

Article

Modeling of an Autonomous Electric Propulsion Barge for Future Inland Waterway Transport

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Abstract: International trade is continuously rising, leading to an increase in the flow of goods passing through transportation hubs, including air and sea. In addition, the aging fleet of inland vessels necessitates renewal through the construction of new vessels, presenting opportunities for the adoption of modern transport technologies. Autonomous barges can transport bulk and containerized cargo between the central port of a specific region and smaller satellite ports, enabling the dispersal of goods over a wider area. Equipping autonomous barges with advanced sensors, such as LIDAR, computer vision systems that operate in visible light and thermal infrared, and incorporating advanced path finding and cooperation algorithms may enable them to operate autonomously, subject only to remote supervision. The purpose of this study is to explore the potential of autonomous electric propulsion barges in inland waterway transport. Given the increasing demand for efficient and sustainable transport solutions as a result of various new policies, which have set new ambitious goals in clean transportation, this study aims to develop a proposition of an electric propulsion hybrid drive inland waterway barge, and compare it to a conventional diesel-powered barge. The methodology involves the creation of a simulation model of an inland waterway class IV electric barge, equipped with advanced sensors and autonomous control systems. The barge's navigation is managed through a multi-agent system, with evolutionary algorithms determining a safe passage route. This research also utilizes a proprietary networked ship traffic simulator, based on real inland vessel recorded routes, to conduct the autonomous navigation study. The energy consumption of the barge on a route resulting from the ship traffic simulation is then examined using the mathematical model using the OpenModelica package. As a result of the study, the proposed hybrid propulsion system achieved a 16% reduction in fuel consumption and CO₂ emissions, while cutting engine operation time by more than 71%. The findings could provide valuable insights into the feasibility and efficiency of autonomous electric propulsion barges, potentially helping future developments in inland waterway transport.

Keywords: autonomous barge; autonomous ship; MASS; electric propulsion; inland waterway; passage route; evolutionary algorithm; tonne-kilometer CO₂ emission



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1. Introduction

1.1. Sea Transport Automation Legal Framework

According to the International Chamber of Shipping data included in the Seafarer Workforce Report [1], the number of trained maritime officers should be increased by 2026, as there is already a deficit in the labor market of approximately 16,500 officer vacancies. Automation of maritime transport is treated as a potential solution to future problems with staffing ships with properly trained and experienced crew.

The International Maritime Organization IMO uses a 5-point scale [2] to determine the degree of autonomy of a MASS (Maritime Autonomous Surface Ship). Degree 0 on this scale means full control of the crew at all times during the cruise, while degrees 1 and 2 reduce dependence on the crew. At degree 3, the ship is controlled remotely and

has no crew on board and, finally, autonomy degree 4 corresponds to a ship that can fully independently perform its tasks.

One of the tools intended to enable the construction of ships with an increasingly higher degree of autonomy is the Strategy for the development and implementation of e-navigation [3]. It assumes the development of five solutions intended to constitute a bridge between contemporary and future shipping, while constantly improving its safety level.

The most important assumptions of the e-navigation strategy include the need to standardize data exchange formats and structures used in shipping, combined with the automation of data exchange functions. These activities are intended to help develop a set of messages with the widest possible coverage of travel data and situations, and the lowest possible level of complexity, translating into low technical requirements for interactive communication. The aim of the above proposals is to improve mutual communication, making it resistant to misunderstandings, robust, and at the same time effective [4].

Standardizing and simplifying the methods of communication in shipping can minimize confusion in its processing by future automatic ship guidance systems, which will, in all probability, coexist in the same environment as manned ships.

Inland and coastal ships are a special type of cargo ships. Due to the limited geometry of typical waterways, they are subject to size restrictions, but for motor barges their length usually does not exceed 150 m, width is less than 15 m, and draft is no more than 2.8 m [5].

1.2. Inland Waterway Shipping Automation

The Mobility Strategy [6] announced by the European Commission in December 2020 calls for ambitious goals of shifting a significant amount of 75% of the goods transport stream within the European Union to rail, inland water, and short-sea shipping. For this reason, an increase in the number of barges in inland and coastal traffic is expected. If conventional crewed barges were used, there would also have to be an increase in the available number of properly trained sailors who, in addition to training, would also have to devote their time to gain the required experience.

Additionally, the report to the project “Modernization of Vessels for Inland waterway freight Transport” [7] stated that the fleet of European inland ships is outdated and, with an average age of over 40 years, will soon require reconstruction, which creates a potential opportunity to implement modern technologies into the new European inland fleet.

1.3. Autonomous Ship Navigation

When navigating a ship, the helmsman’s primary task is to be aware of the ship’s surroundings, which allows him to make decisions about steering his own ship well in advance. The main sense used by the navigator is his eyesight, greatly supported by equipment available on the ship such as a navigation map, radar with ARPA (Automatic Radar Plotting Aid), AIS transceiver (Automatic Identification System), GNSS receivers (Global Navigation Satellite System), and other instruments measuring ship motion parameters, including compasses and logs. Many modern ships use an integrated ECDIS (Electronic Chart Display and Information System) navigation environment [8], which allows the clear presentation of data collected by all available navigation devices on one screen [9].

The ship’s autonomous control system can apply existing technical solutions, similar to the existing decision support systems for navigators, including systems based on genetic algorithms [10], Bayesian Networks [11], or dynamic risk assessment [12]. However, there is a need to introduce a counterpart to the navigator’s sense of sight, i.e., the element of the entire navigation process that prevents the overlooking of navigation threats not detected or detectable by radar or other traditional electro-navigation systems. Taking into account the already developed solutions in the field of land vehicle automation, it is reasonable to make use of computer vision systems operating in the visible and infrared range, as well as LIDAR (LIght Detection And Ranging) devices. Figure 1 shows example screen views of modern maritime navigation devices.

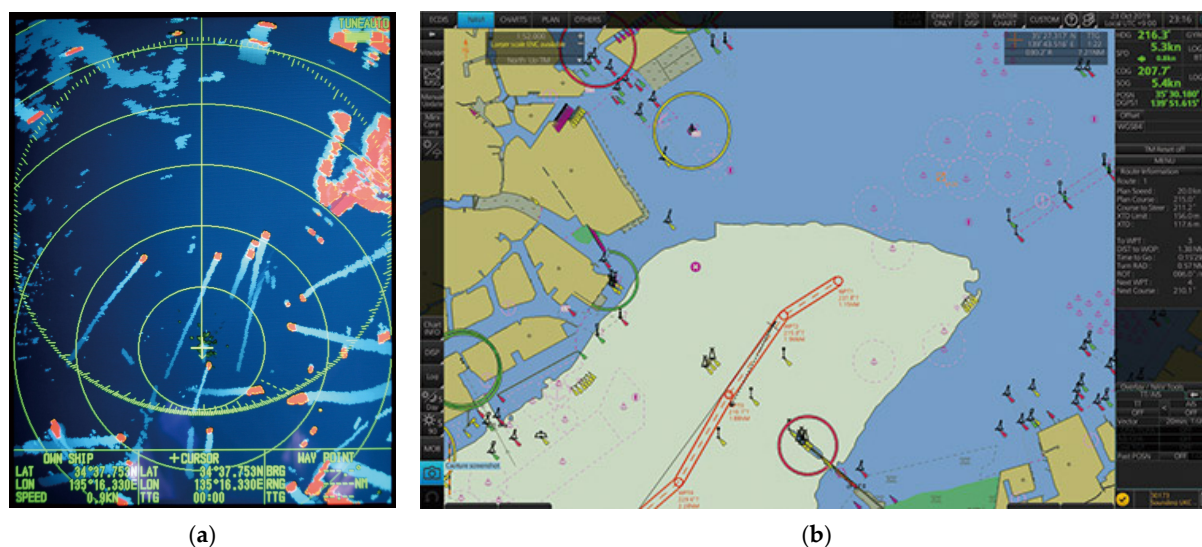


Figure 1. View of the radar screen with the ARPA function (a) and the ECDIS system screen with data from radar and AIS devices (b) [13].

LIDAR systems work similarly to radar, but to detect objects they use focused beams of laser radiation, usually in the near-infrared band. Due to the use of infrared radiation, which has a much shorter wavelength than microwaves used by radar, they have higher resolution and lower range. Unlike the terrestrial environment, the use of LIDAR in the marine environment is characterized by a minimal return signal in calm water, which allows for quick recognition of potential obstacles floating on the surface [14]. The use of data from the LIDAR device allows medium-range data from the radar device to be supplemented with data about the ship's surroundings in its immediate vicinity. The combination of traditional systems used in the marine environment, such as radar or AIS, with sensors operating in the immediate environment [15], such as artificial vision systems and LIDAR systems, allows sufficient understanding to be obtained of the ship's surroundings in the immediate and medium ranges thanks to the fusion of data, in various combinations, such as radar with LIDAR [16], AIS and a visual feed [17], or radar, LIDAR, and a camera feed [18].

Among the algorithms with potential applications in planning the route of maritime autonomous vehicles, various derivatives of the classic A* pathfinding algorithm for both seagoing vessels [19,20] and inland vessels [21,22] are very popular, while the remaining algorithms are usually based on evolutionary methods [23,24], potential fields methods [25], artificial neural networks [26], anticollision neural networks [27], methods using Linear Matrix Inequalities (LMIs) [28], or Rapid Random Tree (RRT) methods [29].

The development of technologies related to MASS allows the presentation of an alternative solution that enables meeting the requirements of the Mobility Strategy regardless of the availability of crews. This article presents a proposal for an autonomous, unmanned electric barge, capable of transporting bulk or containerized cargo between sea and/or inland ports by itself, and supervised only by a remote operator. The solution presented in the article corresponds to the third degree of autonomy according to the scale adopted by the IMO [3].

2. Unmanned Inland Electric Barge Concept

Sailing in a coastal environment and inland waters changes the characteristics of the barge's surroundings, when compared to a seagoing vessel. The first difference is the hydrometeorological conditions. On the one hand, the barge is subject to a limited influence of environmental conditions such as waves [30], due to the waters being confined by the land, and wind, due to the small height of the ship itself. On the other hand, navigation on rivers and some canals usually involves being exposed to the influence of the river

current and the associated asymmetry of the propulsion load, depending on the direction of movement during a usually two-way cruise.

The second difference concerns navigation, because the inland barge is constantly in a water area that is strongly limited in terms of navigation, both by static limitations related to the waterway/land border itself and by the proximity of other users of this route. In European countries with a developed network of waterways, such as Germany, Belgium, the Netherlands, and France, most inland waterways run along natural rivers and artificial navigable canals [31].

Table 1 presents the most important parameters of the proposed barge, which could be the potential future of European inland transport. The hull dimensions and installed propulsion are based on the existing inland fuel tanker “Inka” operating in the Port of Gdańsk area [32].

Table 1. Autonomous hybrid propulsion barge parameters [33].

Parameter	Value
Length	84 m
Width	9 m
Draft	2.5 m
Cargo capacity	1300 T/60 TEU
Waterway class (Europe)	IV
Generator	WarUD25 V12 1 × 810 kW
Battery capacity (nominal)	537.6 kWh
Battery capacity (available)	430.1 kWh
Battery type	Winston LFP200AHA, 200 Ah
Battery configuration	168s5p
Battery mass	6.64 t
Propulsion motor	PMSM, 2 × 420 kW

The proposed autonomous barge with hybrid electric propulsion is a vessel with a hull length of 84 m, width of 9 m, and a draft of 2.5 m, falling into the category of class IV vessels according to the Classification of European Inland Waterways [34]. Figure 2 shows a view of the hull shape of the proposed barge.

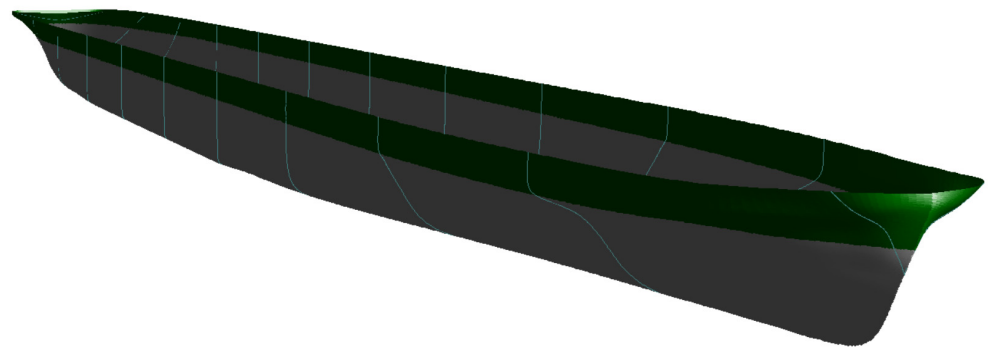


Figure 2. Three-dimensional view of the hull shape of the proposed 84 m long barge.

2.1. Proposed Structure of the Sensor System and Motion Control of an Autonomous Barge

Figure 3 shows the proposed structure of the system of sensors and navigation devices, as well as a diagram of the flow of information and commands in the autonomous movement control system for a hybrid barge.

The autonomous barge is equipped with navigation devices typical of class IV vessels, including navigation lights, radar, GPS receiver, AIS transceiver, compass, and log. Additional equipment related to the autonomous operation of the barge includes an electronic map, LIDAR with a maximum range of 2 km, and a system of cameras operating in visible and near infrared light, along with an image processor using the cameras and LIDAR data to detect potential obstacles floating in the water.

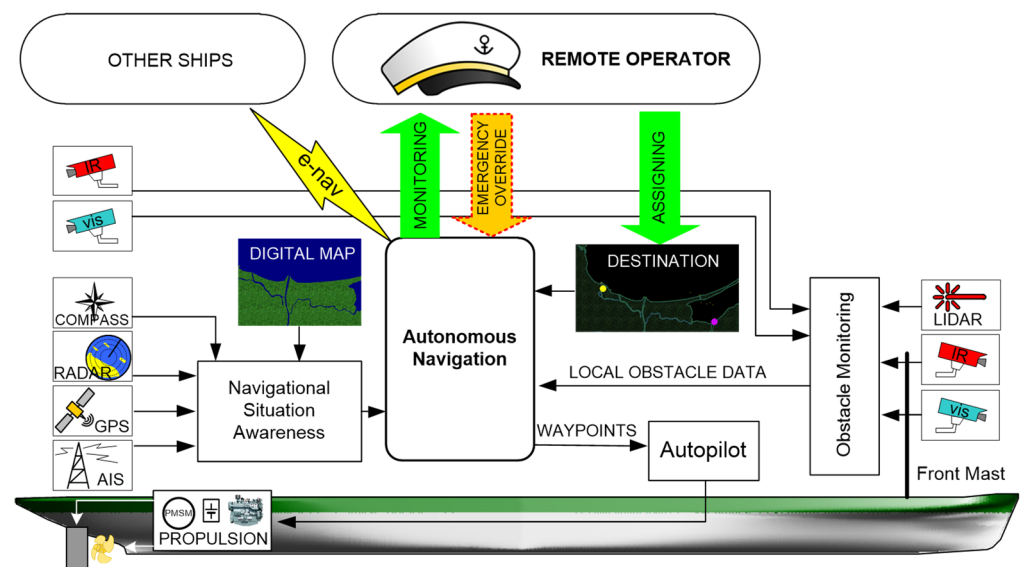


Figure 3. Block diagram of sensor connections, traffic control system, and information flow on board the proposed autonomous barge with hybrid drive.

The autonomous navigation system will be based on a multi-agent system, supported by an evolutionary algorithm-based route determination algorithm. The multi-agent system has the ability to communicate with other waterway users in accordance with the protocols specified in the IMO e-navigation proposal [4]. The result of the autonomous navigation system is a set of frequently updated nearby waypoints, used subsequently by the autopilot to directly control the barge's propulsion system.

The control and supervision of the autonomous barge is performed by a remote operator who has the ability to view data from all on-board devices [35], and has the ability to establish direct control over the barge in special cases.

2.2. Proposed Structure of the Electric Drive System

The proposed propulsion system has parameters similar to those of many class IV barges in service on European waterways. It consists of a DC generating set based on a Wärtsilä UD25 V12 diesel engine with a rated power of 810 kW, driving a permanent magnet brushless generator and a rectifier [36]. The use of an electrical machine with permanent magnets is dictated by its higher efficiency than induction machines [37].

The task of the generating set is to periodically charge the on-board electricity storage, built on the basis of 840 pcs. Winston LFP200AHA Lithium Iron Phosphate cells with a capacity of 200 Ah, in the 168s5p configuration, with a rated voltage of 538 V and rated energy of 537,600 Wh. The usable energy storage capacity has been limited to 80% of the rated capacity by reserving the last 20% of the state of discharge (SOC) to improve cell life and use it as an energy reserve.

The source of torque driving a single fixed pitch propeller is a pair of PMSM motors with a power of 420 kW each, driven by voltage inverters. The engines are connected to the propeller using a reduction gear with a ratio of 1:1.

Figure 4a shows a comparison of a typical propulsion system found on a class IV barge, with the proposed hybrid system in the Figure 4b.

The conventional drive in Figure 4a consists of a high-speed diesel engine (1), with a maximum rotational speed above 1000 RPM, a reduction gear with a reversing mechanism (2), a drive shaft (3), and a single propeller (4). The direct connection of the propeller to the engine means that the engine must run at different speeds depending on the required speed of the barge.

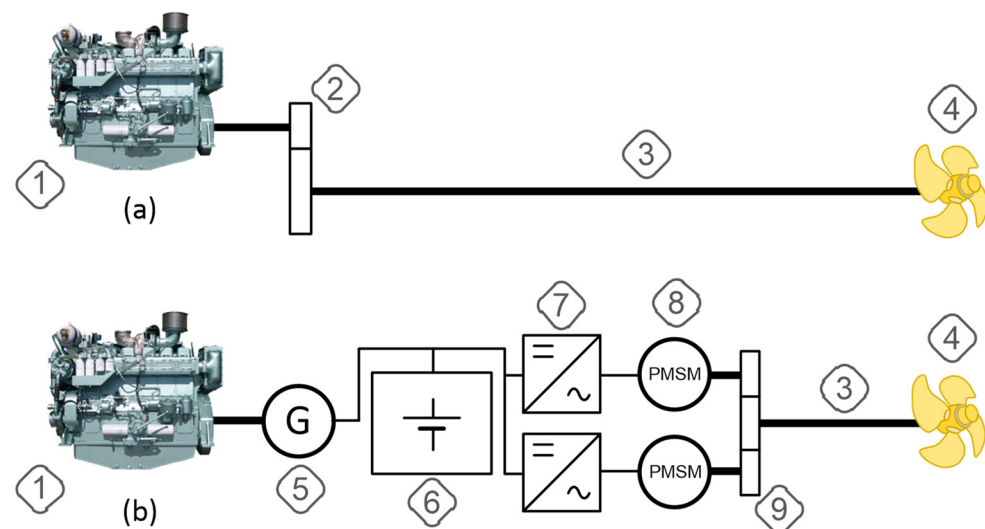


Figure 4. Comparison of the conventional propulsion system on a typical class IV barge (a) with the proposed hybrid system (b).

The proposed hybrid drive system shown in Figure 4b uses a diesel engine (1) identical to the classic drive system, but it drives a generator (5) that produces direct current and powers the energy store and main DC bus (6). The energy store operates in the proposed drive system as an energy buffer, absorbing or supplying electrical energy from the main DC power bus. When the power consumption of the drive system exceeds the power available from the generator, the energy store provides it by discharging internal electrochemical cells. The energy store has enough power capacity to power the drive system at full load, without requiring the engine (1) and generator (5) to run. If the generator provides more power than is consumed by the drive system, the excess power is used to charge the internal energy store cells. The charging/discharging process is supervised by the Battery Management System (BMS) built into the energy store unit, which controls starting and turning off the engine (1) and the generator (5) when the store cells reach certain SOC levels. The source of torque driving the barge is a pair of permanent magnet synchronous motors (PMSMs; 8), powered from the energy store via inverters (7). These motors, drive a two-input gear (9) followed by a short drive shaft (3) and, through it, the propeller (4).

The use of the hybrid drive shown in Figure 4b allows the diesel engine operating point to be independent of the barge speed, which allows the use of any point on the main engine characteristics. Of particular interest is the operating point ensuring minimum fuel consumption and minimum pollutant emissions in relation to the power produced.

The autonomous hybrid propulsion barge, as proposed in this study, incorporates two electric motors, inverters, and a battery energy store. These elements, while adding to the mass of the barge, are offset by the removal of crew facilities.

3. Results

The mathematical model of an autonomous barge with a hybrid electric drive used in the research consists of two elements. The first is the proprietary system of a networked ship traffic simulator, enabling research on ship traffic control algorithms in an environment simulating real conditions. The simulator uses a mathematical model of the geometry of the aquatic environment in the form of two-dimensional polygons constituting land boundaries that form static navigation limitations. Using the networked ship traffic simulator, research on the movement of a barge along a route of approximately 125 km, between a permanent mooring point at the quay in the Port of Gdańsk and two destinations located on the Vistula Lagoon, ending with a return to the mooring site, was carried out. The stopping points of the simulated barge correspond to the stopping points on the route of the fuel barge

“Zosia” (MMSI 261182515), registered using the AIS system via the MarineTraffic website. The route taken by the simulated barge was then compared to the route of the actual barge.

In the second stage of the simulation, a mathematical model of the hybrid propulsion system was developed using the Modelica package [38], in which research related to the energy and fuel consumption of a simulated barge was carried out, with the simulated barge sailing along the route proposed as a result of the operation of the proposed autonomous control algorithms, and closely corresponding to the route covered by a real barge.

3.1. Networked Ship Traffic Simulation Research

The networked ship traffic simulator was built in a client–server architecture, where a single server has information about the geometry of the simulated water environment and the state of dynamic objects located in it. The condition of objects includes the geographical location of their centers of gravity, geometric dimensions (length, width, draft), speed over ground, course, and heading. Figure 5 shows an exemplary connection structure of the networked ship traffic simulator.

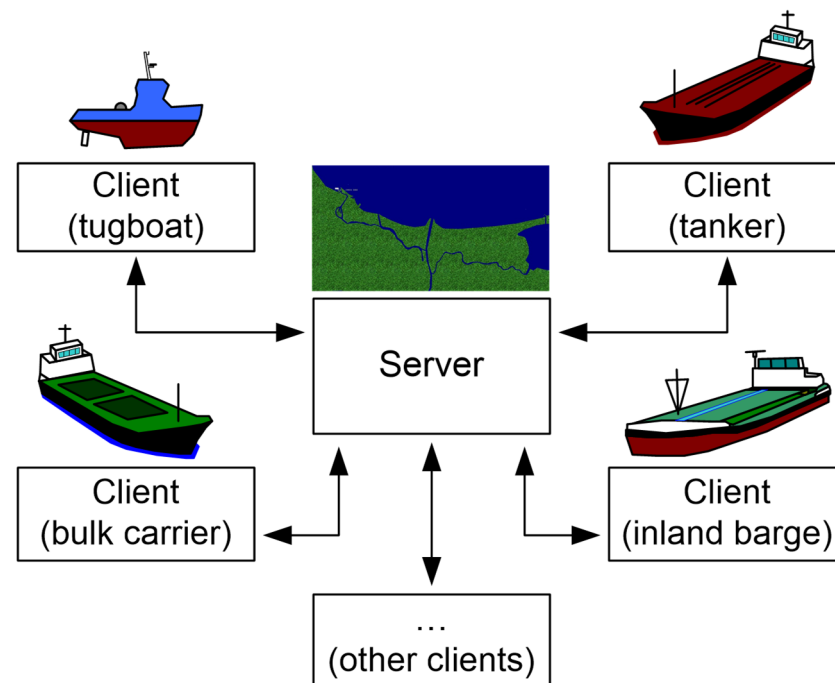


Figure 5. Sample structure of computer connections in a network ship traffic simulator.

Clients participating in the simulation connect to the server via a TCP/IP-based link. Each client is a separate process, and it is possible for clients to work on separate computers. The number of clients is limited only by the bandwidth of the IP network and the performance of the computer housing the server.

The many-to-one communication model used in the simulator allows a ship’s mathematical modeling functions and its motion control algorithms to be separated from other clients, which allows each client to calculate its own movement independently of other clients. In the example shown in Figure 5, four clients participate in the simulation, each of them modeling a different vessel: a tug, a tanker, a bulk carrier, and a motor barge. At set simulation time intervals, each client sends information about its position, speed, and course to the server, and in return receives the same data on other objects active within the simulation. Additionally, the server synchronizes the simulation time between individual clients. In the presented example, such data exchange took place every 0.25 s of the simulation time.

Figure 6 shows a view of the subsequent stages of entering data about the aquatic environment into the simulator.



Figure 6. View of individual stages of processing geographical data of the simulated aquatic environment area.

In the first stage, visible in the upper part of Figure 6, a bitmap of a satellite image or a digital map of the selected area is loaded. Then the bitmap is vectorized by covering the land areas with polygons, in a second step visible in the middle part of Figure 6. At this stage, other elements of the navigation environment are also added, such as fairways, areas excluded from navigation, shallows, and the starting positions of the ships used in the simulation. The bottom part of Figure 6 shows the conversion result, which comes from a screenshot of the server status display.

Figure 7 shows a satellite photo of the Port of Gdańsk area and the western part of the Vistula Spit with the superimposed routes of the compared barges. Green marks the route of the actual motor barge “Zosia”, which was recorded in September 2023 using data transmitted by the AIS system via the MarineTraffic website. The route of the simulated autonomous hybrid barge on the route from the Port of Gdańsk to the mouth of the Bay of Elbląg is marked in blue, and the return route from the mouth of the Bay to the Port of Gdańsk, around the Aestian Island, is marked in red. The purple pin marks the beginning

and end of the route in the Port of Gdańsk, while the yellow pin marks the intermediate point at the mouth of the Bay of Elbląg.



Figure 7. Comparison of the routes traveled by the real motor barge “Zosia” (green trace) and the simulated autonomous barge (blue and red trace).

The route covered by the actual motor barge is 126.3 km long, while the corresponding route between the same start and end points (purple and yellow pin) by the proposed autonomous barge is 122.4 km long, so is 3.2% shorter. This is related to more accurate navigation and the autonomous barge following the given route without the deviations shown in the actual barge route plot.

Figures 8–10 present selected calculation results in the network ship traffic simulator.

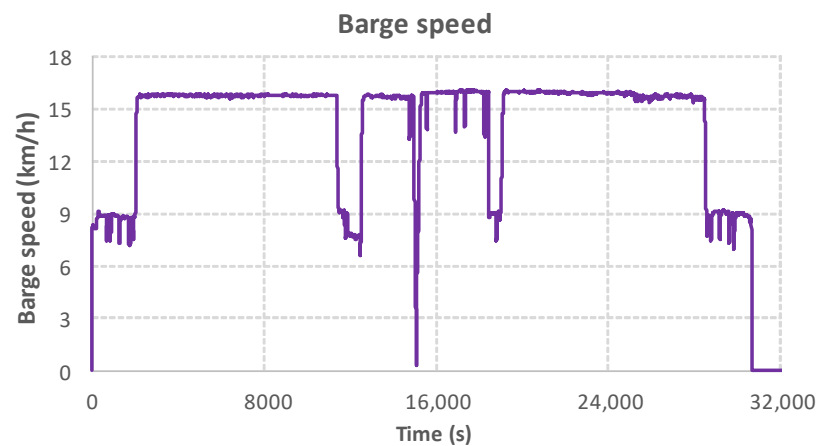


Figure 8. Speed plot of the simulated autonomous barge.

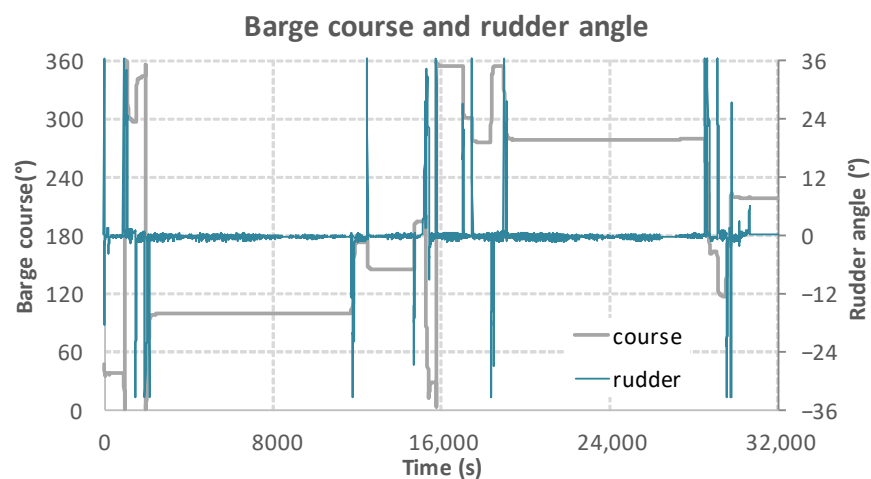


Figure 9. Graph of the course and rudder angle of the simulated autonomous barge.

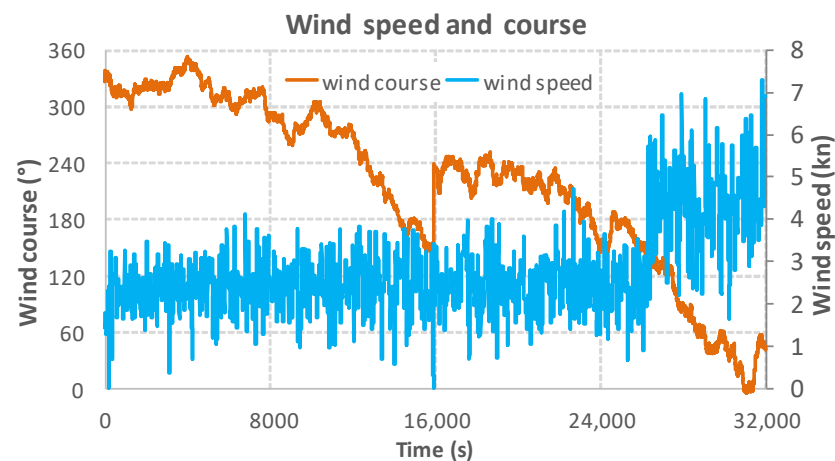


Figure 10. Graph of environmental conditions—wind speed and course during the simulation.

3.2. Barge Energy Consumption Research

Information about the barge's route, calculated using a network ship traffic simulator, served as input to a mathematical model of the hull and propulsion system of a hybrid barge, created in the Modelica environment [38]. Information about the barge's longitudinal speed, rudder blade angle, and wind course and speed allowed for simulation of the operation of the hybrid propulsion system with which the proposed barge is equipped. Figure 11 shows a block diagram of the mathematical model of a motor barge with hybrid drive made in the OpenModelica environment.

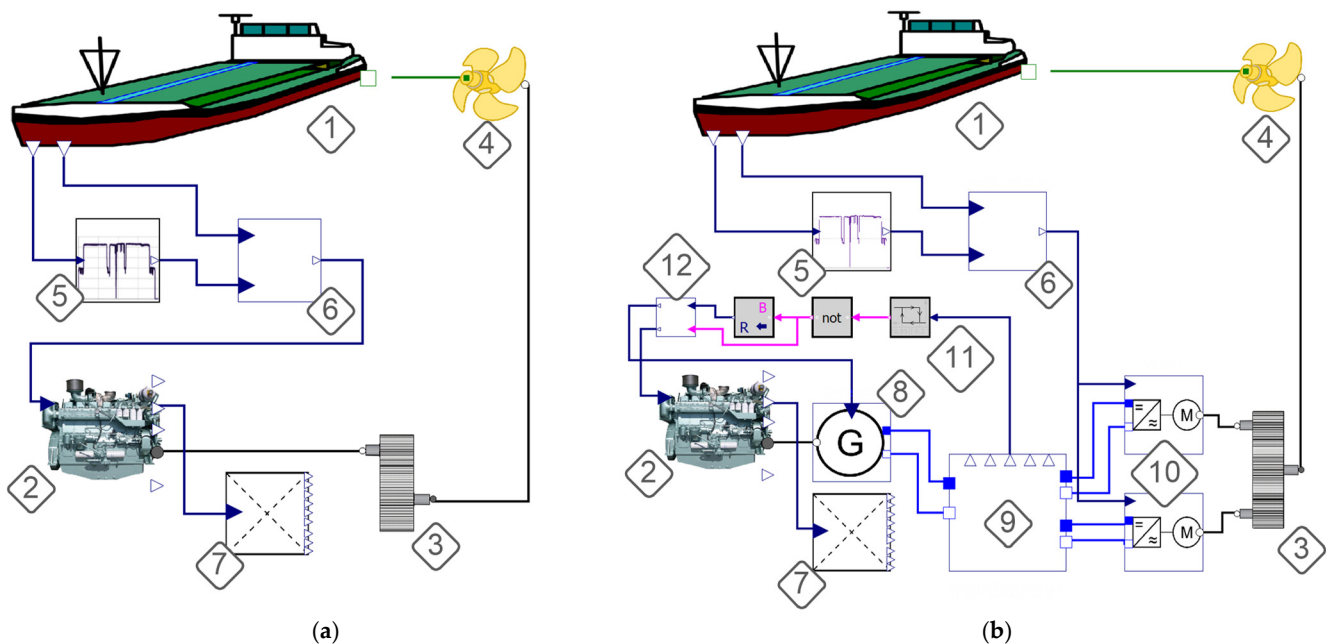


Figure 11. Block diagram of the mathematical model of a barge with a conventional (a) and hybrid (b) propulsion system, made in the Modelica environment.

The OpenModelica environment is a free, open source implementation of the Modelica mathematical modeling language [38]. The Modelica language, including OpenModelica, allows for interactive modeling and simulation of complex dynamic systems. The Modelica language is used in the automotive, aerospace, and energy industries, as well as in many other industrial and research applications. An integral part of the language is the Modelica Standard Library, which allows quick creation of interoperable model elements based on many fields of physics, such as mechanics, electricity, thermal phenomena, and fluid dynamics. In addition to carrying out simulations on complete user models, Modelica also

allows the developed models to work in real time as part of larger research or supervisory systems, with external hardware and software, thanks to appropriate data exchange interfaces. The OpenModelica environment version 1.11 was used in the following research.

The numbers in Figure 11 denote the following: 1—Barge hull block with a model of hydrodynamic resistance and environmental forces, 2—Wärtsilä UD25 V12 combustion engine block, 3—Reduction gear block, 4—Propeller block, 5—Barge speed setting block, 6—Speed controller block, 7—Energy consumption, fuel consumption, and pollutant emission measuring block, 8—DC generator block, 9—main energy store block, 10—PMSM motor and inverter blocks, 11—Energy store charging control blocks, 12—Diesel engine starting block.

Simulation of the operation of the barge with both variants of the propulsion systems was carried out in parallel, and the simulation time was set at 32,000 s. At that time, the main source controlling the simulation was block (5) shown in Figure 11, the input of which received information about the current position of the barge on the route previously simulated in the simulator described in the previous subsection, as well as information about the weather state for each second of the simulation contained in the hull block and resistance models (1). For the variant of the drive system with an energy store, the simulation starts with the store in a fully charged state.

Figures 12–14 show the results of the simulation comparing the operation and fuel consumption of a conventional system with a diesel engine directly driving the screw and in a hybrid system with a buffer in the form of an electrochemical energy store.

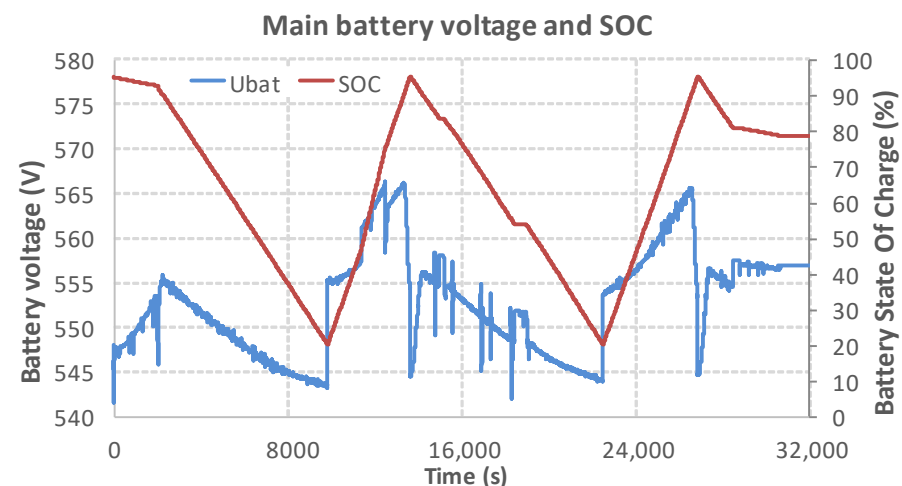


Figure 12. Voltage of the traction battery and its charge status during the simulated cruise.

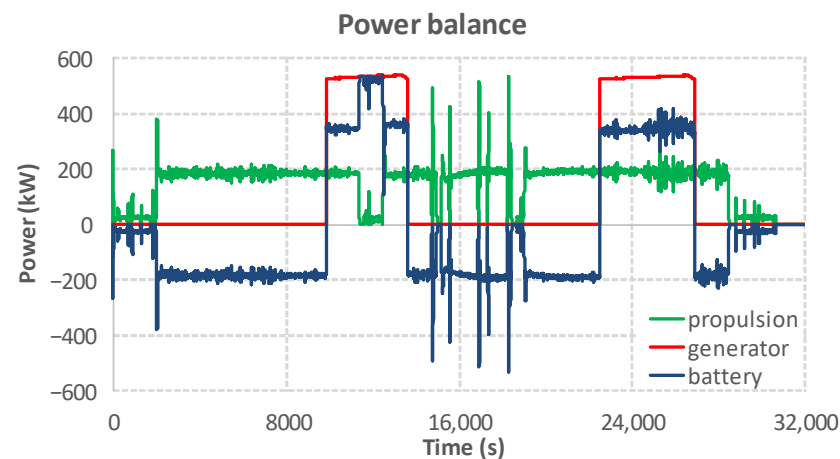


Figure 13. Power balance in the hybrid propulsion system of a simulated autonomous barge. Plots of power consumed by the propulsion system (green), produced in the on-board generating set (red), and flowing through the energy storage (blue).

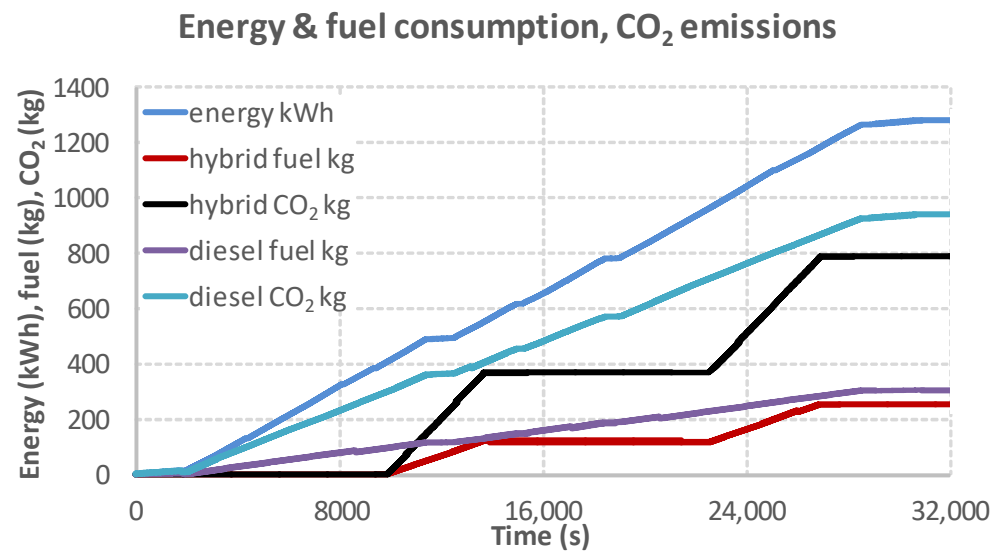


Figure 14. Graph of electricity consumption of the simulated barge propulsion system in kWh (blue), diesel consumption of hybrid barge in kg (red), and CO₂ emissions in kg (black), along with diesel consumption of conventional barge (violet), and its CO₂ emissions (turquoise).

Figure 12 shows the plots of the state of charge (SOC) and the total voltage on the electrochemical cells of the energy store and, consequently, the voltage on the main DC power bus of the simulated barge. In the case of the barge in question, the energy storage uses LFP-type lithium cells with a fairly flat discharge characteristic. Due to this SOC, tracking is done not by voltage levels, but by integrating the current flowing through the energy storage and comparing the result to the nominal capacity expressed in Ampere-Hours.

The rapid changes in voltage that can be observed at the moments of startup (approx. 10,000 s and 22,500 s) and shutdown (approx. 14,000 s and 27,000 s) of the on-board generator are caused by a quick change in the current flowing through the energy storage and the associated change in voltage due to the non-zero internal resistance of energy store cells. Figure 13 shows a graph of three power curves in the barge's hybrid propulsion system. Due to the start of the cruise with a charged energy storage, initially all the power consumed by the propulsion system (green line) is provided by the energy store (blue line). After reaching the minimum preset state of charge level of 20%, the generating set control block starts the engine, which proceeds to charge the energy store at an optimal load of 80% of the rated engine power. During this time, a positive power balance is visible on the energy store power curve, which indicates that the store is being charged with energy from the generator.

Plots illustrating the total energy consumption of the drive system, fuel consumption, and total CO₂ emissions are presented in Figure 14.

The total energy used to drive the barge presented in Figure 14 directly correlates with fuel consumption and the associated carbon dioxide emissions in the case of the conventional drive barge variant. This is, of course, related to the direct connection of the engine to the propeller, which forces the diesel engine to operate all the time while the barge is moving.

In the case of the hybrid drive variant, there is no such requirement, because the energy store serves as a buffer and provides power on the DC bus for the inverters driving the electric motors. Operation of the diesel engine is only necessary after exceeding the set SOC threshold when discharging the energy storage until it is recharged to the set level. The basic source of driving energy in the barge is a diesel engine; however, the use of an energy store with a capacity sufficient for over two hours of operation solely from the energy storage at the typical speed of the barge allows the use of the charging strategy used in Plug-in Hybrid Electric Vehicle (PHEV) cars. If a service enabling the charging of the on-board energy store is available at the destination port, then it is possible to control

the operation of the on-board generating set in such a way that the energy store is almost completely discharged upon arrival at the destination.

This will allow for supplementing energy from shore during cargo unloading/loading, which will not only reduce fuel consumption and associated emissions, but will also reduce costs due to the lower price of energy available from the public grid, than that produced on-board by the diesel generator.

The second, even more flexible option for replenishing energy is to install an energy store in a separate 20' intermodal container placed on the deck of the barge. This makes it possible to quickly replace a discharged container with a fully charged one within a dozen or so minutes, using a standard port crane designed for handling intermodal containers. The exchange procedure may take place at the port during cargo loading/unloading, or even at other points during the journey, e.g., while waiting at the water locks.

Replacing a containerized energy store achieves several benefits. The first is limiting the downtime of the barge itself due to replacement operation, which is comparable to, or even shorter than, the refueling time. The second advantage is the reduction in requirements for the connection power of the shore charging infrastructure, due to the possibility of charging with energy generated locally, using renewable energy sources. The third benefit is the possibility of using the containers waiting in the port as an energy buffer, in the event of a power failure in the public network or another case of power outage.

Table 2 shows a comparison of the simulation results for a drive system with a conventional configuration and the proposed hybrid drive system with energy storage.

Table 2. Performance comparison between conventional and hybrid barge propulsion systems.

Parameter	Conventional Diesel	Hybrid Electric	Difference
Engine working hours	8.06 h	2.27 h	−71.81%
Engine average load	32.59%	80.31%	−
Energy consumed for propulsion	1280.47 kWh	1280.47 kWh	−
Fuel consumption	305.48 kg	256.49 kg	−16.04%
CO ₂ emitted	939.80 kg	789.09 kg	−16.04%

A clear difference in the operating time of a conventional drive unit and a generator set in a hybrid solution arises due to the operation of the energy store as a buffer, which is active throughout the operation of the drive system. This also translates into an increase in the average load to 80%, which ensures maximum efficiency of converting the chemical energy of the fuel into electricity. The small deviation (+0.32%) from the set value of 80% results from the need to start the drive unit twice during the simulated voyage.

In the modeled example, carbon dioxide emissions are calculated based on the equivalent amount of burned diesel fuel, which translates into an identical decrease in both fuel consumption and CO₂ emissions.

The use of an on-board diesel engine to drive a generator powering the energy storage, instead of directly driving the propeller, allows the engine to operate only during periods when energy supplementation is required, with the optimal load level at 80% of the rated power. This eliminates idle or severely underpowered operation of the engine and its operation in the range of suboptimal loads. Figure 15 shows a comparison of the rotational speed of the engine used to directly drive the propeller in a conventional barge propulsion system, and the rotational speed of the same engine driving the generator in a hybrid propulsion system.

An additional advantage of the hybrid system in the given example is the reduction in the operating time of the diesel engine by over 71%, which results in the extension of the periods between engine overhauls, and the reduction in its operating costs.

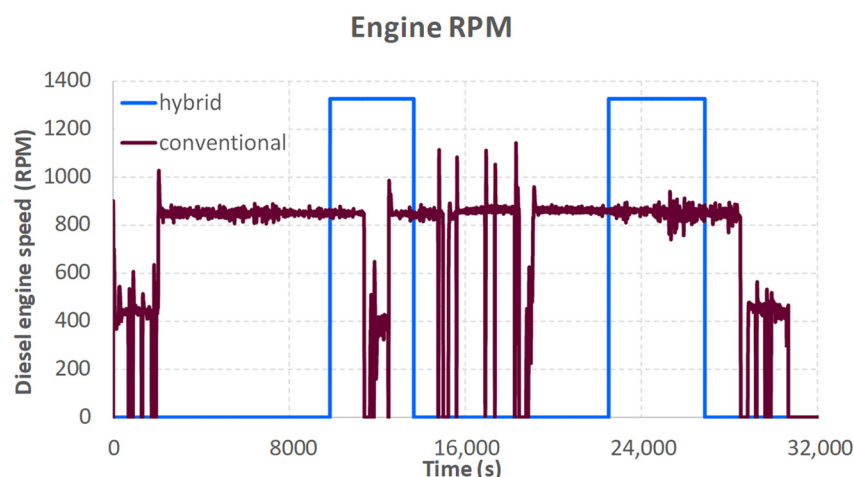


Figure 15. Comparison of the rotational speed of diesel engines in the model with a conventional drive (purple) and in the model with a hybrid drive (blue).

4. Discussion

A two-tiered simulation tests of the proposal for an autonomous category IV inland barge were carried out. Data regarding the geometric dimensions of the barge and the power of the installed machines were derived from actual inland vessels. The first phase of the research focused on the autonomous movement of the barge in navigationally constrained environments, such as inland waters and artificial channels. This involved recording movement parameters and comparing them with a real vessel undertaking a similar journey. This phase was executed using a network ship traffic simulator.

In the second phase, the simulated operational data were utilized to perform mathematical modeling of the drive system in the Modelica environment. Two variants of the barge propulsion system were examined: a variant with a conventional diesel drive and a hybrid drive that incorporated an electrochemical energy storage system, reflecting the latest trends in the field.

As a result of research on the ship traffic simulator, the data were obtained in which the simulated vessel covered the route between the same waypoints, covering a distance that was 3.2% shorter than that of the actual vessel, as a result of more accurate navigation. The total route taken by the simulated vessel was 122.4 km long, with the reference real vessel travelling 126.3 km.

Based on these studies, mathematical modeling of the operation of two variants of drive systems was carried out, combined with tracking their fuel consumption and CO₂ emissions. The results obtained showed that the hybrid system not only reduced fuel consumption and pollutant emissions by over 16%, but also reduced engine operating time by over 71%.

These benefits are possible thanks to the use of a buffer in the form of an electrochemical energy store with a useful capacity of 430 kWh, which can be installed in a removable 20' container. The energy of the batteries used and their weight can be increased more than three times before the maximum permissible capacity of a typical 20' container is exceeded, which may allow for longer routes with a smaller share of the on-board generator and, in extreme cases, even for completely emission-free operation through the use of renewable energy sources for charging replaceable containers containing an energy store.

Table 3 shows a comparison of operational parameters and environmental impact with respect to tonne-kilometers travelled by both barges considered in the paper.

Table 3. Comparative analysis of operational parameters and environmental impact between conventional diesel and autonomous hybrid electric inland motor barges.

Parameter	Conventional Diesel	Autonomous Hybrid Electric
Cargo capacity	1300 t	1300 t
Required crew	2 or 3	0
Distance travelled	122.4 km	122.4 km
Tonne-kilometers	159,120	159,120
CO ₂ emission per tkm	5.91 g CO ₂ /tkm	4.96 g CO ₂ /tkm
Tkm per 1 kg fuel	520.89 tkm	620.38 tkm
Corrected CO ₂ emission per tkm *	6.10 g CO ₂ /tkm	4.96 g CO ₂ /tkm
Corrected Tkm per 1 kg fuel *	504.73 tkm	620.38 tkm

* increased/decreased by 3.2% due to less precise navigation by crew.

Considering both barges are able to carry the same amount of cargo, they can be compared in terms of fuel consumption and CO₂ per tonne-kilometer (tkm) travelled. Tonne-kilometer is a useful unit for comparing different modes of transport, and is defined as transporting one tonne (1000 kg) of goods including packaging over a distance of one kilometer.

The CO₂ emissions per tkm and tkm achieved per 1 kg of diesel fuel for a crewed, conventional propulsion barge are corrected by a factor of 3.2%, with emissions increased and tkm per 1 kg of fuel decreased accordingly in the last two lines of Table 3. This represents the positive impact of employing an autonomous navigation system, which can navigate a slightly shorter route between the same waypoints, due to better control over the ship's movement and its reactions from the environmental forces.

5. Conclusions

The future of European inland waterway transport in light of upcoming new transport requirements is sure to change. The volume of goods transported by barges will probably rise due to a shift in focus, from road transport to rail and inland waterway transport, as described in the Mobility Strategy [6].

The future fleet of inland ships will probably contain a least a part of the presently active vessels, mostly due to high demand on such vessels and the resulting postponement of their scrapping. The advanced capabilities such as autonomous operation will surely be the domain of newly built vessels, but retrofitting a hybrid electric drive, such as the one described in this paper, could be profitable both for the shipowners and the companies providing the retrofit service.

However, the implementation of such advanced technologies also presents challenges. These include the need for a robust legal framework to govern the operation of autonomous vessels, the technical requirements for retrofitting existing vessels, and the potential resistance from stakeholders in the industry. Future research could focus on addressing these challenges and exploring ways to facilitate the wider adoption of autonomous electric propulsion barges in inland waterway transport, as one of the ways of fulfilling the sustainable transportation goals.

The transition from a manned inland barge with conventional diesel propulsion to an autonomous hybrid propulsion barge presents a case of cargo capacity equivalence. In a conventional manned barge, a significant portion of the vessel's volume and mass is dedicated to crew facilities such as living quarters, the bridge, and other amenities. However, in an autonomous barge, these facilities are superfluous, and liberated deck space and weight can be utilized for other components or additional cargo space. The energy store, for instance, can be installed in a removable 20' container on the ship's stern deck, where in a manned barge the crew quarters and bridge would be located.

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