Electrification of Leisure Boats: a commercial State-of-the-Art

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***Abstract*—This paper presents the commercial state-of-the-art of electric leisure boats. Particularly, several kinds of electric propulsion systems for electric and full electric boats are considered and reviewed, by investigating the attendees of some of the most important international boat shows. The analysis highlights that the market proposes electric propulsion systems which cover a wide range of boats in terms of kinds, dimensions, and scopes. Similarly, a number of full electric boats is also available on the market, promising eco-friendly, efficient, exciting and quietly sailing experience. The present overview focuses on motor and battery sizes, as well as on expected performances and optional systems, such as range extenders and hydrofoil systems.**

Keywords—Electrification, Electric propulsion system, Electric vehicle, Inboard, Marine, Outboard, Pleasure boat, Sailboat, State-of-the-Art

I. Introduction

The reduction of greenhouse and pollutant gases is one of the most challenging missions of modern times. Since the transport sector is one of the most emitting, its electrification is widely considered as one of the measures necessary to reach this goal, regardless of the specific subsector (road, rail, aviation or marine). Referring to marine transportation, the International Maritime Organization (IMO) pointed out this need clearly by publishing an ambitious roadmap for reducing overall marine sector emissions by 40% and 70% compared to 2008 levels in 2030 and 2050 respectively [1]. Freight ships surely represent the most impacting fraction of the entire fleet in terms of emissions, and require a balanced mix of short-, mid- and long-term policies [2]; however, a great ferment was registered in the leisure boat sector that already offers tenths of full electric boats and whose overall market value is expected to increase over the forthcoming years [3], [4].

Leisure boats are recreational boats that are used for personal, pleasure, tourism, and/or sport ends. Apart from the indisputable advantages of reducing emissions, full electric boats present a number of advantages that may compensate for the higher purchase investment by the owner [5]. For example, (i) electric propulsion systems are very silent and thus increase the comfort during navigation; (ii) batteries can be recharged on board resorting to renewable energy sources, such as photovoltaic panels or micro-wind generators, as well as during sailing; (iii) operating and maintenance costs are extremely reduced compared to gasoline engines; (iv) electric boats are often allowed to entering areas restricted by environmental concerns; (v) compact, light and reliable electric propulsion systems can be successfully and safely used on kayaks, surfboards, inflatables, enabling a number of new applications and services.

In this context, this paper aims at presenting a survey on the state-of-the-art of commercial electric leisure boats. The review is based on companies attending some of the most important international boat shows [6]–[8], thus it presents only a partial overview of this constantly changing market. Commercial solutions have been grouped into electric propulsion systems solely and full electric boats and are then presented accordingly to this classification. They have been discussed referring to their main characteristics, such as rated motor power, battery capacity, rated and maximum speed, while boat length, beam and displacements have been considered for all electric boats.

The paper is structured as follows: electric propulsion systems for electric boats are presented in Section II; full electric boats are presented in Section III. Concluding remarks are given in Section III.

II. Electric Propulsion Systems for Electric Boats

The main components of an electric propulsion system for electric boats are shown in Fig. 1 [9]–[11]. The propeller is connected to the electric motor directly or through a gear box; the motor is fed by a DC/AC converter, which, in turn, is fed by

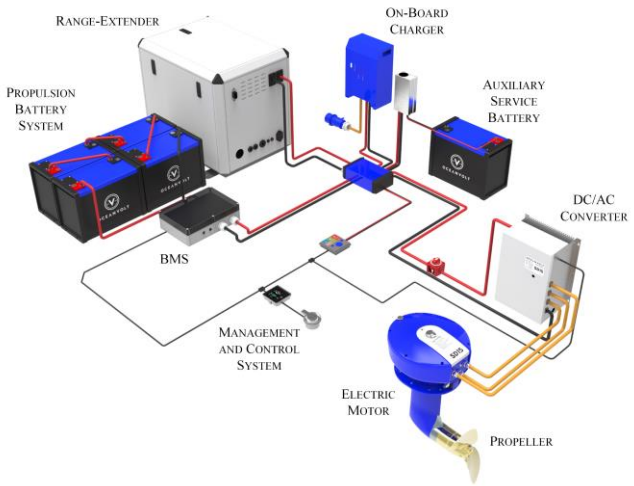

Fig. 1. Main components of electric propulsion systems for electric boats [11].

the propulsion battery system. The Battery Management Systems (BMS) assures that the propulsion battery system operates within its safe operating area. In addition, a secondary battery supplies the auxiliary services, while an on-board charging system manages the charge of the propulsion battery system when connected to the power system. Eventually, internal combustion engine, fuel-cell or renewable power generator may be integrated on-board as range-extender in order to ensure higher autonomy to the boat. Finally, a management and control system supervises the operation of the whole system. Electric propulsion systems for electric boats represent a very promising market, especially because retrofitting is a common and easily executable practice. For this reason, the market proposes a wide variety of electric propulsion systems for electric boats that are suitable for different applications, ranging from kayaking to ten meters motor yacht, as well resumed in Fig. 2.

In this context, Oceanvolt [11] is aimed primarily at owners of sailing boats (both monohull and multihull) up to 15-20 m, but offers interesting solutions also for motorboats, racing and commercial charters and ferries. Oceanvolt's solutions can be classified in *sail drive* and *shaft drive* propulsion systems; they employ synchronous permanent magnet motors fed by a 48 V battery system, which can be scaled based on shipowner's needs. Regarding *sail drive* solutions, *SD* and *Servoprop* systems are characterized by rated powers within the range 6-15 kW, and propeller rated speed of 1140 rpm; these features make them employable on sailboat up to 15 m and 12 tons. One of the most intriguing features of *SD* and *Servoprop* systems is the capability of regulating the pitch angle of propeller blades, assuring an increase of forward propulsion by 30% and the capability of operating as a hydro generator while sailing beyond 11 km/h. Regarding *shaft drive* systems, rated power ranges from 3.7 to 40 kW, so they are suitable for boats up to 20 m and 25 tons. More in details, *AX* systems are characterized by low rated propeller speed (975 rpm) and hydro generation capability, whereas *AXC* systems operate at a higher speed (1400 rpm) and they are the most powerful ones: particularly, *AXC* systems are available in four versions (10, 20, 30 and 40 kW) thanks to their modular structure, as highlighted in Fig. 3.

Torqeedo [12] is surely one of the market leaders of electric propulsion systems for motorboats, whose solution are based on in-house developed brushless motors with rare-earth magnets and external rotor (Fig. 4). *Ultralight* and *Travel* outboard motors are the less powerful models but ideal solutions for kayaks, canoes, tenders, dinghies and, generally, for light boats up to 1.5 tons. In particular, their motor power and battery capacity range from 0.4 to 1 kW and 0.320 to 0.915 kWh respectively, which guarantee a navigation range up to 100 km. Moreover, the easily replaceable battery allows the owner to increase the distance by simply purchasing an additional battery to be swapped on the run. As length and displacement increase, motor power and battery capacity must also increase: *Cruise* outboards are thought for motorboats and sailboats up to 10 tons and are available in 2, 4 and 10 kW versions to push the boat up to 20-25 km/h. Depending on the motor power, two battery systems are proposed (24 V/3.5 kWh or 48V/5 kWh), which assure up to 40-60 km of navigation range at low speed (approximately 5 km/h). However, frequent utilizers, such as commercial operators and green boaters, may require even

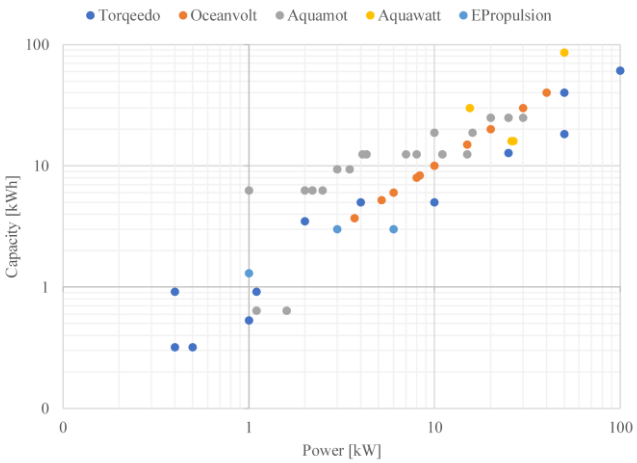

Fig. 2. Graphical representation of electric propulsion system rated power and capacity. (Oceanvolt capacity has been estimated by considering 1 hour autonomy).

Fig. 3. The modular *AXC* system by Oceanvolt [11].

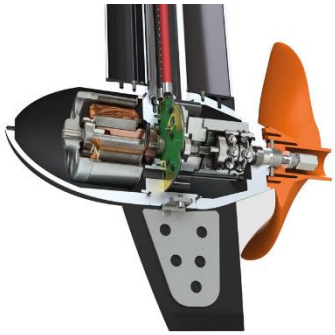

Fig. 4. Cross section of the Torqeedo external-rotor brushless motor [12].

higher performances; in this regard, Torqeedo proposes *Deep Blue* motors, which are their most powerful outboard available in 25 and 50 kW versions; they go with high voltage batteries that are derived from BMW automotive technology (345 V/12.8 kWh or 345 V/30.5 kWh). Electric boats powered by *Deep Blue* outboards can reach up to 55 km/h and 144 km of autonomy at lower speeds. *Deep Blue* propulsors are also available in inboard versions, whose rated speed must be selected based on the specific application for direct drive installation (900-1400 rpm for sailing and heavy displacement boats, 1800-2500 rpm for fast planning boats). In addition, *Deep Blue* propulsion systems can be adequately integrated with renewable energy and diesel generators onboard, as well as with the energy management system, making them a very competitive solution for yachts up to 120 feet, commercial vessels and ferries.

Aquawatt [13] produces full electric outboard and inboard motors from 4 to 50 kW, and a number of accessories, such as batteries for propulsion and auxiliaries, chargers, photovoltaic and wind generators. Focusing on outboard motors at first, they consist of induction machines that can be fed by either Valve Regulated Lead Acid (VRLA) or lithium batteries. The entry level model is *Green Power*, whose power can be regulated up to 15 kW, and which is compatible with 50 V/8-30 kWh batteries. *Green Racing* and *Green Thruster* models have both a rated power of 26 kW and are equipped with 80 V/12.8-16 kWh lithium battery, but they differ in maximum speed (41 vs 48 km/h) and maximum thrust (1.5 vs 3.0 kN). The most powerful model is the *Green Flash* that allows reaching up to 56 km/h thanks to a 50 kW motor fed by a 144 V/23-29 kWh battery. In addition, two additional inboard motors series are currently under development. The *direct drive* solutions will be suitable for light and fast sport boats up to 1.5 tons in three versions: the first is a 48 V, 1500 rpm, 4.3 or 6 kW motor, the second is a 96 V, 1500-2000 rpm motor of 10-20 kW. In case of heavy duty, *geared motors* are available in 20, 30 and 50 kW versions and with different rated speeds; rated voltage is 80 V for 20 and 30 kW motors , whereas the 50 kW motor will be fed at 144 V.

Aquamot [14] offers outboards electric propulsion systems within a wide power range (from 1.1 to 25 kW). The less powerful models (*Trends 1.1, 1.3, 1.6 and 1.8*) are equipped with an integrated and removable 24 V/0.64 kWh lithium battery. Spare batteries with the same capacity can be purchased, but a more capable battery is also available to double the cruising radius (24 V/1.28 kWh). As the rated power increase, the battery is no more integrated and must be modularly designed based on VLRA 12 V/1.02-3.12 kWh modules (*Aquamot ALS*). Almost all of *Trends* models are also available in the fixed pod versions. Compared to *Trends* line, *Professional* line is characterized by very high quality materials, such as permanent seawater resistant aluminium (motor case), stainless-steel (shaft), brass (propeller) and aerospace-derived high-strength and very light aluminium for all other components. Four different versions are available, namely outboard, fixed pod and steerable pod, with a rated power that ranges from 1 to 25 kW, whereas the inboard version can reach up to 30 kW. The corresponding rated voltage ranges from 24 V to 96 V, while an induction machine is employed as a motor.

EPropulsion [15] catalogue consists of four electric propulsion systems for several applications. *Spirit 1.0* is a very light outboard electric propulsion system of 1 kW and 1.3 kWh, representing a good solution for inflatables, dinghies and daysailers up to 3 m or 1.5 tons. Integrated battery capacity is large enough to guarantee a range of about 90 km at 4.3 km/h, 34 km at 6.8 km/h or 12 km at full speed, and it can be extended thanks to external batteries. EPropulsion itself proposes *E-Series* $LiFePO_4$ external batteries in three sizes (2.0, 4.1 or 9.0 kWh), but *Spirit 1.0* is compatible with any 48 V battery system. *Navy* outboards motors are available in 3 kW and 6 kW versions, both are equipped with a 3.0 kWh battery that ensures a range of 35 km at low speed. However, the overall capacity can be increased by parallel-connecting up to eight batteries. *Navy* systems are stated to be very silent and the first outboard electric motor ever equipped with a closed-loop liquid cooling system. In addition, thanks to the employment of brushless DC motors directly coupled to the propeller (Fig. 5), EPropulsion assures their systems to be capable of operating for approximately 8-12 years without maintenance. The company also proposes *Pod Drive* systems (1 and 3 kW) which are very popular for sailboats and *Vaquita* motors for stand up paddle boards.

III. Full Electric Boats

X Shore [16] proposes two full electric boats, one of which is shown in Fig. 6. The smallest is *Eelord 6000*, which is 5.8 m long, 2.3 m wide and 1200 kg heavy, whereas the bigger is *Eelex 8000* (8.0 m long, 2.5 m wide and 2600 heavy). These boats are both powered by a 220 kW inboard motor that ensures a top speed of about 75 km/h, whereas the cruising speed is stated to be about 45 km/h and 33 km/h respectively. The lithium battery capacity can be either 90 kWh or 120 kWh and guarantees more than 180 km range when sailing slower than the cruising speed. X Shore is currently developing two new boats: the *Eelex 6500*, which will be a reduced version of the *Eelex 8000*, and the *Eeltrek 8000*, which will be the only cabin model.

Frauscher [17], [18] has a catalogue of several models of electric boats. Rated motor power and battery capacity of the electric propulsion system can be chosen based on owner's needs. Among the boats, *610 San Remo* is the most compact (6.10 m, 1.8 m wide), it is available in 4.3 kW or 15 kW version, and it is equipped with a 12 V/9.1 kWh or 24 V/18.2 kWh battery; the latter guarantees more than 100 km of autonomy at approximately 10 km/h. Higher performances can be achieved by the *650 Alassio* (6.50 m long, 2.17 m width), which is slightly bigger than *610 San Remo* and which may be available with a more capable propulsion system (60 kW, 360 V/40 kWh). The 60 kW motor is already available on *740 Mirage* (7.47 m long, 2.5 m wide), which can be equipped also with a 110 kW, 360 V/80 kWh system.

Ruban Blue [19] produces several electric pleasure boats that can be driven without licence because of the limited power of their propulsion system. *Mini-boat* and *Ace* are less than 4 m long and have a rated power of 0.65 kW, their maximum speed is 5 km/h and 7 km/h respectively. *Sensas* and *Scoop* are approximately 4.5 m long and equipped with an electric motor of 1.8 kW and 1.6 kW respectively, thus they can reach up to 8 km/h while carrying 6/7 persons. *Legend* and *Most* are the biggest models, they are 5.6 m and 5.9 m long and suitable for 9 and 11 people respectively. Their maximum speed is 10 km/h

Fig. 5. Cross section of the electric motor by EPropulsion [15].

Fig. 6. The X Shore Eelex 8000 [16].

thanks to 2.2 kW inboard motor. Finally, the *Navette* is ideal for passenger transportation: it is 8.50 m long and allows carring up,it is approved for 30 people and can sail for 10 hours at 10 km/h thanks to 2x5 kW inboard motors and 48 V/61.4 kWh battery system.

Rand [20] has five electric boats in its catalogue of luxury, aesthetic and user-friendly motorboats. They ranges from 5.5 m to 8.5 m length and can be fully customized in terms of motor power and battery capacity, which are mainly based on Torqeedo technology. For instance, the smallest model *Picnic 18* can be equipped with either inboard electric motors from 4 to 10 kW or outboard motors from 4 to 50 kW and a battery up to 20 kWh. *Play 24* comes with more powerful motors (up to 130 kWh) and higher battery capacity (up to 26.5 kWh). The biggest models (*Supreme 27* and *Leisure 28*) can be equipped with an extremely powerful motor (up to 240 kW) and one of the biggest battery available on the market (60 kWh), enabling them to achieve impressive performances (up to 75 km/h and 260 km of autonomy at lower speed).

Naviwatt [21] produces three kind of boats (work, rigid inflatable, and transport) which are all powered by Torqeedo systems. Among these, *Cata 6* is a 5.0 m multihull that is capable of moving quietly and without making any waves thanks to its sharp shape; a 12 kW outboard motor and a 10 kWh battery make up its propulsion system that allows *Cata 6* reaching up to 24 km/h and more than 300 km of autonomy. Regarding the rigid inflatables dinghies, four *Zenpro* versions are available, which differs in terms of dimensions (from 3.3 m to 6.9 m) and maximum passengers capability (from 5 to 12). They all mount Torqeedo outboard motors, whose maximum power ranges from 12 kW to 120 kW, thus the battery capacity can be chosen from the supplier's catalogue in accordance with owner's needs. Moreover, *Cata 900* is dedicated to people transportation (up to 12) and it is powered by 2x5 kW motors and a 20 kWh battery system, thanks to which it is capable to reach up to 120 km at approximately 10 km/h.

Natural Yacht [22] develops customized electric propulsion systems that are also employed on their electric motor yachts. *Northman Nexus Revo 870* (8.7 m long, 2.9 m wide, 6 passengers) and *Northman 1200* (12.7 m long, 3.5 m wide, 8 passengers) come along with 10 kW and 20 kW electric motor respectively, and a battery pack that is assembled based on the specific sailing profile and area. The most distinguishing features is the additional fuel cell system that may be integrated as range extender: it runs on green-methanol or methanol to increase the zero-emission mileage. Additionally, the three *Maxus* sailing yachts produced by Natural Yacht can be also equipped with outboard motors.

Lex Handels KG [23] proposes two motorboats available in full electric version too. *Lex 610* is 6.1 m long and 2.1 m wide, can carry up to 5 people and is powered by either outboard (up to 10 kW) or inboard motors (up to 60 kW). Depending on the motor power, two batteries technologies can be chosen, i.e. VRLA or lithium. *Lex 790* is bigger than *Lex 610* (7.9 m long, 2.6 wide, 8 people) and the inboard motorization is available up to 150 kW.

Boesch [24] produces three luxury high-performance motorboats. *620 Acapulco De Luxe* is the smallest one and is 6.2 m long, 2.2 m wide, has a load capacity of 6 persons and it is available in three versions: 50 kW, 80 kW or 100 kW motor power, which comes along with a 216 V/37.5 kWh, 360 V/62.5 kWh or 360 V/75.2 kWh battery system respectively. The most powerful propulsion systems pushes the motorboat up to 55 km/h. On the other hand, *710 Costa Brava De Luxe* is 7.1 m long, 2.4 m wide and can be equipped with either 80 kW or 100 kW motor . The biggest Boesch motorboat is *750 Portofino De Luxe* (7.5 m long, 2.5 wide) and comes with 2x50 kW electric motors and 216 V/2x35.6 kWh battery system, but the motor power can be doubled on request. For all the Boesch motorboats, the battery capacity can be also optionally increased.

Domani Yachts [25] offers the elegant *E32* (9.5 m long, 2.7 m wide, 8 people) with three different versions of external finishes, all of them powered by a 50 kW electric motor. The high voltage battery, which is derived from transport industry, gives to *E32* up to 180 km range at 15 km/h or 70 km at 28 km/h. A range extender is also available, and a hydrogen generator is under development. Domani yachts also proposes the *S30* sailboat (9.0 m long, 2.46 m wide) with an electric propulsion system from Torqeedo Cruise series.

Candela [26] designs and produces high performance motorboat inspired by fighter jet and airplane design. *Candela Seven* is indeed extremely light but highly impact resistant as hull and deck are made up of carbon fibre. Thanks to the hydrofoil system shown in Fig. 7, it can fly on the water, skipping the waves and, thus, offering a more comfortable sailing experience. *Candela Seven* also mounts a 50 kW Torqeedo system (*Deep Blue 50*) and a 40 kWh battery, enabling the boat to sail for more than 90 km at 40 km/h.

Hovercraft [27] promotes *Electricat* as "the fastest, the lightest, affordable inflatable solar electric catamaran" that enable sailing where classic sailing is maybe not so easy. *Electricat* is 8 m long and 3 m wide, carries up to 20 people (or 2000 kg) and it is available with a 3.7 kW or 11.2 kW motor. The battery can be charged by the photovoltaic system on the rooftop, which can guarantee 100 km of autonomy on daily base (at German latitude).

Fig. 7. The Candela Seven on its hydrofoil system [26].

Fig. 8. The Overboat by Neocean [30].

The *Q30* is the only model proposed by Q Yacht [28]: it is a 9.3 m craft powered by an Oceanvolt system made up of ACX 20 kW motor and 30 kWh battery (60 kWh optional). Similarly, Hellwig [29] proposes only an electrified version of the 3.9 m long motorboat *Poros*, which is powered by a 37 kW outboard Torqeedo motor.

The *Overboat* shown in Fig. 8 is a small and compact catamaran developed by Neocean [30], which can silently fly over the water thanks to a four-foil electronically regulated system. A 3 kW electric motor can push it up to 20 km/h, while the foil system starts working at 14 km/h. The autonomy is stated to be 40 km at maximum speed due to the 48 V/3.4 kWh lithium battery.

IV. Conclusion

A commercial overview on electric propulsion systems for electric boats and on full electric boats has been presented in this paper. It has been drafted based on more than a hundred electric propulsion systems that are already available on the market, ranging from few hundreds watts to 100 kW and, thus, suitable for several kinds of boats. All these systems are presented as the ideal solutions to replace the old and pollutant gasoline engines thanks to affordable retrofit operations, but they are also employed on brand new boats. In this regard, several full electric boats are already on the market, which widely differ to each other in terms of kind, application, and performance. Some of these boats present some very innovative hallmarks, such as hydrofoil systems or electricity hydrogeneration. This is made possible by new players that are tackling the challenge of electrifying the leisure boat sector: most of the full electric boats analysed in this paper are indeed developed, designed and produced by new small companies totally devoted to this mission. Although this market is not as ready as automotive, it is foreseen that the disruption will occur soon. This is mainly due to two reasons: first, electric boating will undoubtedly benefit from the driving action of the automotive sector, which is expected to be capable to further reduce costs and increase performance of all its key technologies in the incoming years. Second, there is already a strong demand for full electric boats as they are extremely competitive in specific activities, such as tourism, because they increase the user experience and reduce the operating costs, thus opening to new business opportunities.

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