Hybrid-electric propulsion for the retrofit of a slow-tourism passenger ship

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Abstract — **The increasing interest in air pollutant emissions reduction also influences the shipbuilding industry. In this sense, hybrid-electric propulsion is a promising solution for green navigation, ensuring a Zero Emission Mode navigation close to coastal areas and harbors. Hybrid-electric propulsion is a convenient choice not only for new units but also for the retrofitting of outdated ones. This paper deals with an example concerning the retrofitting of a small passenger vessel, where the study of the application of hybrid-electric systems was possible only thanks to reverse engineering techniques for the identification of the internal spaces. The final hybrid configuration refers to a slow-tourism operative profile in the North Adriatic area.**

Keywords—hybrid-electric propulsion; retrofitting; reverse engineering; Zero Emission Mode navigation; IPES

I. Introduction

In recent years, new forms of tourism have developed aiming the discovery of uncontaminated places that can be obtained by means of reduced environmental impact vehicles. Eco-sustainable tourism is a type of tourism promoted by operators who pay particular attention to the relationship between tourist activities and nature adopting operational strategies so that this relationship is characterized by harmony and respect [1]. There are some tourism segments that already exist, which can be grouped as Slow Tourism [2]: trekking, cycle tourism, horse trails, river and water tourism. More and more tourists have approached a form of tourism or travel that uses the bicycle as a means of transport, the world of cycle tourism.

The "bike and boat" holiday formula is a recent Dutch invention, which soon conquered rivers, canals and cycle paths from other European countries. Bike and boat itineraries can also be found in Belgium, France, Austria, Germany and Italy. Traditionally, boats navigate through rivers and canals, but recently also in coastal regions, such as those overlooking the Adriatic Sea in Croatia. The idea is to ride and enjoy the itinerary during the day while the boat, a real "floating hotel", follows the planned routes. At the end of the day, just like a real hotel, cyclists can return on board and take advantage of the many services available to them for a welcoming refreshment and a pleasant overnight stay.

The vessels used in "bike and boat" holidays frequently are old river boats specially converted. The main reasons behind this choice are lower costs and implementation times. However, in most cases they are only modified in the interior fittings, nothing significant is instead done for the propulsion systems. Therefore, their environmental footprint remains quite high given that the propulsion systems are based on Diesel engines and Diesel generators, only. In part, the problem is justified by the fact that often no reliable design documentation is available for old ships to plan effective refitting operations. Recent studies [3] highlighted the possibility to increase significantly the eco-friendliness of small tourist crafts, when they are specially designed and built. A new design method has been applied [4] and operating simulators [5], [6] have also been developed in order to predict fuel/energy consumptions and operating costs. However, only the application of the modern concept of green shipbuilding [7] in the refitting process allows achieving the same results in terms of eco-friendliness. Therefore, first step is to adopt an integrated design approach capable of conducting a serious reverse engineering activity [8] on the ship chosen for refitting. It is worth noting that Reverse Engineering (RE) is a technique of virtual/mathematical reconstruction of real objects. The 3D model significantly reduces the design time, data inconsistency and errors. The purpose of RE was initially to recover the missing design information directly by surveying an existing object. Subsequently, when the 3D CAD technologies have matured considerably, RE allowed to draw parametric virtual prototypes that can be used for the processing of both digital twins and new projects.

In this paper, the preliminary design of the refitting of a small passenger ship to be used in "bike and boat" holiday formula in North Adriatic Sea area is showed. With the aim to place the refitted ship in a thriving market segment, which could entice future investors, an accurate market analysis (number of passengers per ship, accommodation standards, technologies for sustainable navigation to be adopted, etc.) has been performed. Consequently, a peculiar analysis of possible routes has been carried out considering the integration of adequate harbours (depth, large mooring docks, shore connection, air draught, etc.) within a network of cycle path. Then, applying a modern integrated reverse engineering process, a robust and consistent 3D parametric model of the ship selected for refitting has been drawn after a photo-relief (Fig. 1). Following a complete review of the general arrangement plans, a careful planning of the operating profile and an accurate speed/power / prediction, an energy balance has been drawn up. So, the sizing of all the equipment involved in the new hybrid-electric propulsion system has been performed.

Fig. 1. M/N Ambriabella berthed, during RE data acquisition operations

In order to achieve high standards of eco-friendliness and adequate range along with a low fuel consumption, a new power system has been enabled. Moreover, a conspicuous battery pack has been planned to be installed on board, so ensuring the so-called Zero Emission Mode (ZEM) navigation. Propulsion based on electric motor supplied by batteries reduces both the air pollution and noise. Obviously, in order to maximize its eco-friendliness, the ship will have to operate in a network of harbours equipped with charging facilities supplied by renewable sources or with a low environmental impact. This is to not only obtain the delocalization of air pollution from the harbor to the power plants sites.

II. Slow Tourism and Operative profile

Among the multiple activities that can be provided in a coastal area, a new trending opportunity is given by the touristic activities. With respect to shipping, a coastal area is not only characterised by the conventional large passenger cruising, but can be associated to alternative and new touristic solutions. Nowadays, alternative tourism activities are growing, giving more attention to the relationships between tourist activity and nature, thus offering solutions that are respectful of the nature. This is of utmost importance for the promotion of a sustainable tourism [9], where sustainability is determined by the synergy among environmental, socio-cultural and economical aspects. The correct balance between these three aspects is a continuous process that needs a constant monitoring of environmental impacts, providing corrections and countermeasures, whether a problem occurs. On the other hand, sustainable tourism have to maintain a high level of satisfaction for the tourist, ensuring a complete and significant experience, increasing the tourist consciousness on sustainability related issues.

Among the different possibilities of the sustainable tourism, the specific form of the *slow tourism* [10] is analysed. This tourism typology promotes the quality of the provided experience in contrast with *mass tourism*, which is fast and consumerist and gives no benefits to the peculiarities of the tourist attractions. The main characteristics of the slow tourism can be summarised as follows:

- *Contamination*: stimulate interactions with the local community, sharing experiences and cultural differences.
- *Genuineness*: valorise the specificity, peculiarities and excellences of the visited locations.
- *Sustainability*: minimising the impact on the environment. Ethically and socially fair tourism for the local people.
- *Time*: require more time to plan the activities.
- *Slowness*: the activities are planned to grant a complete and engaging experience to the tourist, gradually absorbing the culture of the local community.
- *Emotions*: generate multisensory experiences, capable to inspire the wish of a comeback.

According to the above-mentioned points, one of the most suitable way to perform slow tourism is by means of bicycles, thus cycle-tourism. This kind of slow solution is particularly attractive for the North Adriatic area, being the targets of this segment related to rural areas, cultural/historical sites and natural reserves (Fig. 2). The area under analysis presents all these kind of point of interests. To this end, a hypothetic travel of eight days has been considered, taking into consideration the following two objectives:

- Valorisation of the landscape and nature peculiarities of the selected area
- Connect the most attractive areas across the North Adriatic, lowering the environmental impact of the tourist transfer, especially for the spring and summer period.

The wide area under analysis and the peculiarities of the morphology of the territory, did not allow to use only the bicycles for transfer. Therefore, it is necessary to provide an environmental-friendly solution for the tourist transport across the main touristic hubs or across the start/end of cycle paths. In this sense, the use of a passenger vessel is attractive, giving the possibility to perform transfers during the night, while the passengers are sleeping on-board. However, the use of a vessel for this service may arise additional technical issues to solve.

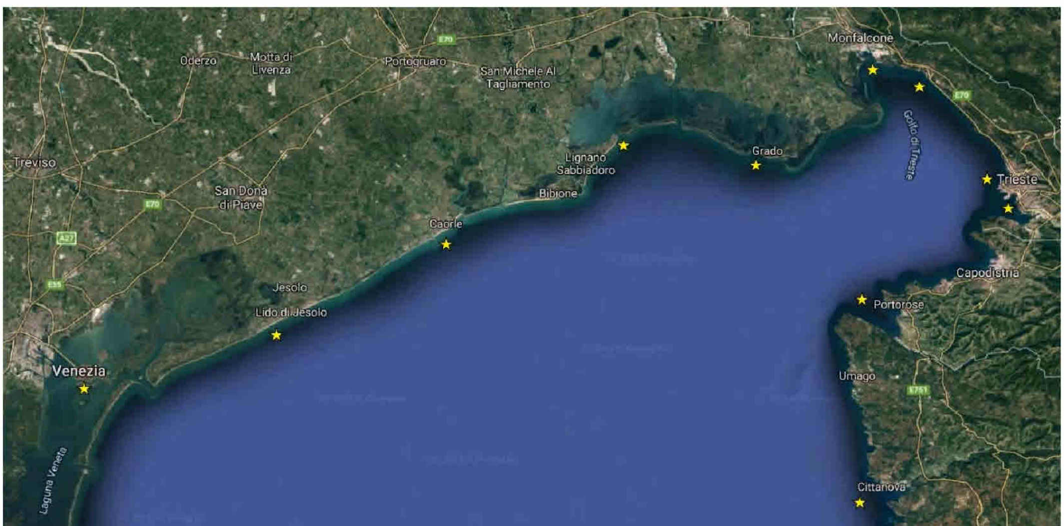

Fig. 2. Sample slow tourism intermodal route in the North Adriatic considered in this study

TABLE I. ROUTES DESCRIPTION

Route		Characteristics				
		Length	*Mean depth*	*Speed*	*Time*	*Remarks*
1	Venice-Marina del Cavalino	29.63 km	4.5 m	6 knots	2 h 40 min	Transit in shallow water
2	Marina del Cavallino – Porto Santa Margheita	27.78 km	12.5 m	6 knots	2 h 30 min	-
3	Porto Santa Margherita - Lignano	31.48 km	12.5 m	6 knots	2 h 50 min	-
4	Lignano - Grado	24.00 km	5.8 m	8 knots	1 h 55 min	Transit in shallow water
5	Grado - Monfalcone	31.48 km	8.8 m	6 knots	2 h 50 min	Transit close to harbours
6	Monfalcone - Sistiana	11.11 km	11.8 m	8 knots	50 min	Transit close to harbours
7	Sistiana - Trieste	18.52 km	12.3 m	6 knots	1 h 40 min	-
8	Trieste - Muggia	7.41 km	12.5 m	8 knots	30 min	Transit close to harbours
9	Muggia - Portorose	27.78 km	>15.0 m	6 knots	2 h 30 min	-
10	Portorose - Cittanova	33.34 km	>15.0 m	6 knots	3 h	-
11	Cittanova – Venice (Lido)	96.30 km	>15.0 m	13 knots	4 h	-
12	Venice (Lido) - Venice	12.96 km	5.0 m	6 knots	1 h 10 min	Transit in shallow water

First, the navigation in the coastal area across the North Adriatic includes the transit in zones characterised by restricted channels and shallow water, thus giving restrictions to the vessel dimensions and increasing the amount of power needed to sail at a given speed. Second, to ensure the environmental friendliness of the unit, modern technologies (i.e. hybrid-electric systems) have to be adopted for the propulsion, ensuring the possibility to perform a ZEM navigation in specific environmental restricted area like natural reserves or nearby urban areas.

Both aspects have to be considered for the selection of the best vessel needed for the transportation service. Moreover, it is essential to define the scheduling in compliance with the speed limitations in the coastal and internal areas. This kind of analysis is necessary to avoid the over dimensioning of the hybrid-electric propulsive system. In this specific case, as already mentioned, the aim is not to design a completely new unit, but to refit an existing one. Therefore, an accurate estimation of the operative profile is mandatory prior to study the refitting operations. To this end, it is worthy to report in detail the route that the vessel is supposed to perform during a complete travel. As highlighted in Fig. 2, the total travel consists of 12 sub tracks, each one having some peculiarities. Table I gives an overview of the distances and constraints of each route segment. It can be observed that some routes are characterized by the transit nearby harbour areas; therefore, in these cases the vessel will be more subject to manoeuvring issue, having to deal also with the local traffic. In other cases, the vessel has to perform navigation in restricted and shallow water, as in the specific case of Venice and Grado Lagoons. In this case, it is important to consider the increase of power generated by restricted water conditions.

A. Operational profile

For a proper approach to the passenger vessel refitting procedure, it has been necessary to further specify the service profile needed to perform the route described in Table I. As highlighted, across the selected routes there are various speeds of interest, varying from 6.0 to 13.0 knots, but also different restrictions due to the different mean water depth. Therefore, the identification of the operational modes must include the variations of these parameters. Specifically, certain water-depths should be considered for the determination of the total power demand.

Based on the above considerations, the following operational modes can be defined for a hybrid-electric passenger vessel devoted to the described service:

A. *Navigation at full speed*: this profile corresponds to an emergency condition. This can occur only for limited periods that, in principle, should not exceed the 10% of the total life of the unit. In this case, all the total available power on board is used.

B. *Navigation at cruise speed with battery charge*: this condition allows the vessel to reach the cruise speed of 13.0 knots in unrestricted waters with the Diesel engines and using the remaining power of the prime movers to recharge the battery packs.

C. *Navigation at cruise speed*: is the same of profile B, but without battery recharge.

D. *Navigation at low speed with battery charge*: this condition is similar to profile B but at a speed of 8 knots in unrestricted waters.

E. *Navigation at low speed*: is the same of profile C, but at a speed of 8 knots in unrestricted waters.

F. *ZEM navigation at low speed*: is the same as profile E, but batteries provide the total power.

G. ZEM navigation at lower speed: is the same as profile F but at a speed of 6 knots in unrestricted waters.

H. ZEM navigation in restricted water: is the same as profile G but considering a water depth of 4.5 meters.

I. Manoeuver: this profile includes all the operations that are executed during the berthing operations, thus while the unit is approaching or leaving the shore. This profile can be performed also in ZEM.

J. Berthed: it is possible to recharge the batteries and supply the on-board users by a shore connection.

Considering the provided operative profiles and design targets, a refitting process can start on an existing vessel.

TABLE II. MAIN CHARACHTERISTICS OF THE ORIGINAL VESSEL

symbol	Characteristic	value	Unit
L_{OA}	Length overall	51.85	m
L_{WL}	Length on waterline	47.00	m
L_{PP}	Length between perpendiculars	45.62	m
B	Breadth	7.40	m
T	Draught	2.21	m
D	Depth	3.25	m
Δ	Displacement in weight	425.00	t
GT	Gross tonnage	292.49	t
Np	Passengers	400	-
V_C	Cruise speed	15.40	kn
P_B	Installed propulsive power	1280	CV

Fig. 3. 3D model of the vessel under analysis

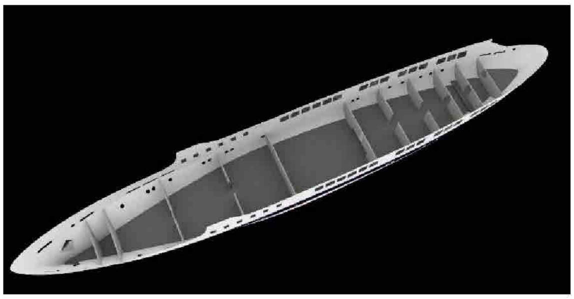

Fig. 4. Internal subdivision of the lower deck

III. THE VESSEL AND ITS POWER BALANCE

The vessel selected for the retrofitting process is the M/N *Ambriabella*, built in 1962 by the Felzegi Shipyard in Muggia (Trieste). It was used for the passenger transport between Trieste and Grado (North Adriatic) until 1976 and then in Greece up to the 2000. From 2009, the vessel is dismissed and waits for a refitting. The main characteristics of the vessel are collected in Table II. The main dimensions of the ship are suitable to perform the service described in the previous section. Therefore, it is possible to use this vessel for the slow tourism scenario described, having in mind that the unit must be converted for the specific use.

A. Power balance

The power balance of the vessel must include all the possible power users, therefore, besides the propulsive demand, all the electrical users installed on board should be considered and their power estimated. For convenience, the power users have been gathered in the following categories:

TABLE III. POWER BALANCE FOR THE VESSEL OPERATIVE PROFILES

		Operational profiles									
		A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*
User categories	1	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.0
	2	17.8	17.8	32.8	17.8	32.8	32.8	32.8	32.8	13.7	13.7
	3	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	8.8	5.5
	4	13.0	13.0	13.0	13.0	13.0	13.0	13.0	13.0	87.2	0.0
	5	23.0	27.0	27.0	27.0	26.3	26.3	26.0	26.0	26.0	8.5
	6	2.9	122.7	2.9	122.7	2.9	2.9	2.9	2.9	2.9	122.7
	7	90.4	107.1	107.1	107.1	92.6	92.6	83.4	83.4	90.4	75.0
	8	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	0.0
	9	100.0	0.0	0.0	0.0	0.0	78.8	30.5	49.2	0.0	0.0
	10	958.0	443.0	443.0	72.9	78.8	0.0	0.0	0.0	24.3	0.0
TOTAL (kW)		***1218***	***742***	***639***	***373***	***259***	***259***	***201***	***220***	***257***	***220***

1. Fuel treatment;
2. Air conditioning;
3. Machinery ventilation;
4. Manoeuvring system;
5. Auxiliaries;
6. Battery charger;
7. Switchboards;
8. Navigation system;
9. Propulsion (electric motors);
10. Propulsion (Diesel engines).

With reference to the previously mentioned operational modes (from A to J) and the user categories just defined, it is possible to determine the power requests for each mode of use. Table III summarizes the power analysis outcomes.

Considering these data, it is possible to size the power components that have to be installed on board and to provide a suitable configuration for the Integrated Power and Energy System (IPES). It can be observed that there is a significant difference among the final levels of absorbed power of the different operational modes, from 1218 kW at full speed to 201 kW for ZEM navigation at low speed. Such a difference for two propulsive configuration can be sustainable only using a hybrid-electric configuration, because, for the lower load, the Diesel engines would be under loaded and consequently inefficient. Moreover, this is not acceptable and not in line with the concept of sustainable navigation.

To achieve this target and satisfy the routes of Table I, it has been evaluated that the engines currently installed on-board of the *Ambriabella* are not suitable for the service. The two main engines should instead be capable to deliver 500 kW each, using two electric engines of 50 kW each as a boost for the full speed mode. Besides, 2 Diesel generators of about 50 kW each should be installed for the energy generation. To satisfy the range in ZEM navigation, the installed battery packs should have a total capacity of 2400 Ah to satisfy 3.5 hours of navigation with profile G.

B. Retrofitting of the internal spaces

There were no available drawings of the vessel general arrangement in the current configuration and lines plan at disposal. Therefore, prior to start the design process of the retrofitting configuration, it was necessary to reconstruct the external surface and the internal layout of the vessel as it is now, solving a challenging *reverse engineering* problem. To provide the dimensions of the internal spaces it was necessary to perform on board measurements. It has been possible to observe that the actual status of the vessel was far away from the original design drawings available. Thanks to this work, it has been possible to reconstruct a full 3D model of the vessel (Fig. 3), with the current internal subdivision. (Fig. 4).

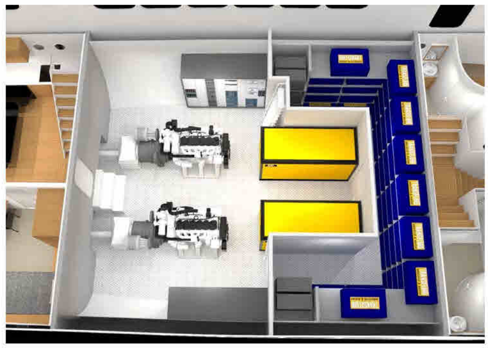

Fig. 5. Engine room internal layout

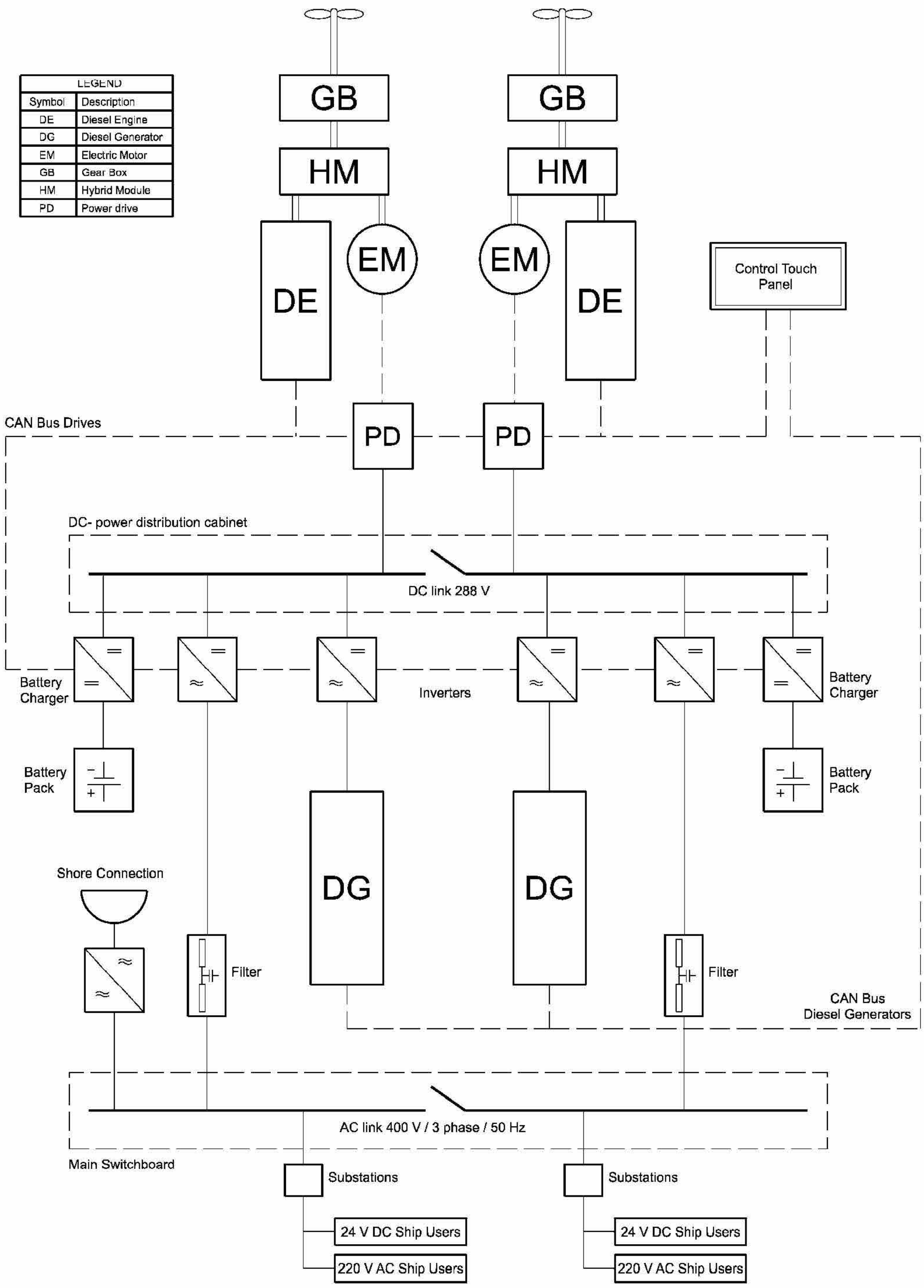

Fig. 6. Low voltage DC Shipboard Power System for the refitted vessel

Thanks to the reconstruction of the internal spaces, it was possible to evaluate directly a suitable layout for the machinery system needed to ensure propulsion and electrical generation onboard of the refitted vessel. The adoption of the integrated approach allows checking also that the selected machinery have respected all the clearance necessary for installation and maintenance, ensuring the feasibility of the proposed solution for the vessel refitting. The resulting layout with propulsive engines, diesel generators, main switchboards and battery package is shown in Fig. 5.

IV. Integrated Power and Energy System

As already explained, the hybrid-electric propulsion is one of the best solution to ensure the ZEM navigation, eliminating the pollutant emissions in the atmosphere and reducing the propulsion noise. To enable the eco-friendly ZEM navigation, the IPES should satisfy all the possible energy requirements reported in Table III. Here (Fig. 6), an LVDC distribution is conceived to easily recharge the battery packages, including also a shore connection. This neglects the use of Diesel generators during mode J, thus reducing the emissions.

A. LVDC shipboard distribution system

Having DC distribution a focal importance in IPES design, as discussed in [11], it is worthy describe the LVDC bus. For the proposed case, the bus has a rated voltage of 288 V and all the shipboard subsystems are connected to it. With reference to Fig. 4, it is possible to distinguish the Diesel generators DG, the battery packs and the shore connection. On the same bus, also the main loads are connected: two electric motors EM (and consequently the power drives PD) with a nominal power of 50 kW each.

Two modules connected in series compose each BP, having a total capacity of 712 kWh, which is sufficient to ensure 3.5 hours of navigation according to profile G, satisfying also the required range of modes F and H, according to Table I. Two battery chargers manage the BP recharging process, allowing the recharge by means of shore connection, Diesel generators DG or by electrical motors EM. Because all the loads and sources are connected to the LVDC bus, interface converters have to be installed. In the case of BP there is an isolated DC-DC stage, all the others are acting as DC-AC inverters to supply the specific electric engines.

B. IPES management

The operational modes (A-J) of the vessel require different settings of the IPES. It is convenient to distinguish between ZEM and non-ZEM profiles. The ZEM profiles (F, G, H) can be performed by switching the DGs and DEs off. In such cases, the loads are supplied by the battery packages.

Operational mode A is a non-ZEM condition. It can be performed only by running the two DEs in combination with the two EMs. In this case, the PDs consider EMs as engines. The electric power to the EMs can be provided by batteries or by the DGs. All the other non-ZEM conditions can be obtained with the IPES, considering that in such cases, the PDs consider the EMs as a shaft generator. In this way, the energy given by the EMs can be used for battery recharge (modes B and D) or for the alimentation of the other users.

V. Conclusions

The increasing sensibility with respect to environmental issues reflects also in the tourism industry. New forms of tourism, as e.g. slow tourism, are becoming more and more attractive and necessitate of modern and ecological transportation systems. In the specific region of the North Adriatic, there is space for the development of an intermodal touristic form, combining cycle-tourism and short distance passenger cruise. This synergy well combines with the definition of slow tourism, providing the correct balance between on shore activities and navigation. On the other hand, it is necessary to provide a vessel capable to decline the ideology of slow tourism, both in terms of speed end eco-friendly navigation. In this sense, the retrofitting of an old ship is advisable, providing a tailored design of the new propulsive system in accordance with the new vessel operative profile. The adoption of a hybrid-electric propulsion, allows the unit to reach the ecological standards required by the slow tourism concept. Since the refitting of an existing vessel ensures the desired targets of eco-friendly transportation, the costs of the refitting can be lower than the design and construction of a completely new unit. However, the final advantages between a refitting and a new construction can be evaluated only by comparing the operative cost of the two units. This means that a good design based on modern integrated approaches may lead to better performances with respect to a retrofitting operation.

References

[1] WTO, "UNWTO World Tourism Barometer", Volume 17, Issue 4, 2019

[2] M. Zago, "Guidelines for the slow tourism", 2011

[3] C. Nasso, U. la Monaca, S. Bertgana, L. Braidotti, F. Mauro, G. Trincas, A. Marinò and V. Bucci, "Integrated design of an eco-friendly wooden passenger craft for inland navigation", International Shipbuilding Progress 66(1), pp. 35-55, 2019.

[4] V. Bucci, A. Marinò, D. Bosich and G. Sulligoi, "Inland waterway gas-fuelled vessels: CASM-based electrification of a pushboat for the euopean network", IEEE Transactions on Transportation Electrification 2(4), pp.607-617, 2016.

[5] F. Mauro, C. Nasso, U. la Monaca and V. Bucci, "A simulation model for hybrd-electric inland waterway passenger vessels", Proceedings of the 19th International Conference on Ships and Shipping Research (NAV 2018), June 20-22, Trieste, Italy, 2018.

[6] F. Mauro, U. la Monaca, C. Nasso and V. Bucci, "A hybrid-electric solution for station keeping and propulsion of a small coastal research vessel", Proceedings of the 2018 IEEE International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM 2018), June 20-22, Amalfi, Italy, 2018.

[7] J. Li, H. Yi and Y. Zhang, "Research on Green Shipbuilding and Concurrent Green Ship Design", *Applied Mechanics and Materials*, vol. 44 – 47, pp. 614 - 618, 2010.

[8] T. Varady, R. R. Martin and J. Cox, "Reverse Engineering of Geometric Models an Introduction", Computer-Aided Design, 29(4), pp. 255-268, 1997.

[9] WTO, Transport-related CO2 Emissions of the Tourism Sector – Modelling Results, World Tourism Organization, Madrid, Spain, 2019.

[10] Zago, M. et al., Context anlysis of the Slowtourism area, Technical Report, 2011

[11] V. Bucci, F. Mauro and A. Marino',"A new concept design solution for pleasuresailing yachts", Maritime Technology and Engineering 3, pp. 627-634, 2016