POLISH MARITIME RESEARCH 2 (114) 2022 Vol. 29; pp. 12-18
10.2478/pomr-2022-0012

50' SAIL CATAMARAN WITH HYBRID PROPULSION, DESIGN, THEORETICAL AND EXPERIMENTAL STUDIES

Wojciech Litwin*
Daniel Piątek
Wojciech Leśniewski
Konrad Marszałkowski
Gdańsk University of Technology, Poland

* Corresponding author: *wlitwin@pg.edu.pl (W. Litwin)*

ABSTRACT

The development of modern lithium batteries and propulsion systems now allows the use of complex propulsion systems for vessels of various sizes. As part of the research and implementation project, a parallel hybrid drive system was designed, built and then tested in the laboratory. The experimental studies conducted allowed for the measurements of power, fuel consumption and electric power distribution in various operating modes of the propulsion system. The research proves that in the analysed case, the hybrid parallel system meets the demand for electric energy during a typical cruise scenario, and thus there is no need to install a power generator on the yacht.

Keywords: sail catamaran, green shipping, zero emission, hybrid propulsion

INTRODUCTION

A huge number of recreational vessels of various sizes sail on the seas of the world, from quite small yachts, just 6–7 metres in length, to luxury catamarans several dozen feet long. It is difficult to obtain reliable data on their number, as a significant number of them are built by enthusiasts, so often a certain scope of work is performed independently, and only some tasks are entrusted to specialised shipyards. In addition, historic vessels are being rebuilt, including several dozen-year-old yachts often made of wood or steel. They appear in registers, then disappear for years to reappear sometimes under a changed name.

The latest data from the Polish Economic Institute (PIE) shows that Poland is the eighth in the world and the fifth in Europe exporter of yachts and other recreational and sports vessels. The global pandemic has not changed the market situation. In 2018, Polish exports accounted for 60% of the overall value of yacht exports across the EU. Moreover, it doubled between 2014 and 2018, rising from 184.8 million to just under 396 million euro.

The data quoted by PIE show that in the first half of 2021, Poland's share in global yacht exports increased by 1.2 percentage points, to 4.7%. Polish shipyards annually produce approx. 22 thousand motor and sailing yachts - these are both luxury yachts and watercraft for beginner sailors, 95% of which are exported. They specialise mainly in motor yachts up to 9 metres long, numbering over 20 thousand. Seventeen thousand yachts built in Poland belong to this category. Polish shipyards also carry out contracts under specific orders and develop their own structures. Polish specialties, apart from small motor yachts, are luxury motor yachts up to 24 metres long, luxury sailing yachts up to 15 m, and luxurious personalised catamarans up to 30 m. An example of such a unit is the catamaran described below.

The styles and expectations of shipowners have changed over the years. There is no doubt that the growing public awareness means that especially wealthy shipowners look for technical solutions that will meet their expectations, i.e. in addition to obtaining an appropriate level of comfort, they expect reliability and safety. At the same time, today it is said that the vessel should be environmentally friendly throughout its entire life from design to utilisation. Often, it can be difficult to find reliable data on, for example, the environmental impact at the stage of building a yacht's hull made of classic polyester or epoxy composite. For the shipowner, fuel combustion is a measurable negative impact on the environment, which he perceives as operating costs. Interestingly, even for large sea-going vessels, the environmental impact is assessed on the basis of the amount of fuel used, and emission measurement installations are rarely found on board the ships. Therefore, it can be said that the shipowner is interested in the amount of fuel consumed by the engine for at least two key reasons: it is the source of operating costs and, additionally, it results in the emission of substances harmful to the environment. It can also be mentioned that the noise of the combustion engine, especially at night, is difficult to accept on recreational vessels, especially on rented boats. It is also ensured that the exhaust gases blown by the wind do not end up in the area where passengers are present. This applies to both the operation of the drive engine and the power generators.

Therefore, various types of propulsion have been worked on for a long time, which would allow exhaust emissions to be reduced and vibration [1] and noise pollution to be minimised on vessels of various sizes [2][3][4][5] The ideal would be a zero-emission ship [6], although it is said today that the production of synthetic or even natural fibre sails also has a negative impact on the environment, so there is no absolutely clean technology. The literature more and more often shows research on the effects of the product during the entire life cycle of the product, from its construction to its disposal [7]

When looking for propulsion system solutions and environmentally friendly sources of electricity to power the devices on the vessel, one is quickly pointed to photovoltaic cells, miniature wind turbines, energy recovery through generators submerged in water while sailing on sails, or finally fuel cells powered especially by hydrogen. Other solutions, such as the use of a Stirling engine [8], are also considered. In practice, however, various types of hybrid drives are currently widely used, in which electric and combustion engines are used [9]. A significant limitation in the widespread use of electric motors on vessels is the significant price of lithium batteries and fuel cells. The price of lithium batteries has dropped significantly in recent years, but this technology remains expensive and the acquisition of raw materials, production and finally disposal of batteries is not indifferent to the environment. Data on this subject can be found in the literature [10][11]. Fuel cells are an amazing source of electricity. Ecologically obtained hydrogen can be used to generate electricity. However, such systems are rarely used on vessels due to very high costs [12][13][14].

It is predicted that "green shipping" will not be complete without routing and the automation of certain navigation and decision-making processes [15]. Optimising the route and speed profile as well as the desired time in which the destination will be achieved is often a task for optimisation processes based on artificial intelligence or fuzzy logic.

The work carried out at the Gdańsk University of Technology has for years focused on low-emission propulsion systems, especially for smaller vessels [16][17]. In later years, various designs of hybrid drive systems were developed, which were subjected to laboratory tests [18][19][20][21]An extraordinary challenge was to design a new ferry with a plug-in hybrid [22][23], based on the example of which research was undertaken on the energy management of a vessel operating in undetermined states – on a short route [24].

Based on the experience gained earlier, the task of designing a completely new, 50' long sailing vessel with a hybrid diesel-electric drive was taken up (Table 1). One of the important utility values of the vessel for the yacht manufacturer was to obtain a certain energy autonomy, enabling the use of an electric drive, for example, for sailing in sheltered waters or within the port, and in particular to obtain at least eight hours of energy autonomy under conditions of anchor or sailing with sails at night when the passengers are asleep and the operation of the generator is not recommended due to the noise.

The presented unit has been designed from scratch. The yacht has a vinyl ester glass and carbon fabrics structure (Fig. 1, 2)

Tab. 1. 50' long catamaran 'Wave' main data

1.	Length	49 ft 1 in / 14.95 m
2.	Beam	27 ft 4 in / 8.34 m
3.	Draft	4 ft 9 in / 1.4 m
	Displacement	21.84 tons
	Sails: main sail / genoa / gennaker / spinnaker	70 m^2/ 69 m^2 / 185 m^2 / 220 m^2
	Engines / motors (parallel hybrid)	2 x 60 HP / 2 x 18.5 kW
	Fuel tanks	2 x 420 litres
	Lithium battery energy storages (battery bank)	2 x 21.6 kWh
	CE categories	A
	Catamaran design team – WAVE CATAMARANS Designer Technical Designer Naval Architect Constructor	 Agnieszka Bona Andrzej Chmielewski Agata Kowalska-Strycharz Radosław Michalik

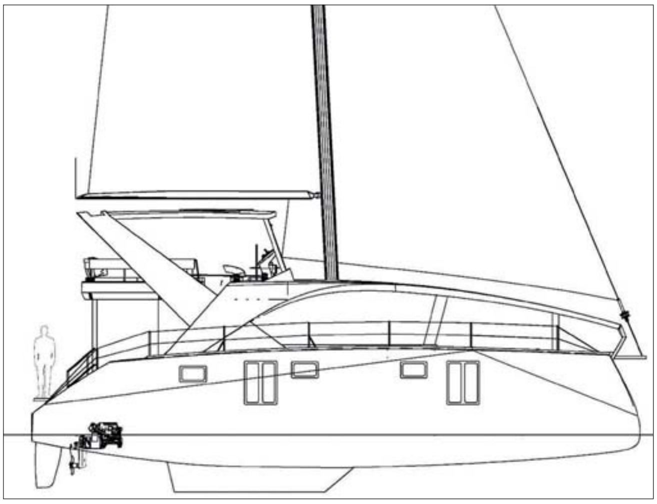

Fig. 1. Drawing of 50 ft long catamaran Wave 50'

Fig. 2. Photograph of Wave 50' during tests

METHODS

The catamaran hull design was the result of a complex design process [25] and flow analysis in specialised CFD software. Based on the calculations, the characteristics of the catamaran's towing power as a function of speed, which is crucial for the design of the propulsion system (Fig. 3), were determined. Assuming the typical values of the efficiency of the serially produced propeller with folded wings $\eta_{propo} = 0.4$, the angular gear in the power transfer system $\eta_{gear} = 0.95$ and the bearings and reduction gear $\eta_{propo} = 0.9$, the forecast of the power on the shaft connected directly to the drive motor was obtained (Fig. 3).

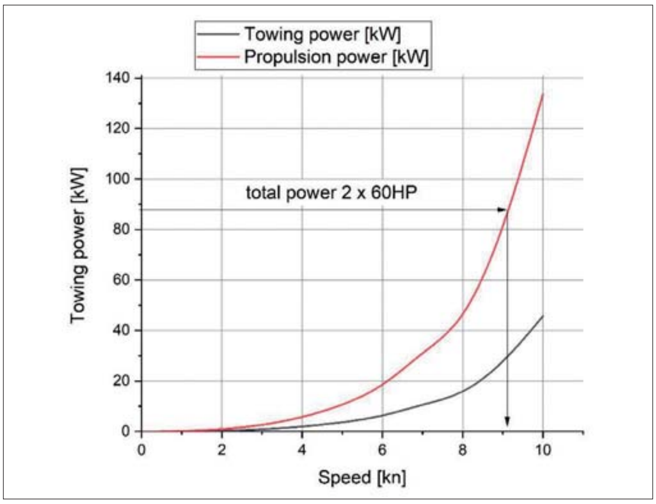

Fig. 3. Towing power and expected powered demand based on CFD studies

Initial calculations show that a catamaran equipped with two combustion engines with a power of 60 HP each (44 kW) will possibly be able to achieve a maximum speed of about 9 knots, which is sufficient for a sailing vessel for which the mechanical propulsion system is an auxiliary system.

The catamaran is equipped with 2 parallel hybrid propulsion modules designed at the Polytechnic, which include combustion engines and electric motors, one set per hull (Fig. 4).

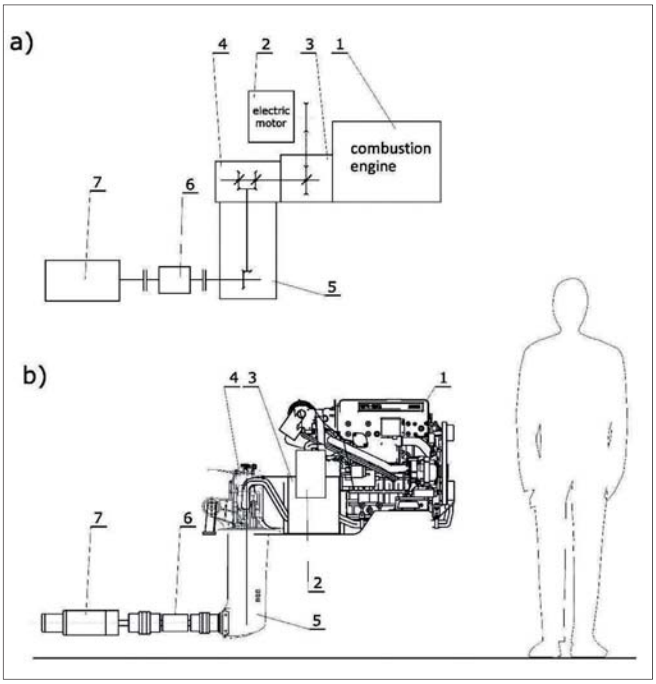

Fig. 4. Parallel hybrid propulsion system of Wave 50'; a – schematic of the system, b – test rig drawing; 1 – combustion engine, 2 – electric motor, 3 – belt gear, 4 – main gear with reverse, 5 – sail drive unit, 6 – torque meter, 7-load – hydraulic pump

The drivetrain can operate in four different operating modes:

- drive by means of an internal combustion engine, when the electric motor operates in generator mode and charges the batteries,
- drive by means of an internal combustion engine, when the electric machine is in the mode of supporting the internal combustion engine; the power steering system is activated when the engine load increases, which results in a reduction of the rotational speed,
- electric motor drive, with the combustion engine turned off,
- while sailing on sails (with fixed blade propellers), when the electric motor operates in generator mode and charging of batteries is possible.

Interestingly, the capacity of the batteries was not selected for electric navigation. The catamaran is a sailing vessel and the mechanical drive serves as an auxiliary. The capacity of the batteries is selected to meet the demand for electricity at night, so that it is not necessary to start the combustion engine. It is also worth noting that the catamaran does not have a power generator. This is quite a bold solution, and the batteries can be charged while the drive motor is running, when the electric machine is in generator mode or while sailing on sails. The saving of space on the unit resulting from abandoning the power generator has an important consequence that could be used by shaping the unit. This allows a recreational deck at the bow, which usually does not exist as this space is taken up by a power generator (Fig. 2).

During the stay in port, the catamaran can be powered from the shore, and then there is no need to start the electricity generation system.

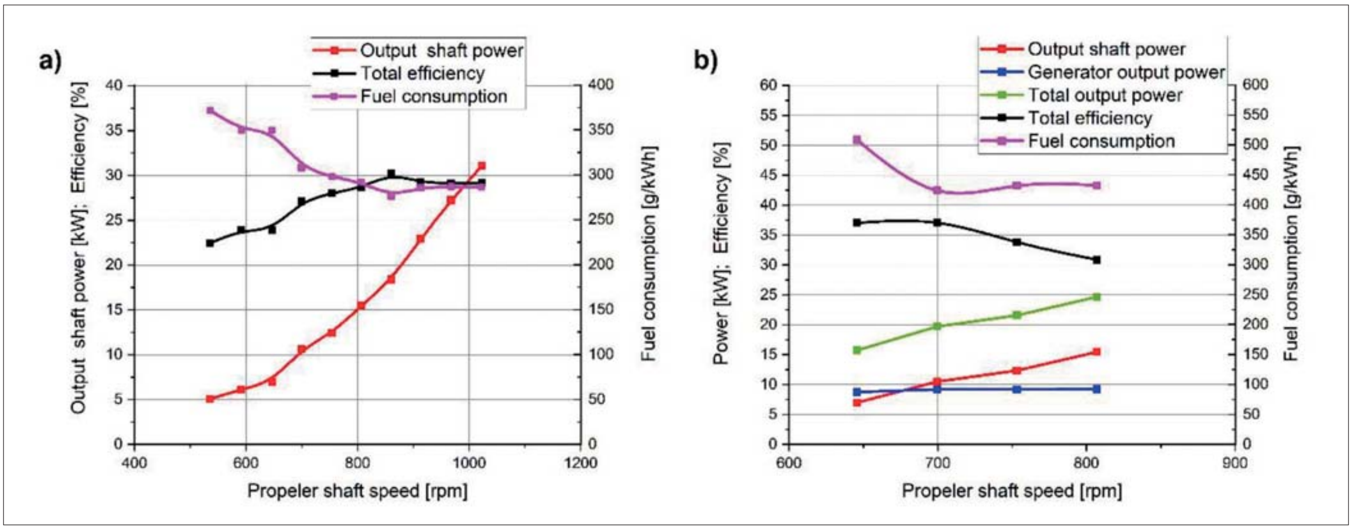

Fig. 5. Test rig measurements of the operational parameters of the propulsion system when the whole of the power is transferred to the propeller (a), and when additional load is applied by the generator (b)

RESULTS

The tests were carried out in the laboratory by conducting an experiment on the object at the real scale (Fig. 4).

Measurements of the mechanical power on the propeller shaft and the fuel consumption of the combustion engine (Fig. 5.a) were also carried out for the conditions when the electric machine was operating in the generator mode (Fig. 5.b). It must be remembered that the mechanical power was measured on the output shaft where the propeller is mounted, so the engine power is reduced by the losses resulting from the operation of the power transmission system (two gears, bearings and seals). Measurements for the operation of the generator-loaded system were made in the range from 650 to 800 rpm as this is the predicted, typical rotational speed of the propeller during the voyage.

The measurements prove that the total energy efficiency of a conventional drive system, manufactured by one of the renowned global manufacturers, which includes the combustion engine, the main gear with a reverse and the bottom of the drive with the gear, is from 22 to a maximum of 30% (Fig. 5.a). This value is small but typical for small drive systems with piston engines. The low overall efficiency also results from energy losses in the power transmission system, especially in the right-tooth bevel gear installed in the lower case.

At the design stage, it was anticipated that the recreational unit, which is a catamaran, would charge the batteries when sailing when the internal combustion engine was running. As the range of rotational speeds of the combustion engine between 1400 and 1800 rpm (650–800 of the output shaft) is optimal in terms of fuel consumption (Fig. 5a) and the low noise and vibration level, the gear ratio of the belt transmission was selected so that the electric machine would work in this speed range effectively as a generator (Fig. 5b) with a power of about 9.5 kW. It is also worth noting that in such a case the global energy efficiency of the entire system increases, especially at lower rotational speeds.

As mentioned before, the priority function of the electric motor operating with the combustion engine was to work in the generator mode. The propulsion and power supply system also allows the electric motor to power a vessel, for example, during manoeuvres in a port, a protected area where internal combustion engines cannot be used, or during sails work, when the unit is purposefully kept upwind thanks to the propulsion system. Thus, the drive functionality of the designed hybrid system is very useful because during the voyage it is less often necessary to start the internal combustion engine. The global energy efficiency of the drive system powered by an electric motor reaches 75% (Fig. 6), which is a value almost twice as high as during the operation of an internal combustion engine. The time necessary to charge the batteries is up to 3 hours and depends on the degree of discharge of the batteries and the current energy consumption.

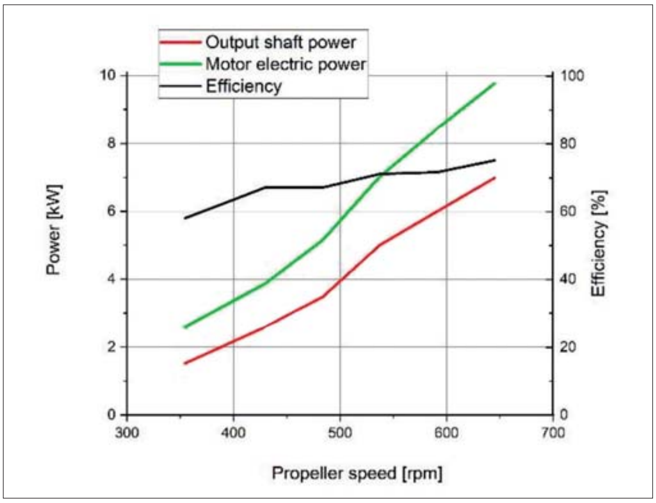

Fig. 6. Power and efficiency of the system in electric motor mode

The propulsion system of the vessel and the DC/AC converter that controls the operation of the electric motor also has a significant advantage, namely it provides the possibility of generator operation in the area of lower power and shaft rotation speed when the sails are used to drive the vessel and the propellers act as hydrogenerators. The results of the calculations show (Fig. 7) that during navigation, when the conditions are favourable, i.e. the wind speed allows sailing at higher speeds, it is possible to meet the energy needs of the vessel and turning on the combustion engine may be unnecessary. Whether it will be possible to use this method in practice is not known because, as shown by practical experience, on some units the noise associated with the propeller's generator operation is so significant that such a possibility is excluded, especially at night. The consequence of regenerative operation can also be an intense cavitation process that can quickly damage the propeller.

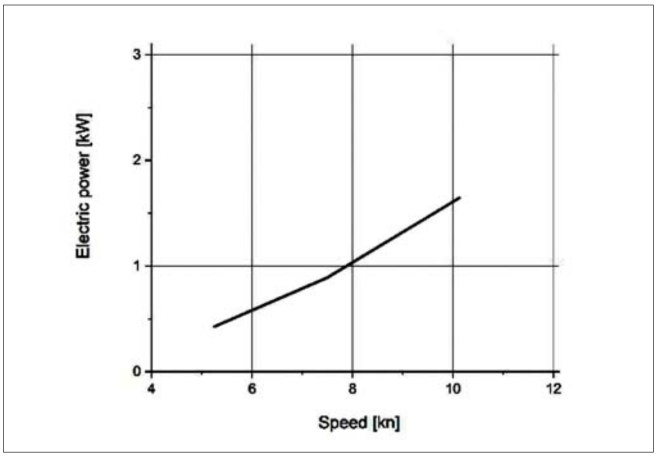

Fig. 7. Calculated electric power generated by an electric motor operated in generator mode during sailing

CONCLUSIONS

- The experimental research conducted allowed for the performance of tests of the designed and constructed propulsion system. What is extremely important, at the stage of experimental tests in the laboratory, it was possible to perform initial tests of the hybrid drive and supply system in terms of durability and reliability. Performing measurements of the mechanical power and electrical parameters allowed for the determination of real work parameters.
- The research proved the great advantage of operating the generator system in parallel to the combustion drive. Within the typical cruising speed, by loading the combustion engine with the power necessary to charge the batteries, the energy efficiency of the entire system is improved in the range of 12 to 5% (which corresponds to an increase of 40 to 10%). Such an operational scenario helps to increase the overall efficiency of the system compared to the individual generator and combustion modes The gain can be up to 34% of saved fuel although this decreases with the increase of the power of the combustion engine, which is due to the decreasing excess power of the combustion engine that can be used by the generator.
- The research work carried out made it possible to set an attractive task for scientists and engineers, such as "design – build – test". It enables the acquisition of new knowledge and skills, which are also used in the didactic process.
- The designed catamaran was nominated for the fair award in the category of multihull of the year (www.multihulloftheyear.com).
- The second stage of work will be research on a real object. It will be an attractive phase of works for scientists and engineers, when it will be possible to verify whether the assumed operating parameters have been achieved.

Funding

This work was a part of research grant no. POIR.01.01.01-00-1091/18 entitled "Development of a prototype sea-going catamaran with hybrid propulsion and energy recovery during sailing", financed by the Polish National Centre for Research and Development. The APC was financed by the Faculty of Mechanical Engineering and Ship Technology, Gdansk University of Technology, Poland.

Author Contributions

Wojciech Leśniewski and Wojciech Litwin designed and constructed the hybrid propulsion system. Konrad Marszałkowski designed and built the electrical and data acquisition systems. Wojciech Leśniewski, Daniel Piątek and Konrad Marszałkowski designed and performed the experiments. Wojciech Leśniewski analysed and processed the acquired data. Wojciech Litwin was a corresponding author. All the authors discussed the results and contributed to the final version of the manuscript.

REFERENCES

1. N. Xiao, R. Zhou, X. Xu, and X. Lin, "Study on Vibration of Marine Diesel-Electric Hybrid Propulsion System," *Math. Probl. Eng.*, vol. 2016, 2016, doi: 10.1155/2016/8130246.

2. O. B. Inal, J. F. Charpentier, and C. Deniz, "Hybrid power and propulsion systems for ships: Current status and future challenges," *Renewable and Sustainable Energy Reviews*, vol. 156, p. 111965, Mar. 01, 2022, doi: 10.1016/j.rser.2021.111965.

3. N. R. Ammar and I. S. Seddiek, "Evaluation of the environmental and economic impacts of electric propulsion systems onboard ships: case study passenger vessel," *Environ. Sci. Pollut. Res.*, vol. 28, no. 28, pp. 37851–37866, Jul. 2021, doi: 10.1007/s11356-021-13271-4.

4. P. Serra and G. Fancello, "Towards the IMO's GHG goals: A critical overview of the perspectives and challenges of the main options for decarbonizing international shipping," *Sustain.*, vol. 12, no. 8, 2020, doi: 10.3390/su12083220.

5. V. Ruggiero, “New methodology to approach project of small hybrid propulsion passenger ferries for Italian scenario,” in *2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2020*, 2020, pp. 425–429, doi: 10.1109/SPEEDAM48782.2020.9161881.

6. C. A. Reusser and J. Perrez Osses, “Challenges for Zero-Emissions Ship,” *J. Mar. Sci. Eng.*, vol. 1042, no. 9(10), pp. 1–19, 2021, doi: 10.3390/jmse9101042.

7. J. Ling-Chin and A. P. Roskilly, “A comparative life cycle assessment of marine power systems,” *Energy Convers. Manag.*, vol. 127, pp. 477–493, Nov. 2016, doi: 10.1016/j.enconman.2016.09.012.

8. J. Kropiwnicki, “Application of Stirling engine type alpha powered by the recovery energy on vessels,” *Polish Marit. Res.*, vol. 27, no. 1, pp. 96–106, 2020, doi: 10.2478/pomr-2020-0010.

9. V. Ruggiero and F. Morace, “Innovative Use of Hybrid Propulsion System in Fast Passenger Ferries over 300 Passengers and 20 Knots,” in *12th Symposium on High Performance Marine Vehicles*, 2020, no. October, p. 10, doi: 10.3233/pmst200044.

10. A. R. Shekhar, M. H. Parekh, and V. G. Pol, “Worldwide ubiquitous utilization of lithium-ion batteries: What we have done, are doing, and could do safely once they are dead?,” *Journal of Power Sources*, vol. 523, p. 231015, Mar. 01, 2022, doi: 10.1016/j.jpowsour.2022.231015.

11. Q. Cheng, B. Marchetti, X. Chen, S. Xu, and X. D. Zhou, “Separation, purification, regeneration and utilization of graphite recovered from spent lithium-ion batteries – A review,” *Journal of Environmental Chemical Engineering*, vol. 10, no. 2, p. 107312, Apr. 01, 2022, doi: 10.1016/j.jece.2022.107312.

12. C. H. Choi et al., “Development and demonstration of PEM fuel-cell-battery hybrid system for propulsion of tourist boat,” *Int. J. Hydrogen Energy*, vol. 41, no. 5, pp. 3591–3599, 2016, doi: 10.1016/j.ijhydene.2015.12.186.

13. A. M. Bassam, A. B. Phillips, S. R. Turnock, and P. A. Wilson, “Design, modelling and simulation of a hybrid fuel cell propulsion system for a domestic ferry,” *PRADS 2016 – Proc. 13th Int. Symp. Pract. Des. Ships Other Float. Struct.*, no. September, 2016.

14. [14] V. Alfonsín, A. Suarez, A. Cancela, A. Sanchez, and R. Maceiras, “Modelization of hybrid systems with hydrogen and renewable energy oriented to electric propulsion in sailboats,” Int. J. Hydrogen Energy, vol. 39, no. 22, pp. 11763–11773, 2014, doi: 10.1016/j.ijhydene.2014.05.104.

15. A. Stateczny, P. Burdziakowski, K. Najdecka, and B. Domagalska-Stateczna, “Accuracy of trajectory tracking based on nonlinear guidance logic for hydrographic unmanned surface vessels,” *Sensors (Switzerland)*, vol. 20, no. 3, 2020, doi: 10.3390/s20030832.

16. W. Litwin and A. Olszewski, “Assessment of possible application of water lubricated sintered brass slide bearing for marine propeller shaft,” *Polish Marit. Res.*, vol. 19, no. 4, 2012, doi: 10.2478/v10012-012-0040-4.

17. W. Litwin, “Water lubricated marine stern tube bearings – Attempt at estimating hydrodynamic capacity,” 2010, doi: 10.1115/IJTC2009-15068.

18. J. Kowalski, W. Leśniewski, and W. Litwin, “Multi-source-supplied parallel hybrid propulsion of the inland passenger ship STA.H. Research work on energy efficiency of a hybrid propulsion system operating in the electric motor drive mode,” *Polish Marit. Res.*, vol. 20, pp. 20–27, 2013, doi: 10.2478/pomr-2013-0031.

19. W. Litwin, W. Leśniewski, and J. Kowalski, “Energy Efficient and Environmentally Friendly Hybrid Conversion of Inland Passenger Vessel,” *Polish Marit. Res.*, vol. 24, no. 4, 2017, doi: 10.1515/pomr-2017-0138.

20. W. Leśniewski, D. Piątek, K. Marszałkowski, and W. Litwin, “Small Vessel with Inboard Engine Retrofitting Concepts; Real Boat Tests, Laboratory Hybrid Drive Tests and Theoretical Studies,” *Energies*, vol. 13, pp. 1–13, 2020, doi: 10.3390/en13102586.

21. W. Litwin, W. Lesniewski, D. Piatek, and K. Niklas, “Experimental research on the energy efficiency of a parallel hybrid drive for an inland ship,” *Energies*, vol. 12, no. 9, 2019, doi: 10.3390/en12091675.

22. P. Gełesz, A. Karczewski, J. Kozak, W. Litwin, and Ł. Piątek, “Design Methodology for Small Passenger Ships on the Example of the Ferryboat Motława 2 Driven by Hybrid Propulsion System,” *Polish Marit. Res.*, vol. 24, no. s1, pp. 67–73, 2017, doi: 10.1515/pomr-2017-0023.

23. M. Kunicka and W. Litwin, “Energy efficient small inland passenger shuttle ferry with hybrid propulsion – concept design, calculations and model tests,” *Polish Marit. Res.*, vol. 26, no. 102, pp. 85–92, 2019, doi: 10.2478/pomr-2019-0028.

24. M. Kunicka and W. Litwin, “Energy demand of short-range inland ferry with series hybrid propulsion depending on the navigation strategy,” *Energies*, vol. 12, no. 18, pp. 1–14, 2019, doi: 10.3390/en12183499.

25. A. Karczewski and J. Kozak, “Variant designing in the preliminary small ship design process,” *Polish Marit. Res.*, vol. 24, no. 2, pp. 77–82, 2017, doi: 10.1515/pomr-2017-0052.

CONTACT WITH THE AUTHORS

Wojciech Litwin
e-mail: wlitwin@pg.edu.pl

Daniel Piątek
e-mail: freitag@pg.edu.pl

Wojciech Leśniewski
e-mail: wojlesni@pg.edu.pl

Konrad Marszałkowski
e-mail: konmarsz@pg.edu.pl

Gdańsk University of Technology
Narutowicza 11/12
80-233 Gdańsk
POLAND