

Article

Experimental Research on the Energy Efficiency of a Parallel Hybrid Drive for an Inland Ship

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Abstract: The growing requirements for limiting the negative impact of all modes of transport on the natural environment mean that clean technologies are becoming more and more important. The global trend of e-mobility also applies to sea and inland water transport. This article presents the results of experimental tests carried out on a life-size, parallel diesel-electric hybrid propulsion system. The efficiency of the propulsion system was analysed for two modes of operation (electric and diesel) and for different engine speeds and loads. Analysis of the impact of using a hybrid propulsion system on fuel consumption was carried out on a case study vessel and for six actual journeys. The use of hybrid propulsion in “zero emission” mode enables up to four times higher energy efficiency when compared to a conventional drive, while reducing CO₂ emissions and air pollution to zero, as well as a hundred-fold reduction in noise emissions. High flexibility in the operation of such a drive enables the use of intelligent power control technology (smart propulsion). This article shows that the use of hybrid propulsion reduces the negative impact on the environment to a minimum and allows for a significant reduction in the vessel’s operating costs.

Keywords: green shipping; hybrid propulsion; energy efficiency; smart propulsion; zero-emission

1. Introduction

Maritime transport plays a key role in the globalised world. Most goods are transported by sea and their total mass is currently estimated at 10 billion tonnes per year [1]. It should be noted that transport by sea over longer distances is currently the most economical and, at the same time, most environmentally friendly form of transport. The same applies to inland waterway transport, which is well-developed in some countries. It is generally recognised that ships have higher energy efficiency when compared with other means of transport (Figure 1) [2]. In the aforementioned comparison, the mass of CO₂ emitted during the transport of 1 tonne of cargo over a distance of 1 km was taken to be a measure of energy efficiency, i.e., a measure of carbon dioxide emissions during transport work. The data presented show that the average transport efficiency of vessels is about four times higher than rail transport and about eight times higher than that of road transport. The measurement of actual emissions is not easy and so they are usually estimated on the basis of data on the fuel used [3,4].

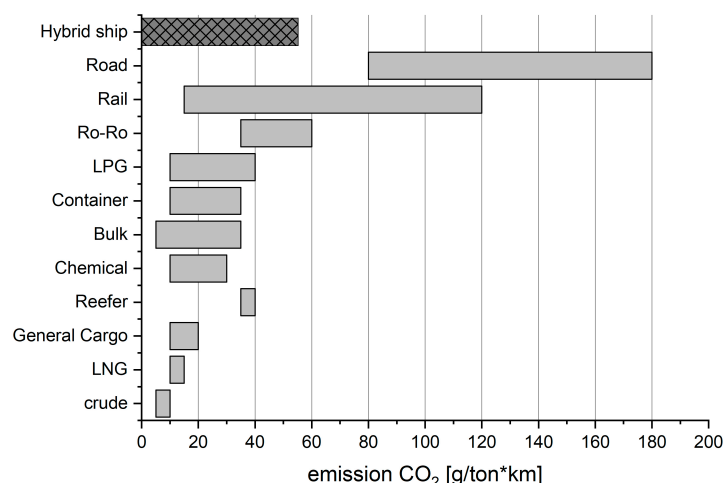


Figure 1. Comparison of different transport modes concerning the CO₂ emission per tonne-km of cargo [2]; analysed case of an inland ship with hybrid propulsion and solar modules was added.

The water transport industry is subjected to enormous pressures, which are reflected in the new requirements introduced by the International Maritime Organisation (IMO). In the last decade, the IMO has implemented the Energy Efficient Design Index (EEDI) [5–8] which enforces the introduction of solutions for the protection of the natural environment in the maritime industry. It should be noted that the index has been defined in such a way that it does not impose the actual method of increasing energy efficiency, but rather, leaves the choice of applied propulsion technology to the designers. What is more, the analysis carried out in one of the reports [9] indicates that through the application of existing technological solutions and improvements in the use of the ship, it is possible to increase energy efficiency by 25 to 75% when compared to 2014. This increase can be largely affected by the operational efficiency of the ships (i.e., more effective use of the means of transport), including better operation of the drive system under optimal conditions for the engine and propeller. In practice, for many vessels the power of the main engine is set up with an excess that ensures a high level of safety, but the drive is used inefficiently. Apart from the EEDI, another milestone in reducing the negative impact on the natural environment by ships was the introduction of requirements for the quality of the fuels used for propulsion by the IMO (the so-called “Tier” limits).

From 1 January 2020, in accordance with MARPOL Annex VI [10], the Sulphur content of fuel oil used on board commercial ships trading outside Sulphur Emission Control Areas (ECAs) must not exceed 0.50%. This is a significant reduction from the current global limit of 3.50% which has been in place since 2012. The guidance on the development of a Ship Implementation Plans (SIP) was issued [11]. Special guideline was also prepared by International Chamber of Shipping [12]. Moreover, new regulations are going to take into force on the Emission Control Areas (ECA). The resolution MEPC.286(71) will cover the limit of NO_x in addition to SO_x [13]. Engines having power above 130 kW installed on vessels constructed on or after 1 January 2021 must be Tier III certified. The regulation also applies to non-identical replacement engines or additional engines installed on existing ships on or after 1 January 2021.

Together with the IMO, the EU Parliament also introduced a limit to the allowed sulphur content in fuel of 0.5% [14]. Interestingly, analysis of the impact of new regulations has shown a slight influence on the competitiveness of transport companies, in the Baltic Sea basin for example [15,16].

Far-reaching regulations apply to the internal combustion engines used as main or auxiliary propulsion on inland vessels. In the inland waterways of EU countries, the directive has regulated the requirements for combustion engine emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and particulate matters (PM) since 1 January 2017 [17]. The maximum permissible emission level depends on the engine category. For example, for an engine of the NRE category with a power of 56 to 130 kW, the permissible emission levels of CO, HC, NO_x, PM are 5.0 g/kW h, 4.0 g/kW h, 4.0 g/kW h, and 0.3 g/kW h, respectively. What is more, for future travel in urban environments, it is very likely that

local authorities will introduce special requirements, even including a total ban on the use of internal combustion engines. For example, a complete traffic ban in the centre of Oslo will apply from 2019 and a complete shut-down of combustion engines is planned to take effect by 2050. In Amsterdam, the plan is to completely switch cars to electric drives by 2025. Since 2017, zones have been introduced in the city where traffic is prohibited for vehicles with older internal combustion engines. Therefore, in many countries the regulations are dynamically introduced to reduce emissions of carbon dioxide and other harmful substances (mainly SO_x, NO_x, and PM). However, most announcements regarding the new regulations that will be introduced in water transport contain only a general description. Therefore, the quantitative description of pollution reduction from the maritime sector is important and one of the methods was proposed in [18]. Water transport inside urban agglomerations has other significant limitations for several important reasons, such as the high level of safety required, minimisation of noise pollution, and the limitation of the destructive influence of waves and undercutting by high-powered marine engines. Local travel speed restrictions are also often in force.

Taking into account the above considerations, the mode of transport's environmental load becomes the key aspect. From the entrepreneur's point of view, the profitability of the means of transport is of fundamental importance. It depends significantly on operating costs, including fuel consumption and transport time. High shipping speeds generate significant costs resulting from large fuel consumption. At low speeds however, long transport times mean that inland waterway transport is not always competitive compared to rail transport, for example. Therefore, it is important to find an optimal shipping speed, which results directly from the resistance of the ship's hull rapidly increasing as a function of speed.

At the design stage of a ship, the main propulsion power is usually chosen for the contracted speed, which in practice is often close to the maximum speed of the ship. The fuel consumption can be predicted with uncertainty equal 12% up to 4% depending on the design stage of a ship [19].

However, in the practical operation of the unit (especially in restricted areas) the propulsion can be used beyond the optimal design parameters for a significant period of time. It transpires that in regions covered by speed limits, when the propulsion operates on a fraction of its nominal power, the energy efficiency of the internal combustion engine significantly decreases. Therefore, for at least several previously described reasons, it is beneficial to install a hybrid propulsion system on the vessel [20–22]. Then, in the areas covered by speed limits (when the power demand is lower), the optimal solution is to use electric propulsion.

The use of electric propulsion may also result from the expected limitations on the acceptable emissions of harmful substances in urban areas. However, outside densely populated areas, when the ship is moving at the cruising speed due to the limited capacity of current energy storage technologies and the higher power demand, it is necessary to use an internal combustion engine. At the same time, the use of a combustion engine in a hybrid drive does not preclude driving it with low-emission fuel (e.g., LNG instead of diesel fuel), [23–25]. The drive could have two modes of operation depending on the actual operational load. In the first operating mode, only an electric motor powered by batteries or fuel cells assisted by solar cells is used to drive the unit [26–28]. Then the ship could be operated for a limited time at a low speed and in areas where there is no significant surge. This seems to be a very advantageous solution in urban areas where the requirement for zero emissivity of the drive used could be met. The second mode of operation of the hybrid drive (when the internal combustion engine is running) would enable effective operation of the ship over longer distances and at higher speeds. An additional function of the internal combustion engine should include recharging the batteries when the electric motor is in generator mode. The combustion engine would also be an emergency drive function for the electric drive and vice versa. This fact has already been recognised by the certification bodies of vessels, which appreciate the high level of security provided by the parallel hybrid drive. Switching between the aforementioned modes of operation could be carried out automatically based on the current power demand and could constitute an important component developed by the authors of the Smart Propulsion System [29].

The above-described benefits resulting from the use of a parallel hybrid drive on the ship led to the decision to carry out experimental testing on a real system, designed and built at the Gdansk University of Technology.

2. The Aim and Scope of the Experimental Tests Performed

The aim of the tests was to determine the energy efficiency of a hybrid propulsion system in two typical modes of operation (diesel engine operation mode and electric motor operation mode), in order to identify noise pollution in the two operation modes and assess the real environmental impact, based on the amount of fuel consumed.

The efficiency measurements of the propulsion system were conducted under different operating conditions, corresponding to different rotational speeds of the internal combustion engine and electric motor, and for different loads. The results from the experimental measurements were analysed in order to estimate the impact of the use of hybrid propulsion in a case study of an inland vessel (described in Section 3) and on six journeys connecting the container port with cities located at a distance of about 100 km. The impact of using a hybrid propulsion system on fuel consumption, estimated air pollution and noise emission was calculated. Thus, two independent variants of the propulsion system were analysed for the test vessel. The first variant of the ship's propulsion is based on two classic diesel engines with reduction gears. The second variant of the engine room for the same case study vessel has two parallel hybrid drives consisting of an internal combustion engine (the same as in the first variant) as well as an electric motor powered by a lithium battery and solar panels. The hybrid drive has two basic modes of operation, due to its specificity. The first "manoeuvring and low speed mode" is a small power operation when the ship is moving at low speed in restricted areas, for example in urban areas, or when the ship is traveling with the river current. In these areas, due to the necessary reduction of exhaust emissions and noise pollution, an electric motor is used for the drive. The second mode is called "cruise speed mode" and is used when the demand for power and, therefore, energy is several times higher. Then, it is economically justified in order to use an internal combustion engine operating in the optimum field of work (optimum range of performance). It should be noted that long-term use of the electric motor as a propulsion method in the first operating mode is possible when photovoltaic panels (a source of clean energy) are installed on the ship. The analysis of the above-mentioned propulsion variants and operating modes was carried out based on the results of experimental testing of a hybrid drive in laboratory conditions. Additionally, in order to determine the hull resistance curve of the analysed ship, model tests were carried out in the towing pool, which was an indirect goal of the tests.

3. Case Study Vessel

An inland container ship with a total hull length of 40 m, taking 36 containers of 20' length on board was used as the case study vessel for analysing the impact of the use of hybrid propulsion on selected economic and ecological factors. The general plan of the case study vessel is shown in Figure 2 and its basic data are presented in Table 1. The choice of the type of ship was motivated by the expected demand for such units in the future. The ship analysed in the article is based on a concept developed for building a family of inland vessels, adapted for sailing along the E70 route (connecting Berlin with Kaliningrad) and a concept of building a family of similar ships of various lengths, see [30–33]. The ship has appropriate dimensions that allow it to overcome the locks on the established travel routes and pass under low bridges. The propulsion system in the described variant of the ship consists of two twin hybrid propulsion units, described in detail in Section 4. Each propulsion unit drives the controllable pitch propeller through a shaft line, supported by ecological water-lubricated bearings [23,34,35]. Azimuth thrusters may be used as an option. To provide the unit with good manoeuvrability, it can be equipped with one or two bow thrusters with an electric drive powered by hybrid drive batteries. As an option, the ship can also act as a pusher with the use of the barge control system, developed for passenger ships, and the 'breaking' of the whole system during complicated manoeuvres [33].

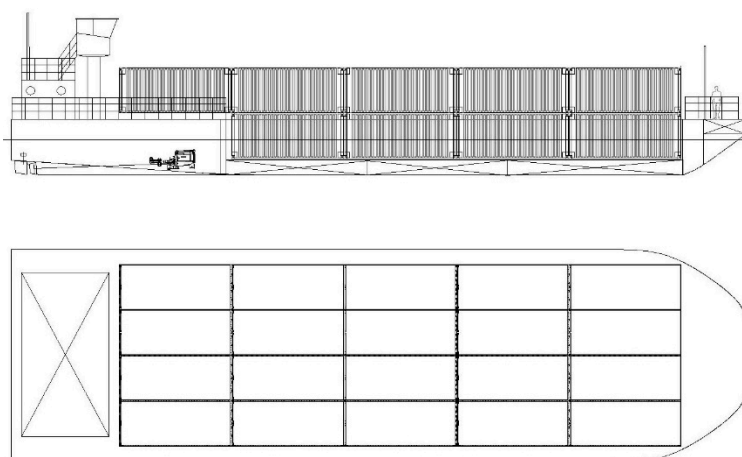


Figure 2. General plan of the case study vessel (inland-coastal container ship with hull length of LOA = 39.64 m).

Table 1. Basic parameters of case study vessel.

| Parameter | Value |
|---|-----------|
| Total length (LOA) | 39.64 m |
| Maximum width (B) | 11.42 m |
| Maximum draught (T) | 1 m |
| Light displacement (D) | 280 tonne |
| Cruise speed for hybrid propulsion: | |
| -electric motor mode-'manoeuvring and low speed mode' | 7 km/h |
| -combustion engine mode-'cruise speed mode' | 14 km/h |
| Maximum speed | 15 km/h |
| Maximum number of containers 20' | 36 |

Resistance tests were carried out for the vessel in the towing tank in order to determine the resistance curve of the hull. Two anticipated load conditions were analysed: a 'lowly loaded ship' and a 'heavy loaded ship' corresponding to different weights of the transported load. Power demand characteristics as a function of ship speed were determined (Figure 3). Based on these, the vessel's demand for power was determined for the two previously described operating modes of the hybrid propulsion system.

The values measured for the model and the actual towing power calculated for the object can be roughly converted into the required power of the propulsion engines necessary to achieve the assumed speed. For this purpose, the efficiency of the propeller was assumed to be $\eta_{prop} = 0.55$ and the efficiency of the power transfer system was assumed to be $\eta_{gear} = 0.98$. Taking into account the assumed ratios, the nominal power of the diesel propulsion is 98 kW and the electric module is 13 kW. In practice, a 10% reserve of power is often assumed to take into account the gradual increase in hull resistance resulting from fouling of the underwater hull, as well as a reserve of power for shipping in more difficult weather conditions, when additional resistance increases (due to waving) and aerodynamic resistance. In the analysed case, the power reserve was not intentionally taken into account, the size of which is determined individually, taking into account the specificity of the basin in which the unit will be operated. The omission of the power reserve enables a more transparent comparison of the analysed modes of operation of the hybrid propulsion system.

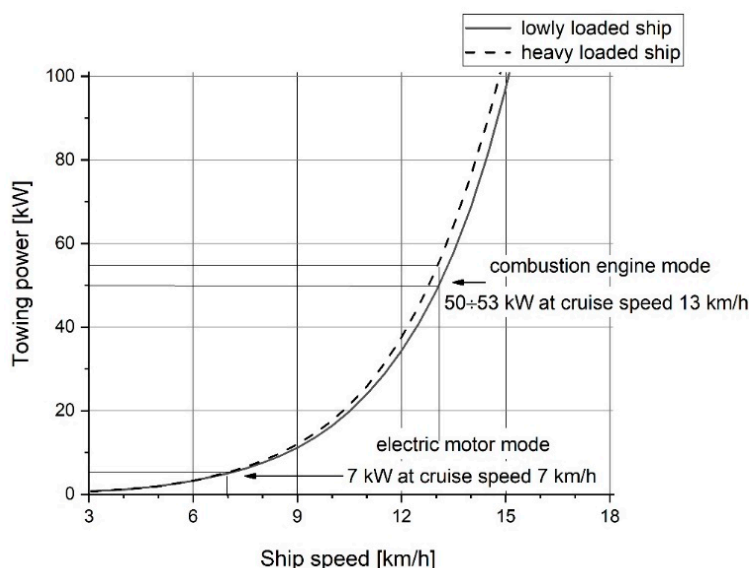


Figure 3. Graph of the power demand of the case study vessel as a function of speed for two loading states (lowly loaded ship and heavy loaded ship); two analysed modes of hybrid propulsion operation ('electric engine mode' and 'combustion engine mode') were selected.

4. Research on a Parallel Hybrid Propulsion System

For research purposes, a life-size, hybrid parallel propulsion system was built in the laboratory. It consisted of a 100 kW, medium-speed diesel engine with a reduction gear and a 7 kW electric drive module. The hybrid propulsion system presented meets the power requirements for the case study vessel in both previously described modes of operation. The schematic diagram and simplified assembly drawing of the drive system are shown in Figure 4. The tested hybrid propulsion required an examination of energy efficiency for the assumed configuration and working conditions resulting from the anticipated operating states of the vessel (Figure 3). The stand of the hybrid propulsion system was designed to allow power measurements in various operating states. Therefore, a remotely operated clutch, typical for such a solution, was replaced during testing with a torque gauge (Figure 4, element number 6) [36].

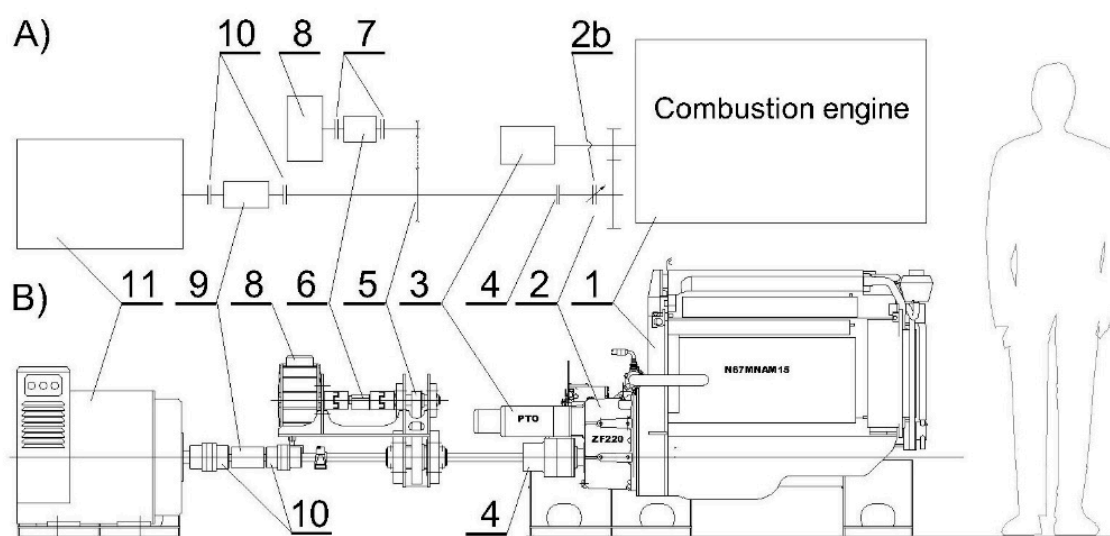


Figure 4. Test stand for hybrid drive; (A) simplified schematic diagram, (B) assembly drawing; 1—combustion engine, 2—reduction gear with integrated controlled clutch (2b), 3—hydraulic pump for loading the main engine, 4, 7, 10—clutches, 5—electric drive gear reduction belt, 6, 9—torque gauges, 8—electric motor, 11—electric generator-load.

Power measurements were carried out on the shaft in the following way. During the tests of the drive in the electric motor's (8) operating mode, the load was exerted on the main shaft by a direct current generator (11). Torque measurements were made using a torque gauge (9). During operation in the drive mode of the internal combustion engine (1), the load was exerted by a pump (3) connected to the engine. The torque was calculated indirectly, on the basis of the measured pressure in the oil pump. The load was changed by controlling the hydraulic pressure via the throttling valve. During the mechanical power calculation, the efficiency of the reduction gear and the pump previously tested in another stand were considered. The mechanical efficiency measurements for the hybrid propulsion system were carried out in accordance with the adopted test program. First, tests were carried out in the electric motor operation mode. At various speeds, attempts were made to gradually increase the load on the electric motor. Similar tests were carried out for the second mode of operation in which only the internal combustion engine was used for the propulsion. During the tests, data for specified work points were recorded for both modes of operation. For each operational condition, the fuel consumption (by measuring the loss of fuel mass in the intermediate tank) and noise level (using a sonometer measuring the sound pressure at a distance of 1 m from the propulsion system) were also recorded.

5. Results and Discussion

The measurements were made under various propulsion operating conditions and allowed for the preparation of energy efficiency graphs (Figures 5 and 6). The medium-speed, marine diesel engine used (whose design was created in the nineties), combined with a dedicated reduction gearing from a reputable manufacturer, achieved efficiency not exceeding 40% (Figure 5). It is worth noting that the installed internal combustion engine was practically brand new and had only worked a few dozen motor-hours. The test results confirmed that working with low-power combustion engines yields low energy efficiency. This is particularly well seen in the graph below (Figure 6), which compared the efficiency of the drive system in the electric motor operating mode with the operation mode of the internal combustion engine. The measurements show that at the 7 kW needed to obtain a speed of 7 km/h by the ship, the energy efficiency of the internal combustion engine does not exceed 22%, while the electric propulsion, together with the belt reduction gear under the same operating conditions, achieves efficiency equal to 85% (Figure 6). The developed efficiency charts for both analysed modes of operation of the hybrid propulsion show that the increase in the load of the internal combustion engine or electric engine (under practically all operating conditions) results in an increase in energy efficiency. Importantly, the increase in efficiency of the analysed electric engine was much higher than that of the internal combustion engine for each load, in the analysed field of operation.

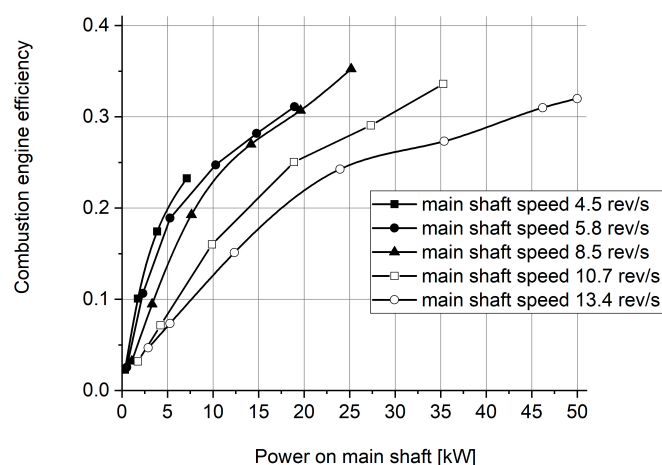


Figure 5. Measured efficiency in the internal combustion engine operation mode with a dedicated reduction gear as a function of the load and rotational speed of the main shaft.

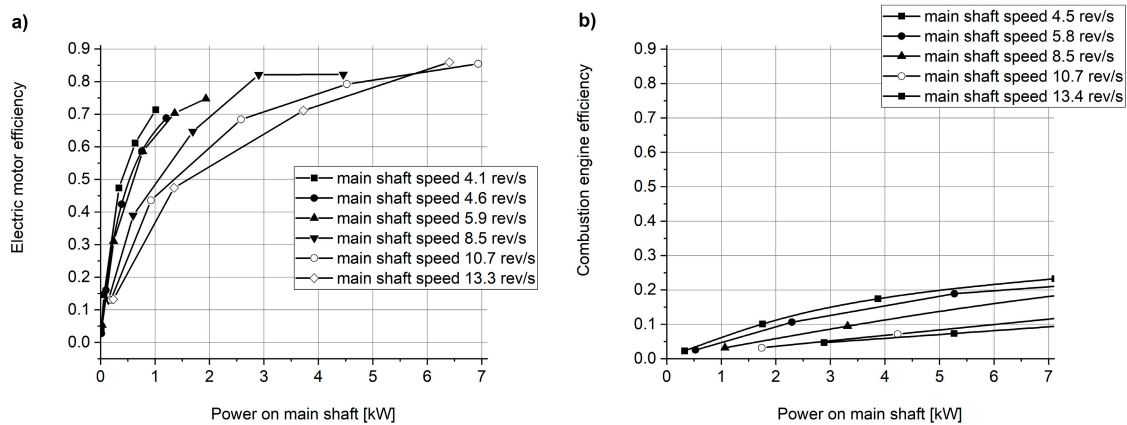


Figure 6. Efficiency of a ship propulsion as a function of the load and rotational speed of the main shaft for manoeuvring and low speed mode; (a) electric motor mode, (b) combustion engine mode.

During the tests, the diesel engine fuel consumption was measured for each measurement point, as well as the energy consumption in the case of the propulsion in the electric engine mode.

The results are presented in Figures 7 and 8. The vertical axes provide the information on unit consumption per one hour of the drive operation in pre-defined conditions.

The results of the measurements presented below show that, during the operation of the internal combustion engine, specific fuel consumption depends significantly on the engine speed. For example, with a specific, constant power output on the shaft, fuel consumption strongly depends on the speed and can increase three times for higher rotational speed and low torque load. The electric drive behaves differently. The amount of electricity required depends on the rotational speed of the shaft, but the difference decreases with increase transmission of power.

It is worth noting that, in the case where a vessel is equipped with a pitch propeller, there is an extended possibility of adjusting the setting parameters to increase the propulsion efficiency.

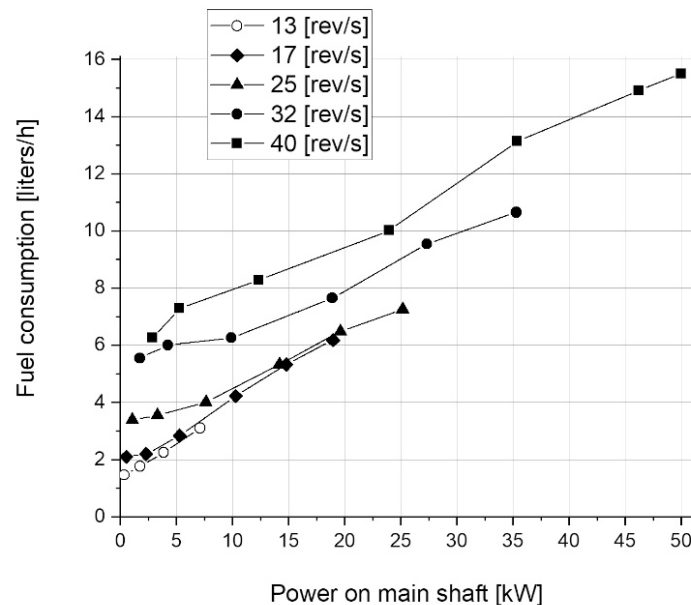


Figure 7. Measured fuel consumption as a function of rotational speed and power received from the main shaft during operation of the propulsion in the internal combustion engine operation mode.

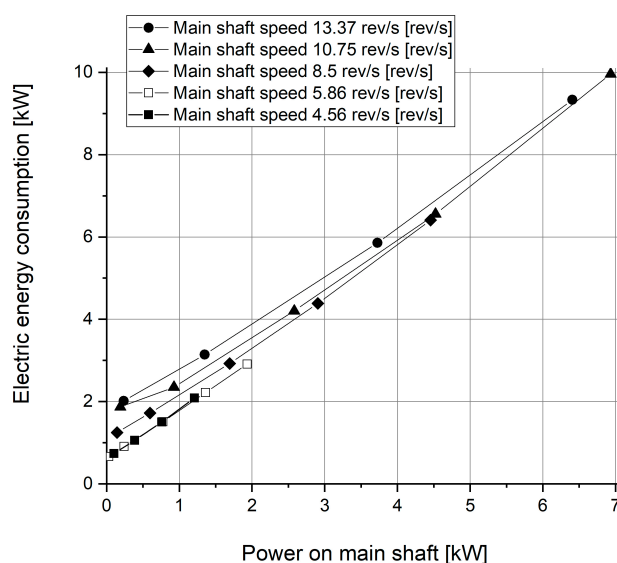


Figure 8. The measured energy consumption as a function of the main shaft speed during the operation of the propulsion in electric engine mode.

During the tests, noise measurements were also taken, using a sonometer placed 1 m from the hybrid propulsion. These data are presented in Figure 9. The results indicate significant differences in noise emissions, depending on the mode and parameters of hybrid propulsion operation. Considering the fact that the power room is built inside the ship, it can be claimed that the drive in the electric operation mode will be practically silent (it will emit negligible noise to the environment).

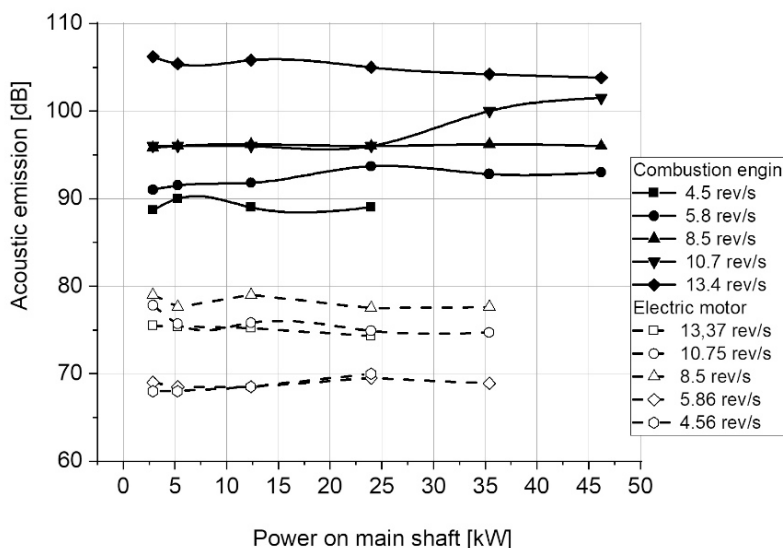


Figure 9. Results of acoustic emission measurements for the analysed operating points of the hybrid propulsion in the electric and combustion engine operation mode.

The results indicate that the use of a hybrid propulsion system in the vessel may, in some cases, be more advantageous than the use of a conventional propulsion (diesel engine). The advantage of hybrid propulsion is particularly visible when the ship is operating at low speed, which takes place in areas with limited maximum speed (e.g., urban areas) and areas of limited noise emission (e.g., reservoirs protected by the Natura 2000 program). Then, the hybrid propulsion can use the efficient operation of the electric engine, with a power that is sufficient for moving at speeds of up to 7 km/h. At such a low ship speed, the use of diesel for propulsion is extremely inefficient in energy.



As a consequence, the use of the ship at low speeds in urbanised areas or those protected by the environmental regulations, causes high emissions of harmful substances (Figure 10) [37–39] and the propulsion system works with an energy efficiency below 22%.

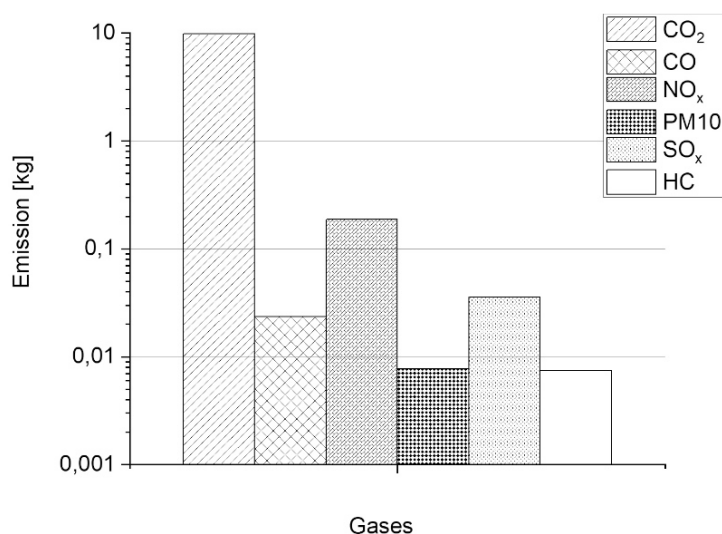


Figure 10. Graph of exhaust emissions of a diesel engine transmitting power of 7 kW to the main shaft during one hour [37].

In comparison, the efficiency of a hybrid propulsion system in the electric work mode is approximately 85%, which is up to four times greater. In addition, during operation of the propulsion with a power of 7 kW, switching to the electric operation mode reduces noise emissions by 20 dB (i.e., one hundredfold). This is a significant difference and the impact on people and the environment cannot be overstated. The impact of noise, including underwater noise, is currently a strongly developing area of research [40,41]. The use of hybrid propulsion in the case study vessel enables the operation of a ship in the so-called “zero emission” zone, at speeds of up to 7 km/h. One should bear in mind the limited capacity of batteries, which should be charged from the shore during unit stops (e.g., when in port or during locking procedures). It is also worth paying attention to the possibility of additional equipment for the ship with a photovoltaic installation, which can significantly extend the travel time with electric propulsion. Of course, the energy efficiency of solar modules depends on the time of day, time of year and the weather but such an additional opportunity to obtain energy seems very attractive. The parallel hybrid propulsion system has one more important advantage: it allows batteries to be charged while the combustion engines are running, allowing the electric engine to be connected to the propulsion system and work as a generator. The batteries must be charged if the internal combustion engine is loaded below its optimal working area. Then the additional load of the diesel engine increases its efficiency when recharging the batteries. The possibility of recharging the batteries is especially valuable in the areas deprived of power from the land and during cruises with short stops. Section 5 presents the analysis of 6 sample journeys to illustrate selected economic and ecological aspects resulting from the use of hybrid propulsion in the case study vessel.

6. The Benefits of Using a Hybrid Propulsion System in the Case Study Vessel

An analysis of the impact of using a diesel-electric hybrid propulsion instead of a conventional propulsion (diesel) was carried out for the test vessel. In both cases, the propulsion used the same combustion engine, installed on the test stand. The estimation of the ecological and economic effects (fuel consumption) was carried out for 6 sample journeys, differing in length and speed limits (Figure 11 and Table 2).

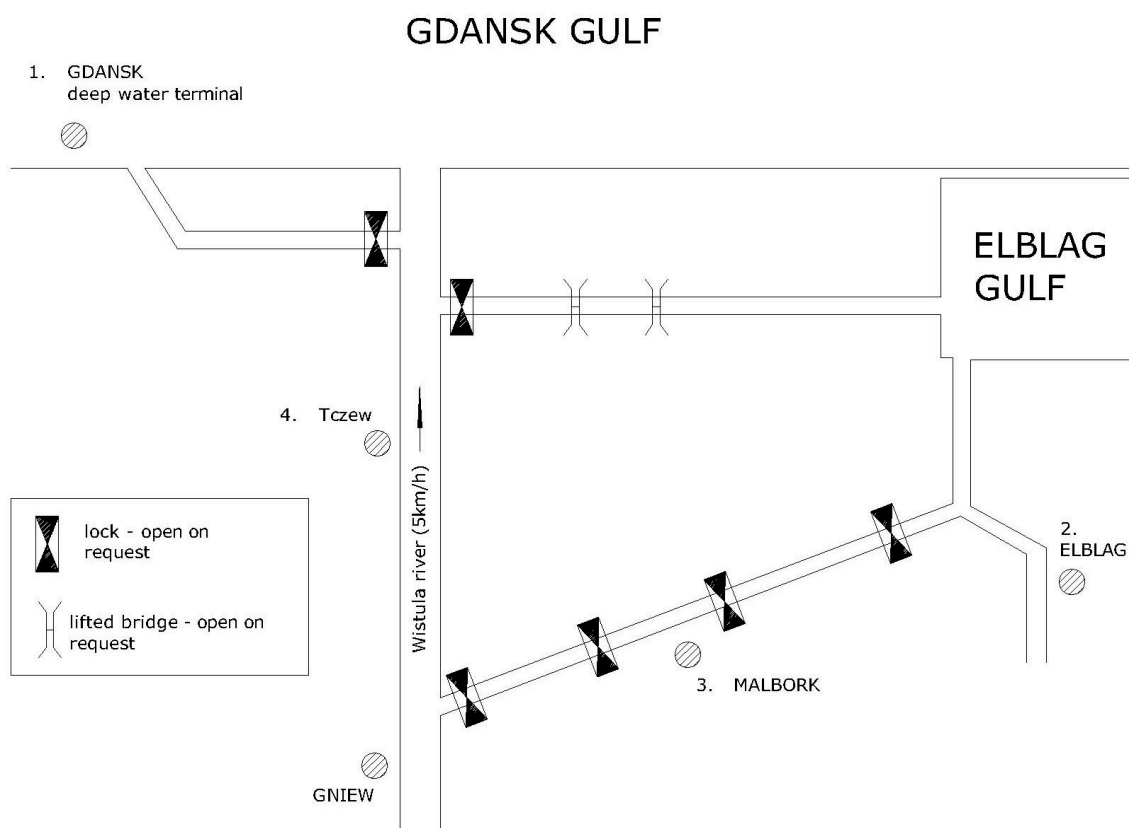


Figure 11. Sample journeys for the case study vessel.

Table 2. Sample journeys for the case study vessel divided into stages.

| Travel | Distance [km] | Notes |
|--------------------|---------------|--|
| 1-2 Gdansk-Elblag | 67 | Mostly still water, two locks, two drawbridges |
| 2-3 Elblag-Malbork | 40 | Still water, two locks |
| 3-4 Malbork-Tczew | 50 | Partly on the river with a stream, two locks |
| 4-1 Tczew-Gdansk | 50 | Mostly down the river, one lock |
| 1-4 Gdansk-Tczew | 38 | Mostly up the river, one lock |
| 4-3 Tczew-Malbork | 38 | Partly up the river, two locks |

The calculated total fuel consumption and exhaust emissions were determined on the basis of laboratory tests, during which fuel consumption measurements were made (Figure 7). The data used for the calculations concern actual shipping journeys and are an alternative to the currently used road transport mode. On the basis of measurements of fuel consumption as a function of engine speed and engine power, unit fuel consumption was determined and then total fuel consumption (diesel oil) and electric energy were calculated for both ship variants and for each of the sample journeys connecting the container port with a specific city/place of unloading. The fuel consumption results are shown in Figure 12. The economic benefits (in the form of savings in fuel costs) as well as the environmental benefits resulting from the reduction of CO₂ emissions and air pollution can be estimated from the fuel consumption graph.

Analysis of fuel and electric energy consumption for six different inland journeys showed that there are potential economic benefits in using a hybrid propulsion system and it may be possible to reduce operating costs, depending on the specificity of the travel. If the travel does not include protected areas or sections with speed restrictions and the ship's propulsion works for most of the time at full-power, then the fuel savings are minimal (Figure 12, cases 1-4 and 4-3). However, if the travel takes place with the current of the river or in regions with speed limits and the demand for propulsion

power allows the use of the electric drive, then the fuel savings can reach up to 40% (Figure 12, cases 3-4 and 4-1).

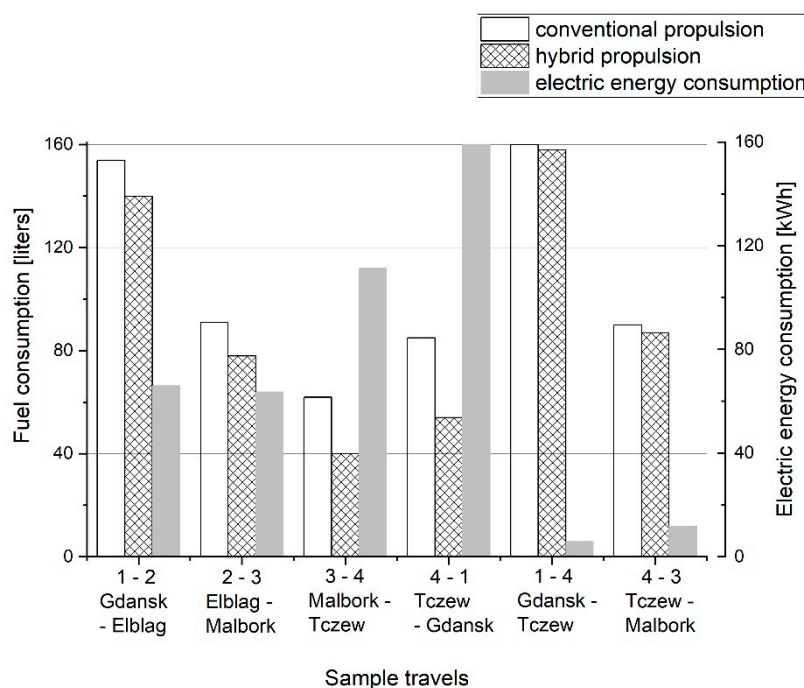


Figure 12. Calculated fuel and electricity consumption for two variants of the propulsion system (conventional and hybrid) made for 6 sample journeys.

Analysis of the results confirms the familiar analogy with respect to road transport using hybrid cars. They are especially useful and effective in crowded cities but not when travelling on highways and at constant speeds. The importance of the impact of environmental noise pollution is becoming increasingly appreciated. The noise emissions from electric motors are much smaller than those from combustion engines, especially diesel ones. During tests carried out on hybrid propulsion, noise of an average intensity of 105 dB was recorded in the vicinity of a 50 kW internal combustion engine. During operation of the hybrid drive in low power mode (i.e., only the electric engine), noise of an average intensity of approximately 70 dB was recorded. An analogous traditional propulsion system, i.e., without an electric engine, emits approximately 90 dB as a result of the combustion engine's operation. Thus, at ship speeds up to 7 km/h and by enabling the operation of a hybrid propulsion system (in electric mode) the noise emitted by the propulsion can be reduced by one hundredfold. This is a significant advantage of the tested hybrid system.

By considering different variants of the propulsion and power system for the analysed vessel and its journeys, an important role could be played by the photovoltaic installation that is installed on the unit. If photovoltaic panels are installed on transported containers, the peak power of such installations can be an important source of energy. Photovoltaic panels installed on a surface area corresponding to one 20 m container can generate a peak power of about 2.5 kW. This means that the installation of photovoltaic panels on eight of the twenty containers in the spring-summer-autumn period can cover the entire demand for electricity for the drive system operating in the 'manoeuvring and low speed mode'. As a result, it becomes possible to become independent from shore power or operate electric engines in generator mode. Furthermore, it can allow longer travel time by using the electric propulsion or supporting the internal combustion engine by an electric drive. It is worth noting that more and more importance is being attached to particular delivery times to recipients and it should become possible to adopt such a strategy to cover the distance when the ship is slower for a



longer time using cheaper electricity. This concept fits perfectly in the ongoing trends toward green shipping and smart shipping.

7. Conclusions

In recent years, the concept of a parallel hybrid drive, especially for inland vessels, has been developed at the Faculty of Ocean Engineering and Ship Technology at the Gdańsk University of Technology.

Experimental research has been carried out to assess the impact on the natural environment of two alternative ship propulsion systems. It has been experimentally proven that the difference in the amount of fuel consumed, and thus the difference in exhaust emissions, is significantly lower when using parallel hybrid propulsion. The results indicate that the use of a hybrid propulsion system can be beneficial from both economic and ecological point of view. The advantage of hybrid propulsion is particularly visible when the ship is operating at a low speed. This takes place especially in areas with limited maximum speed (e.g., urban zones) and areas of limited allowable emission of noise. The full-scale measurements showed that at a low speed mode (ships' speed of 7 km/h) the energy efficiency of the combustion engine was below 22%. For similar conditions the hybrid propulsion in electric mode, had the energy efficiency equal to 85%. Moreover, the major benefit resulting from hybrid propulsion in electric mode was significantly reduced noise pollution. In analysed cases it was experimentally verified that the noise emission was reduced by 20 dB (one hundred times). It may be essential factor for urban or environmentally protected areas.

Analysis of fuel and electric energy consumption for six different journeys using inland waterways showed potential economic benefits resulting from using hybrid propulsion system. The analysis showed that there is possible to lower operating costs due to lower fuel consumption. However relative benefit resulting from using hybrid propulsion is strongly dependant on the specific aspect of route (i.e., speed limits, current) and vessel speed. If the combustion engine works for most of the time at optimum load (80% of full-power), then the fuel savings are minimal. However, if the travel includes different power demands, resulting i.e., from speed limits, then the fuel savings can reach up to 40%.

Additionally, the potential of additional photovoltaic energy can be mentioned here. Solar panels installed on the ship can have a very significant impact on the reduction of the load on the natural environment. The solar modules on transported containers may allow for generating significant amounts of electricity during the voyages, and to an amount sufficient for travel at speeds of up to 7 km/h. Because of this, all-day travel in zero-emission mode may be possible on specific sites.

When designing hybrid propulsion systems, it is particularly important to precisely determine the power demand for different propulsion modes. In general, different modes of drive operation will result from the maximum speed limits of the ship. In low speed mode, the demand for power drops many times due to the lower resistance of the hull. In the case of the analysed vessel, the power demand at 7 km/h was over seven times lower than at the economic speed of 13 km/h. The use of hybrid propulsion in the electric engine operation mode allowed up to a fourfold increase in the drive's energy efficiency to be achieved, while reducing CO₂ emissions and air pollution to zero, as well as a hundredfold reduction in noise emissions. On the other hand, it is worth paying attention to the rapid increase in the demand for power as a function of speed, especially above 13 km/h. In order to reach the maximum speed (set as 15 km/h) the power of the propulsion system must increase twice (Figure 3). This entails a significant increase in fuel consumption and, consequently, a significant increase in exhaust emissions. Therefore, according to the authors, the 'smart propulsion system' must be designed for a specific, dedicated application, the operational strategy of which has been thoroughly analysed.

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Nomenclature

| | |
|-----------------|--|
| Ro-Ro | Acronym for Roll-on/roll-off. Roll-on/roll-off ships are vessels that are used to carry wheeled cargo. |
| IMO | International Maritime Organisation |
| EEDI | Energy Efficient Design Index |
| LOA | Ship length overall |
| HC | Hydrocarbons |
| NO _x | Nitrogen oxides |
| PM | Particulate matters |
| η_{prop} | Propeller efficiency |
| η_{gear} | Reduction gear efficiency |

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