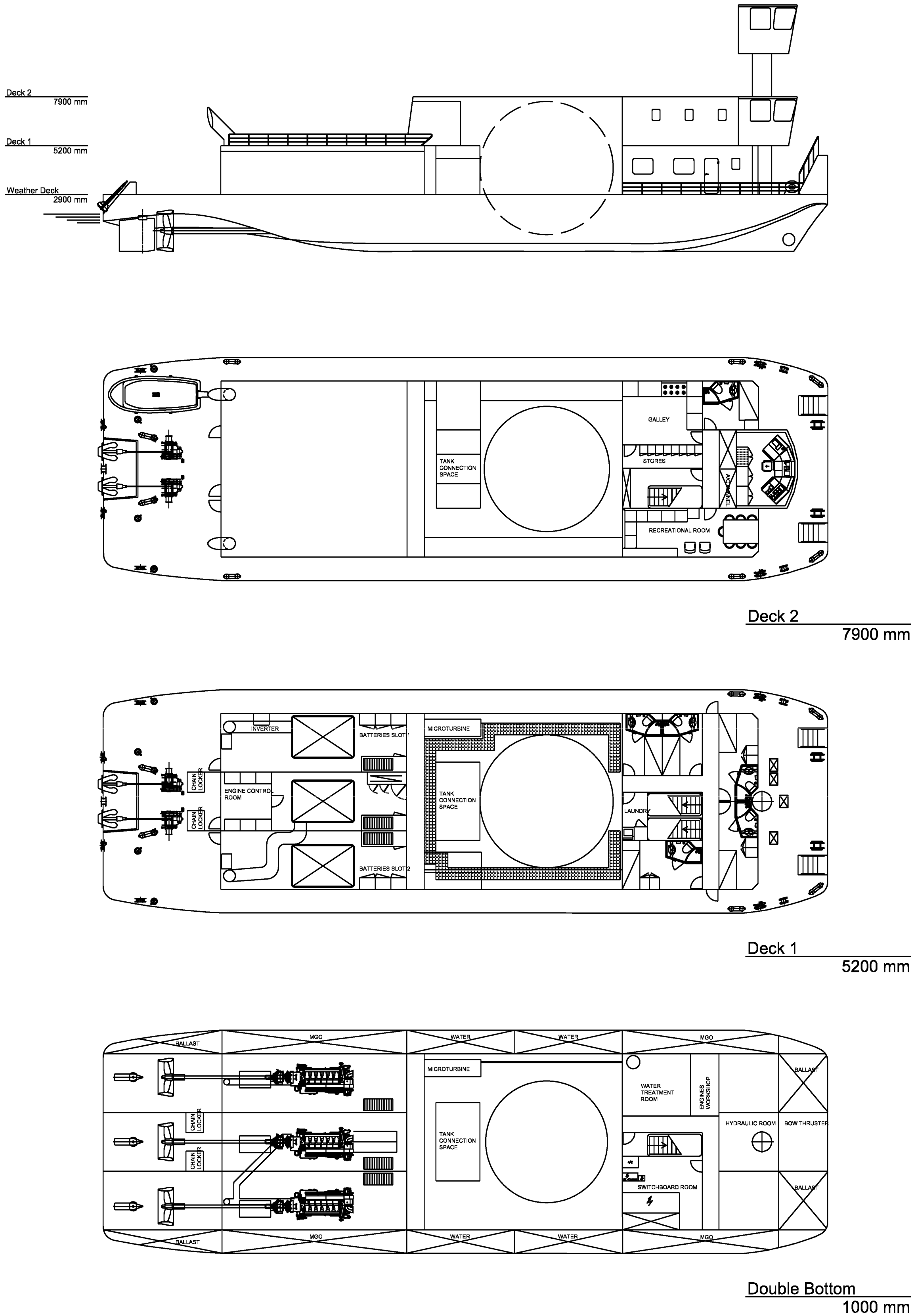


Fig. 5. General arrangement of the pushboat.

employed to interface the two buses, i.e., the ac distribution (generators/loads side) and the one based on dc (hybrid propulsion side). Basically, the interface converters 1 and 4 are ac-dc controlled rectifiers aimed at properly recharging the two BPs, whereas the power converters 2 and 3 are dc-ac frequency-controlled inverters. In case that the BPs are

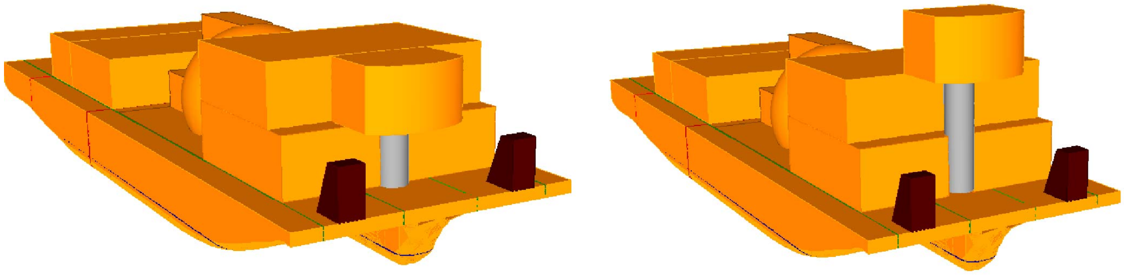


Fig. 6. 3-D model of the pushboat automatically generated by CASM, with the retractable wheelhouse in down and up position.

item	description
GT	micro gas turbine [38 kW @ 45000 to 96000 rpm]
DE	dual fuel engine [1060 kW @ 1200 rpm]
SC	shore connection [480 V AC 200 A]
G1	controlled electric generator [30 kW @ 50 Hz]
G2	electric generator [870 kW @ 200 rpm]
M	electric motor [315 kW]
MG	electric motor / shaft generator [870 kW @ 200 rpm]
RG	reduction gear [4.11:1]
FT	filter [400 V]
BP	battery pack [600 kWh]
LNG aux	LNG auxiliaries [15 kW DC or AC]
AC swb	AC switchboard [300 kW]

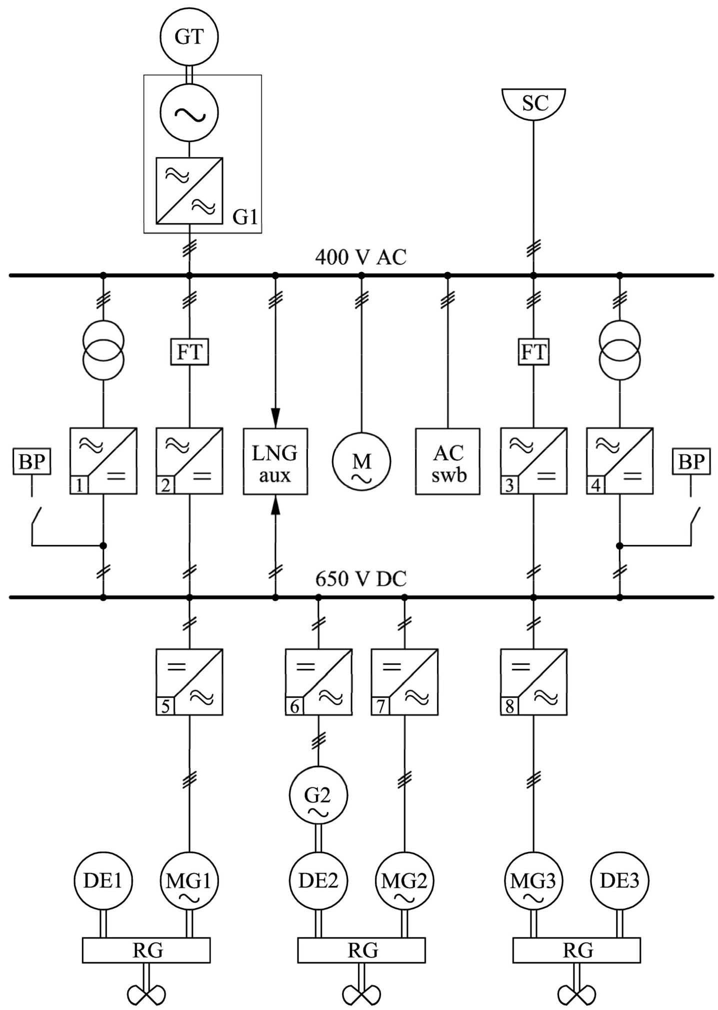


Fig. 7. Low voltage ac-dc shipboard power system.

exploited as sources or the electric Motor/shaft Generator (MG) machines work as shaft generators, the latter are able to provide a filtered ac sinusoidal voltage (50 Hz), in order to fulfill the power demand from the ac side.

C. Low-Voltage DC Distribution System

The lowest section of Fig. 7 shows the dc bus, whose installation ensures the power flow among upstream components and hybrid propelling system. Particularly, two main subsystems are connected to the dc bus: the BP and the parallel hybrid propelling machinery. The former has an aggregated capacity of 600 kWh provided by two slots (BPs) of 153 cells, which are to be placed in different zones (i.e., port side and starboard side of the battery room) to maximize the power

TABLE IV
OPTIMAL OPERATING PROFILE

	Hybrid mode (A)	Slow speed mode (B)	Normal speed mode (C)	Booster mode (D)
DEs	X/V	X	V	V
MGs	M	M	G	M
BPs	S	S	R	S

TABLE V

POWER BALANCE (kW) FOR THE OPTIMIZED PUSHBOAT

		A	B	C	D
User categories	**1**	94	94	94	94
	2	25	25	25	25
	3	62	62	62	62
	4	510	60	510	60
	5	27	27	27	27
	6	26	26	26	26
	7	270	270	1800	3300
	TOTAL	**1014**	**564**	**2544**	**3594**

system's reliability, while the latter constitutes the core of the shipboard power system, being capable of furnishing the desirable hybrid operational profile. By exploiting Dual fuel Engines (DEs, 1060 kW at 1200 r/min) and MG machines (870 kW at 200 r/min) properly linked through a clutch to a reduction gear (gearbox ratio 4.11:1), the three-shaft-line hybrid system is not only able to activate each propeller, but it can also be used for providing electric power to the dc bus. Specifically, the three propellers depicted in Fig. 7 can be moved separately either by the DEs or by the MG machines (electric motors' configuration) fed by the downstream power converters (5, 7, and 8) working in inverter mode (dc-ac). Conversely, the reverse operation of MGs (shaft generator configuration) allows transforming the DEs' mechanical power into electrical power, and therefore, the dc bus can be supplied by the previous controlled converters operating in rectifier mode (ac-dc). Particular attention has to be paid in describing the hybrid system of the middle propeller, which is characterized by an additional electric generator (G2). When the ship sails downstream and the mechanical power demand is therefore low, a double-bell housing allows us to directly interface dual fuel engine DE2 and G2 machine. In such a way, the DE2 mechanical power may be quasi-entirely converted into the electrical one transformed by G2. The latter is usually used for recharging BPs by means of the action of ac-dc rectifier 6.

D. Energy Management

To properly explain the energy management during the optimal operating profile, the related navigation modes (i.e., hybrid mode, slow speed mode, normal speed mode, and booster mode) are proposed in Table V. In correspondence of each navigation mode (column), the three rows are able to clarify the role covered by the main subsystems, i.e., dual fuel engines (DEs), electric machines (MGs), and BPs. The letter X is used for describing offline dual fuel engines, whereas V means the operation of DEs. The M symbolizes the electric motor mode, while G the shaft generator one. Finally, the recharging of BPs is represented by R symbol and the S letter signifies the use of BPs as sources of energy.

In hybrid mode, the vessel may sail by means of the MG electric motors (M) powered by the BPs in supply configuration (S). Such batteries are designed to completely substitute the DEs' mechanical power (X) or alternatively, in the case of low charge, they can provide an additional power to help the dual fuel engines (V) in moving the propellers. Conversely, the DEs are voluntarily declutched from the gearbox (X) in the slow speed mode. In such a case, the BPs are supplying (S) the electric motors (M), thus providing the required power to the propulsion. This mode is practicable up to 6 km/h or in harbor operations. The normal sailing mode is a configuration for recharging the batteries (R) by means of the electrical energy provided by shaft generators (G). Certainly, the DEs are responsible for producing the primary mechanical power (V) during the normal mode. Finally, a booster mode is to be conceived in shallow waters or currents, where the engine power demand becomes excessive. Therefore, the electric motors (M), fed by BPs (S) and installed at the PTI/PTO connection, are aimed at providing the sufficient power quota to support the DEs' operation (V).

VI. CONCLUSION

A deeper analysis of the IWT in Europe has constituted the first stage of this study, highlighting the peculiarities of the various European networks along with the relevant composition of the fleets. A particular attention has been addressed on the Rhine-Danube corridor, which has been assumed as the best environment for the proposed ship. In particular, an early-stage design of a pushboat for barges convoys has been developed based on the morphologic and infrastructural characteristics of Rhine-Danube waterway and taking into account the various requirements (i.e., the compulsory international and regional rules and guidelines for the construction and navigation of inland waterway ships).

The main vessel sizing has been optimized through a CASM, where several parameters can be evaluated in order to take into account not only technical requirements but also environmental, logistic, and economic matters. Great attention has been paid on the installation of on-board LNG facilities, where the LNG tank with an adequate capacity has strongly influenced the general arrangement of the vessel. Being the EU normative strictly focused on issues related to the environmental protection, the new ship project has been addressed mainly toward eco-friendly technologies. Specifically, a hybrid electric propulsion system in parallel configuration has been adopted with dual-fuel LNG main thermic engines. In this regard, an innovative complex architecture endowed with a double distribution system (low-voltage ac and low-voltage dc) has been conceived for guaranteeing desirable outcomes, in terms of high efficiency, low operational costs, and enhanced eco-friendliness. By taking into account such notable results given by the proposed design, this paper may represent a useful contribution for the innovation of the IWT fleet and the first stage for performing the POC of commercial technology for the electrification of inland waterway vessels. To this aim, further aspects related to the ship design will be developed in future and wider research program.

APPENDIX

For the correct choice of the machinery to be used for the propulsion and the on-board generation, for each design solution, it is required to evaluate an overall power balance. However, in the power balance, the load due to the propulsion has a much greater weight to those relating to other utilities on board. In order to draw up a correct power balance, the operational framework of a pushboat sailing in the European inland waterway must be divided in the standard phases described in Section V-D. Then the various users present on board must be gathered in large categories as follows:

1) maneuvering systems (bow thrusters, windlasses, and capstans);
2) auxiliary machinery (steering gear, stabilizers, fire pump, bilge pump, sludge pump, sewage treatment plant, water-maker pump, hydraulic plant, and battery chargers);
3) air conditioning (chiller units, air treatment units, fan coil units, and water heaters);
4) electrical users (galleys, wheelhouse, cabins, and laundry);
5) engine room ventilation (extractors and fans);
6) fuel treatment (diesel oil transfer pumps and purifiers, and LNG evaporator skid);
7) propulsion.

For each design solution, with reference to the above-mentioned operational profiles and user categories, the results of the analyses carried out in terms of power requirements can be synthesized in a power balance. Obviously, the greatest contribution will be those due to the maneuvering systems and propulsion. In Table IV, the power balance for the optimized concept design is shown.

The power that is required to propel a ship or a pushboat-barge convoy, over a given waterway at a given speed, is determined in the block of the CASM as the result of the contributions of the following components:

1) ship hydrodynamic resistance in deep water;
2) current effect correction on hydrodynamic resistance;
3) shallow water effect correction on hydrodynamic resistance;
4) pushboat-barges convoy effect correction on hydrodynamic resistance;
5) propeller open water characteristics and efficiency;
6) wake fraction and thrust deduction;
7) drive train efficiency.

In general, in the early-stage design, the ship hydrodynamic resistance is calculated through mathematical methods based on systematic study carried out on models tested in a towing tank, but there are not fully developed resistance prediction methods for pushboat-barge convoy. In the past, a sensitive analysis has been carried out by MARIN Institute at Delft and the UBC method for fishing vessels [28] resulted the more adequate to estimate the deep water resistance R_D of a pushboat, so this one has been used in the CASM. The current effect on the hydrodynamic resistance R_C has been considered as a flow propulsion velocity reduction up to 2–3 km/h in upstream navigation. The shallow water effect R_S has been investigated by means of the Jiang method [29], while the additional resistance R_B due to the presence of the barge convoy has been estimated using the Howe formula [30]. In this manner, the total resistance R_T of the pushboat-barge

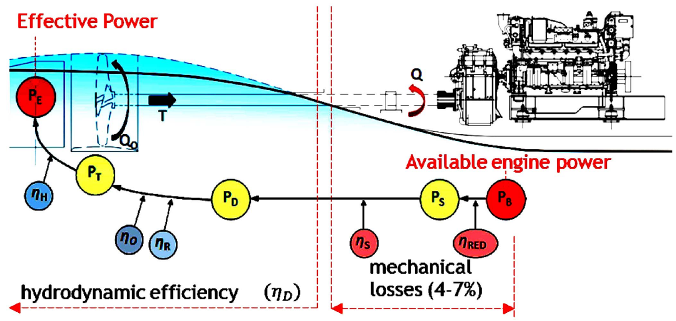


Fig. 8. Scheme for the calculation of ship power.

convoy sailing in shallow waters in the presence of a given current can be calculated as

$$R_T = R_D + R_C + R_S + R_B. \tag{1}$$

In order to obtain the power to be transmitted to the propeller by the engine—-from the hydrodynamic resistance of the ship/convoy—-it is necessary to determine the various efficiency as sketched in Fig. 8.

The power delivered by the propeller, the effective power P_E, for the different speeds can be directly calculated from the total hydrodynamic resistance of the ship

$$P_E = R_T V \tag{2}$$

where V is the ship speed (m/s) and R_T (kN) is the total hydrodynamic resistance. Due to the interaction between the propeller and the hull, the total power P_T must consider the hull efficiency

$$P_T = \frac{P_E}{\eta_H}. \tag{3}$$

The hull efficiency η_H is expressed by

$$\eta_H = \frac{1-t}{1-w} \tag{4}$$

where t is the thrust deduction and w is the wake fraction. The delivered power P_D is the power transmitted by the shaft to the propeller

$$P_D = \frac{P_T}{\eta_0 \eta_R} \tag{5}$$

where η_0 is the propeller open-water efficiency and η_R is the relative rotative efficiency.

In the CASM, the propulsive coefficients t, w, and η_R have been evaluated according to the van Oortmerssen formulas [31] considering the shallow water effect on propellers with Latorre correction [20], while η_0 and the other propeller characteristics have been calculated by the means of the Keller [32], Papmel [33], and Yosifov [34] theories.

The shaft power P_S takes into account the shaft mechanical loss η_S conventionally assumed equal to 1%

$$P_S = \frac{P_D}{\eta_S}. \tag{6}$$

Finally, the brake power P_B (kW) that is the power that must be produced by the propulsion engine is given by

$$P_B = \frac{P_S}{\eta_{\mathrm{RED}}} \tag{7}$$

where η_{RED} is the gearbox mechanical loss, conventionally assumed equal to 2%. Also the bow thruster electric motor is sized in block ⑤ of the CASM, according to the Beveridge formulas [35].

REFERENCES

[1] J. Rohács and G. Simongáti, "The role of inland waterway navigation in a sustainable transport system," *Transport*, vol. 22, no. 3, pp. 148–153, 2007.

[2] *Review of Developments in Transport in the ESCAP Region*, United Nations Pub., New York, NY, USA, 2003.

[3] *Inland Waterways & Environmental Protection*, Eur. Conf. Ministers Transport, Paris, France, 2006.

[4] *Waterborne Transport, Ports and Waterways: A Review of Climate Change Drivers, Impacts, Responses and Mitigation*, PIANC, Brussels, Belgium, 2007.

[5] *Guidelines for Sustainable Inland Waterways and Navigation*, PIANC, Brussels, Belgium, 2003.

[6] *Full Final Paper, PINE—Prospects for Inland Navigation Within the Enlarged Europe*, Brussels, Belgium, 2004.

[7] *Contribution to Impact Assessment of Measures for Reducing Emission of Inland Navigation*, PANTEIA-Res. Prog., Zoetermeer, The Netherlands, 2013.

[8] V. Bucci and A. Marinò, "Hybrid electric propulsion for an eco-friendly inland waterway passenger catamaran," in *Proc. INT-NAM, Int. Symp. Naval Archit. Maritime*, Istanbul, Turkey, Oct. 2011, pp. 57–67.

[9] V. Bucci, A. Marinò, D. Bosich, and G. Sulligoi, "Propulsion system design of a yacht catamaran: Comparisons between conventional and different diesel-electric solutions," in *Proc. MARINELIVE*, Athens, Greece, Jun. 2012, pp. 1–8.

[10] V. Bucci and A. Marinò, "Integrated ship design: Automated generation of production deliverables with new generation shipbuilding CAD systems," in *Proc. 12th Int. Conf. Comput. IT Appl. Maritime Ind. (COMPIT)*, Cortona, Italy, Apr. 2013, pp. 1–14.

[11] R. G. Hekkenberg, "Determination of key design parameters in conceptual inland ship design," in *Proc. 8th Int. Conf. Comput. IT Appl. Maritime Ind. (COMPIT)*, Budapest, Hungary, May 2009, pp. 204–213.

[12] D. J. Jurkiewicz, J. Chalfant, and C. Chryssostomidis, "Modular IPS machinery arrangement in early-stage naval ship design," in *Proc. IEEE Electr. Ship Technol. Symp. (ESTS)*, Arlington, VA, USA, Apr. 2013, pp. 121–127.

[13] C. Chryssostomidis and C. M. Cooke, "Space reservation for shipboard electric power distribution systems," in *Proc. IEEE Electr. Ship Technol. Symp. (ESTS)*, Alexandria, VA, USA, Jun. 2015, pp. 187–192.

[14] J. Chalfant, M. Ferrante, and C. Chryssostomidis, "Design of a notional ship for use in the development of early-stage design tools," in *Proc. IEEE Electr. Ship Technol. Symp. (ESTS)*, Alexandria, VA, USA, Jun. 2015, pp. 239–244.

[15] J. Chalfant, "Early-stage design for electric ship," *Proc. IEEE*, vol. 103, no. 12, pp. 2252–2266, Dec. 2015.

[16] T. Jiand and R. Henn, "Numerical investigation of shallow water wave equations of Boussinesq type," in *Proc. 14th Int. Workshop Water Waves Floating Bodies (IWWWFB)*, Port Huron, MI, USA, Apr. 1999, pp. 52–55 .

[17] R. G. Hekkenberg and J. J. Hopman, "Estimation methods for the steel weight of inland tank ships," *Ship Technol. Res.*, vol. 62, no. 2, pp. 63–71, 2015.

[18] A. Simić and D. Radojčić, "On energy efficiency of inland waterway self-propelled cargo vessels," *FME Trans.*, vol. 41, no. 2, pp. 138–145, 2013.

[19] Y. Tamura, Y. Nanke, M. Matsuura, T. Taketani, K. Kimura, and N. Ishii, "Development of a high performance ducted propeller," in *Proc. 21st Int. Tug Salvage Convent. Exhibit. (ITS)*, Vancouver, BC, Canada, May 2010, pp. 1–8.

[20] G. Luthra, K. Tang, and R. Latorre, "Improvement of inland waterway vessel and barge tow performance. Translations of selected Chinese, German and Russian technical articles," Dept. Naval Archit. Marine Eng., Univ. Michigan, Ann Arbor, MI, USA, Tech. Rep. 249, 1982.

[21] V. Bucci and A. Marinò, "Inland waterway gas-fuelled vessel: The basis of an innovative concept design for European rivers," in *Proc. 5th ed. Int. Conf. Develop., Energy, Environ., Econ. (DEEE)*, Florence, Italy, Nov. 2014, pp. 305–313.

[22] "Living and working conditions in inland navigation in Europe," Working Paper 297, ILO, Geneva, Switzerland, 2013.

[23] P. Sanders and Y. Guedj, "Ownership cost drivers in ship design & construction," BMT Design Technol., Melbourne, VIC, Australia, Tech. Rep., 2012.

[24] G. K. Saha, G. Mortuja, and M. E. Haque, "Optimization of the preliminary design parameters and cost evaluation of container vessel for the inland waterways of Bangladesh," in *Proc. Int. Conf. Marine Technol. (MARTECH)*, Dhaka, Bangladesh, Dec. 2010, pp. 195–200.

[25] H. Schneekluth and V. Bertram, *Ship Design for Efficiency and Economy*. Oxford, U.K.: Butterworth-Heinemann, 1998.

[26] V. Bucci, A. Marinò, D. Bosich, and G. Sulligoi, "The design of a slow-cruising superyacht with zero emission navigation and smart berthing modes," in *Proc. IEEE EVER*, Montecarlo, Monaco, Mar. 2014, pp. 1–8.

[27] D. Bosich and G. Sulligoi, "Voltage control on a refitted luxury yacht using hybrid electric propulsion and LVDC distribution," in *Proc. IEEE EVER*, Montecarlo, Monaco, Mar. 2013, pp. 1–6.

[28] S. M. Calişal, D. McGreer, G. Rohling, and G. Sadasivan, "Resistance of a systematic series of West Coast seiner hulls," Dept. Mech. Eng., Univ. British Columbia, Vancouver, BC, Canada, Tech. Rep., 1987.

[29] T. Jiang, "Investigation of waves generated by ships in shallow water," in *Proc. 22nd Symp. Naval Hydrodyn.*, Washington, DC, USA, Aug. 1999, pp. 601–612.

[30] B. Christopoulos and R. Latorre, "River towboat hull and propulsion," *Marine Technol.*, vol. 20, no. 3, pp. 209–226, 1983.

[31] G. van Oortmerssen, "A power prediction method and its application to small ships," *Int. Shipbuilding Prog.*, vol. 12, no. 207, pp. 397–415, 1971.

[32] W. H. A. Keller, "Extended diagrams for determining the resistance and required power for single screw ships," *Int. Shipbuilding Prog.*, vol. 20, no. 225, pp. 133–142, 1973.

[33] A. M. Basin and I. Y. Miniovich, *Theory and Calculation of Screw Propellers*. Sudpromgiz Publushing House, Leningrad, USSR, 1963.

[34] K. Yosifov, Z. Zlatev, and A. Staneva, "Optimum characteristics equations for the K-J ducted propeller design charts," in *Proc. 3rd Int. Congr. Marine Technol.*, vol. 1. Athens, Greece, 1984, p. 13.

[35] J. L. Beveridge, "Design and performance of bow thrusters," Dept. Navy, Naval Ship Res. Develop. Center, Bethesda, MD, USA, Tech. Rep. 3611, 1971.

Vittorio Bucci received the M.S. degree (Hons.) in naval architecture and marine engineering from the University of Trieste, Trieste, Italy, in 2005.

In 2006, he became a Post-Doctoral Researcher. In 2007, he joined as the Project Manager with Meccano Engineering, Trieste. In 2011, he joined as an Assistant Professor of Ship Structures and Marine Engineering with the University of Trieste. His current research interests include ship design and integration and the development of early-stage ship design tools to assess new technologies for sustainable navigation.

Alberto Marinò received the M.S. degree (Hons.) in naval architecture and marine engineering from the University of Trieste, Trieste, Italy, in 1982.

He is currently an Associate Professor of Ship Construction and Marine Engineering with the University of Trieste and an Associate Professor of Ship Technology with the Italian Navy Academy, Livorno, Italy, where he teaches Naval Ships and Submarines, and Ship Construction. His current research interests include the safety of ships and marine systems, integrated ship design, hybrid-electric propulsion, gas-fuelled ships, yacht design, and optimization of ship structures.

Daniele Bosich (M'07) received the M.S. degree (Hons.) in electrical engineering from the University of Trieste, Trieste, Italy, in 2010, and the Ph.D. degree in energy engineering from the University of Padua, Padua, Italy, in 2014.

He has authored over 20 scientific papers in the fields of marine shipboard power systems and voltage control.

Dr. Bosich is a member of PES and IAS.

Giorgio Sulligoi (M'02) received the M.S. degree (Hons.) in electrical engineering from the University of Trieste, Trieste, Italy, in 2001, and the Ph.D. degree in electrical engineering from the University of Padua, Padua, Italy, in 2005.

He was an Intern with Fincantieri Electric Systems Office, Trieste, and a Visiting Scholar with University College Cork, Cork, Ireland. In 2005, he joined MAI Control Systems, Milan, Italy, an Italian firm operating in the field of power stations and alternator voltage control systems. Since 2007, he has been an Assistant Professor of Electric Power Generation and Control with the Department of Engineering and Architecture, University of Trieste.

Prof. Sulligoi is a member of PES, where he serves on the MARSYS and GOLD committees.