TRANSNAV
http://www.transnav.eu
the International Journal on Marine Navigation and Safety of Sea Transportation
Volume 12
Number 2
June 2018
DOI: 10.12716/1001.12.02.05

Evaluation of the Possibility of Using Hybrid Electric-Propulsion Systems for Inland Barges

A. Łebkowski
Gdynia Maritime University, Gdynia, Poland

ABSTRACT: The paper presents issues related to the possibility of using an electric propulsion system for inland craft, in this particular case self-propelled barges. Perspectives for development of inland water transport in Poland are presented. Historical engineering designs used in water transport at the turn of the 19th and 20th centuries are shown. The current status of stock used in inland navigation along with the condition of waterways available in Poland is presented. Energy consumption by inland craft using various configurations of propulsion systems is discussed, along with comparison of energy consumption during transport of goods using road transport, rail transport and inland waterway transport. In addition to the hybrid electric and diesel propulsion systems, the alternative is to use the electric rail mules for moving the barges.

1 INTRODUCTION

The need to reduce the negative impact of road transport on the environment is the basis for considering the concept of reconstruction of inland transport.

In 2017 Poland ratified the AGN Convention, it indicates the direction of development of the inland waterway network in Europe [1,2]. The AGN Convention - The European Agreement on Main Inland Waterways of International Importance, which was concluded in Geneva on 19 January 1996. AGN's goal is to introduce a regulatory framework that will establish a coordinated plan for the development and construction of inland waterways networks of international importance and established infrastructure and operational parameters. The AGN Convention covers an inland waterway network of a total length of more than 27,000 km, connecting 37 European ports [3].

There are three sections of international waterways in Poland (Fig.1):

- E30 - connecting the Baltic Sea from the port of Swinoujscie through the Oder, the future Danube-Odra-Elbe Canal through the Danube to Bratislava,
- E40 - connecting the Baltic Sea from Gdansk via Vistula to Warsaw, Narew and Bug to Brest and further through the Dnepr to the Black Sea in Odessa,
- E70 - connecting the Odra River from the estuary of the Odra-Havel Canal to the Warta estuary in Kostrzyn, via Bydgoszcz, the Lower Vistula and Szkarpawa or the Vistula River to the Vistula Lagoon, creating a European waterway route between Rotterdam and Klaipeda [1-3].

By ratifying the AGN Convention, Poland has committed itself to upgrading the main waterways to at least IV class of navigability. Table 1 shows the inland waterway operating parameters. Waterways of Classes Ia, Ib, II and III have been classified as of regional importance, while classes IV, Va, Vb as of international importance [4].

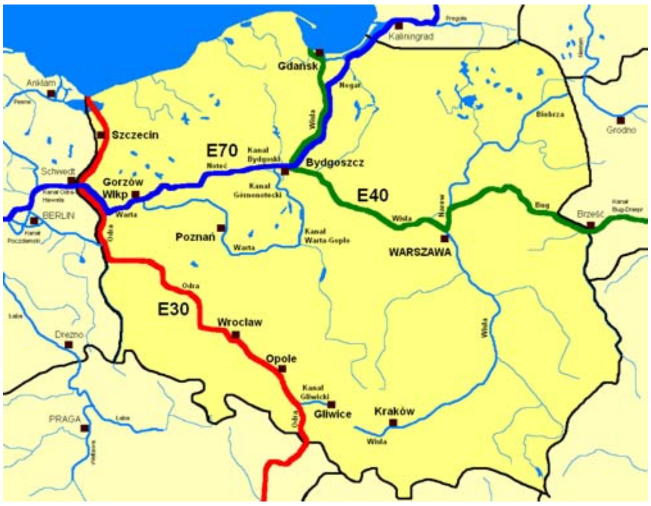

Figure 1. Planned waterways in Poland [2]

Table 1. Classification of inland waterways [4]

Waterway class	Waterway width [m]	Transit depth [m]	Minimum clearance under bridges [m]	Clearance under power lines [m]	Max. ship / barge length [m]	Max. szerokość statku/barki [m]	Max. ship / barge width[m]	Max. ship / barge gross tonnage [t]	Sluice width [m]	Sluice length [m]
Ia	15	1,2	3,0	8	24	3,5	1,0	<180	3,3	25
Ib	20	1,6	3,0	8	41	4,7	1,4	180	5,0	42
II	30	1,8	3,0	8	57	9,0	1,6	500	9,6	65
III	40	1,8	4,0	10	70	9,0	1,6	700	9,6	72
IV	40	2,8	5,25	12	85	9,5	2,5	1500	12,0	120
Va	50	2,8	5,25	15	110	11,4	2,8	3000	12,0	120
Vb	50	2,8	5,25	15	185	11,4	2,8	>3000	12,0	187

At present there are 3655km of waterways in Poland, of which 2417km are regulated navigable rivers, 644km of channeled sections of rivers, 336km of canals, and 259km of navigable waters. About 92% of accessible waterways (3365km) are used in shipping. Unfortunately, the requirements for Class IV and V waterways in 2015 were met by only 5.9% of waterways (214km). The remaining 94.1% of waterways (3441 km) were in classes I, II and III [5].

Plans of the Polish government included in the regulations are forcing designers of new waterways to build them in the highest possible class Vb.

An important element in the implementation of inland waterway transport is the quality of stock in inland navigation. According to the Central Statistical Office in Poland, in 2015 in operation there were: 217 pusher and tugboats, 89 self-propelled barges, 511 barges and 101 passenger ships. The majority of operated units, namely 73.0% of pushers, 48.7% of pushers, 100% of self-propelled boats, were build between 1949 and 1979. The insufficient use of waterways in Poland causes the share of inland waterway transport in total transport in 2000-2015 to decrease from 0.8% to 0.4% [5].

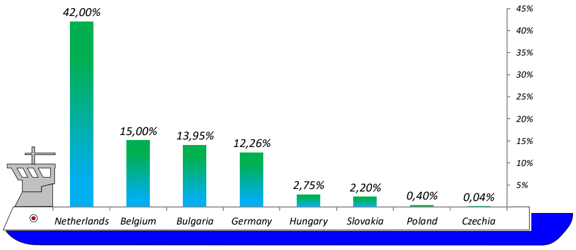

Figure 2. Volume of inland waterway transport [2]

In Poland, it is planned to transfer about 30% of road transport of goods at distances of more than 300km, to water or rail transport by 2030 and 50% by 2050 [2] (Fig.2, Fig.3).

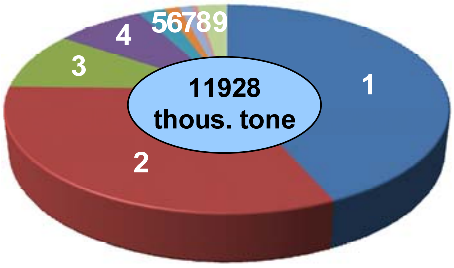

Figure 3. Structure of transported goods by inland waterway in 2015, where: 1–Agricultural products; 2–Metal ores and other mining products; 3–Coal, lignite, crude oil, natural gas; 4–Secondary (recycled) raw materials, municipal and other waste; 5–Non-metallic products; 6–Chemicals and chemical products; 7–Metals, finished metal products; 8–Coke and refined petroleum products; 9–Other; [2].

When comparing the energy consumption for each mode of transport, inland transport is most beneficial. According to the Ministry of Development, one ton of cargo using an inland vessel using internal combustion engines can be transported at a distance of 370 km, using rail transport at a distance of 300 km and a 100 km wheeled transport [2].

From the information presented above, it is clear that inland waterway transport has a huge potential, which, unfortunately, needs to be stimulated by investing considerable resources in both technical infrastructure and floating stock. Being on the verge of realizing the task of reconstruction of inland waterway transport in Poland, a question worth asking is: Isn't using electric or hybrid power transmission systems on inland transport vessels a good idea? One of the proposals for propulsion for the barge is the possibility of using electric tracked towing vehicles – called electric mules (EM).

2 HISTORY OF ELECTRIC INLAND TRANSPORTATION

The oldest waterways were built in Mesopotamia around 4,000 BC, in Girnar 3000 years BC, in India 2600 years BC, in Egypt 2300 years BC, and in China 500 years BC. The first sluices regulating the flow of water were already used by the Greeks in the third century BC. The canals and rivers were eagerly used to transport wood and other goods initially propelled by the strength of human muscles and the river current, and with the development of steam, diesel and electric engines. The medieval period was the time when water transport was several times cheaper and faster than land transport.

In the 10th century the Glastonbury Canal was built in the United Kingdom, with a length of 1750m, which was used to transport construction stone, grain, wine and other products up to the fourteenth century. At the same time, water and canals were developed around the world. The development of canal infrastructure continued until the end of the 19th century when the rapid growth of rail transport and later on the road. The most famous channels are Panama Channel (1920, length 80km), Suez Channel (1869, 163km long), Kiel Channel (1895, length 98km), and Corinthian Channel (conceived from the antiquity, but built in the late 19th century (1893, 6.3km in length).

For goods transport by inland waterways, barges without propulsion were used, towed by pushers or tugs, and self-propelled barges. In the initial phase of inland transport for the propulsion of rafts, barges and boats, animal teams were used that moved parallel to the towed unit along the canal or river (Fig.4).

Figure 4. Animal carriages used for moving barges [6].

With the development of technology, horses and mules were replaced by engine powered tractors and then with rail tractors, which were powered from the electric traction network (Fig.5).

Figure 5. The truck and rail tractor used to move the barges [6].

At the beginning of the twentieth century, the electric propulsion systems of barges could be divided into:

– Manned and unmanned electric locomotives (mules), moving on rails along the bank of the waterway and towing a floating unit via a towline (Fig.6).

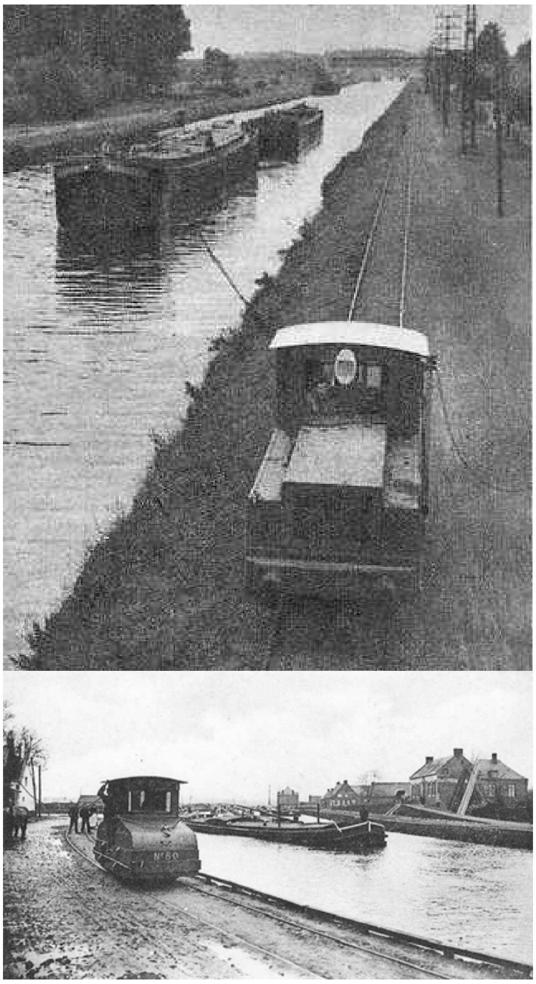

Figure 6. Example of electric rail tractors used for moving barges [6].

– Self-propelled electric tractors mounted along waterways, powered by electric traction and moving on ropes installed on columns. The most famous of those days were the Lamb (Fig.7) and Zinzins systems.

Figure 7. Example of an unmanned electric tractor system designed by Richard Lamb at the end of the 19th century [6].

– Vessels powered directly by overhead line trolley, using on-board electric motor to tow the vessel along a submerged chain (Fig.8).

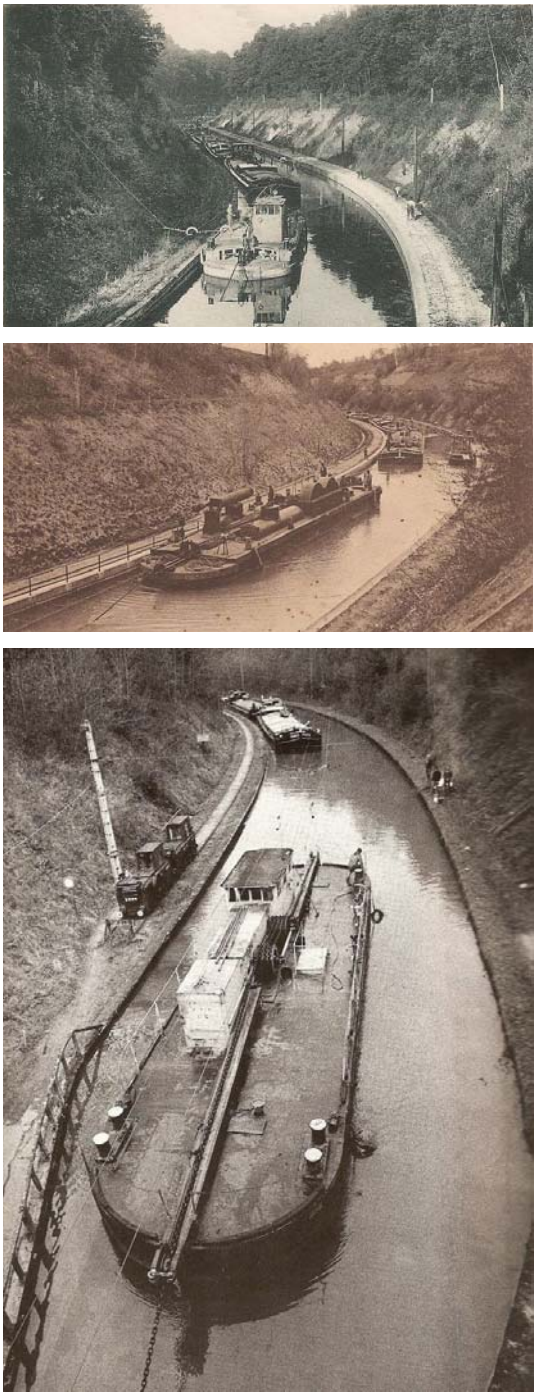

Figure 8. Examples of electric traction and submerged systems along the waterway [6].

– Vessels powered directly by overhead line trolley, using on-board electric motor to power conventional propeller system (Fig.9).

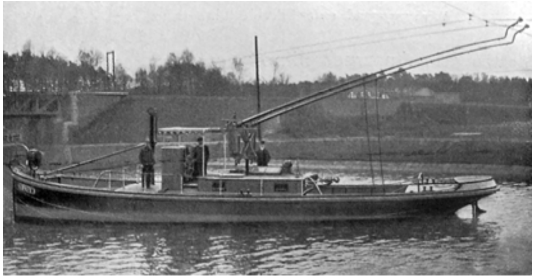

Figure 9. Example of electric rail tractors used for moving barges [6].

Some of the presented solutions are used in France, Germany, the United States and Great Britain to this day, like the current collector designs engineered in those days (Fig.10) [7].

Figure 10. An example of electric propulsion systems from the beginning of the twentieth century used for the present time [8,9].

3 COMPARISON OF TRANSPORT COSTS

The energy consumption figures gathered during the use of various types of wheeled, rail or intermodal vehicles used in intermodal freight transport, confirm that inland water transport is energy efficient and environmentally friendly [10-12]. Even more energy efficient and environmentally friendly compared to all means of transport is sea transport. It is estimated that the medium barge capacity (54 TEU), having approximately 85 m in length, 9.5 m in width and 2.5 m in draft, is approximately 15 times larger than the 4 TEU rail car and 27 times that of containers hauled by truck with semi-trailer (2 TEU) [1,2,4,10-12]. According to the materials published by the European Commission in 2003 on energy efficiency, for each liter of burnt diesel, the barge can transport a tonne of cargo at a distance of 127 km, a train can do the same at a distance of 97 km, and a truck at 50 km (Fig.11) [10,11].

Figure 11. Efficiency of consumption of 1 liter of diesel used for the transport of 1 ton of cargo by various means of transport [10].

11 years later on the Wasserstraßen- und Schifffahrtsverwaltung des Bundes website, other values are presented. According to information from 25.09.2014, an inland vessel with a length of 80 ÷ 85m and a width of 9.5m, is capable of using one litre of diesel fuel to transport 1 tonne of cargo at a distance of 370 km, the same cargo transported by rail using the same amount of fuel can be transported on the distance is 300 km and in the case of semi-trailer truck it's 100 km (Fig.12) [12].

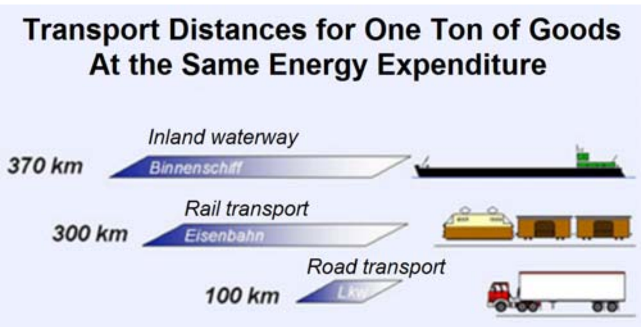

Figure 12. Transport distances for one ton of goods at the same energy expenditure [12].

The Polish Ministry of Development in 2016 presented the same statistics, stating that an inland vessel with a length of 80 ÷ 85 m and a width of 9.5 m, is able to transport one tonne of cargo using one liter of diesel fuel over a distance of 370 km, the same can be accomplished by rail transport over a distance of 300km and in case of truck over 100km [1,2,4]. In addition, both ministries report that CO2 emissions are 164 g/tkm for road transport, 48.1 g/tkm for rail transport, and 33.4 g/tkm for inland waterway transport (Fig.13).

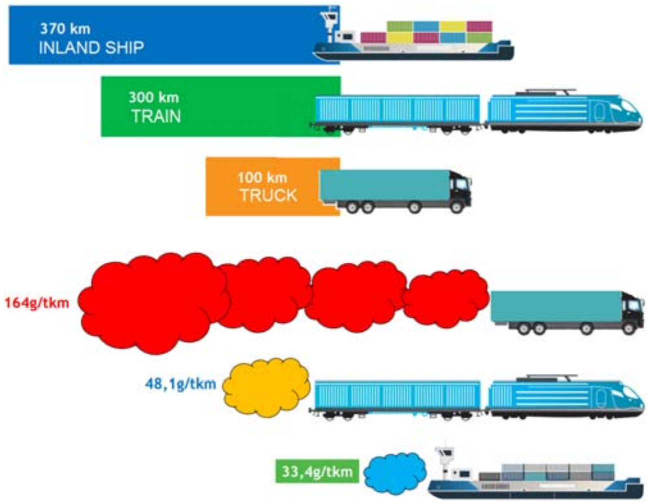

Figure 13. Inland waterway transport advantage [1,2,4].

Based on independent data and simulation and model studies [13-30], energy efficiency and CO2 emission levels were measured for inland, rail and road transport. The data is shown in Figures 14 and 15.

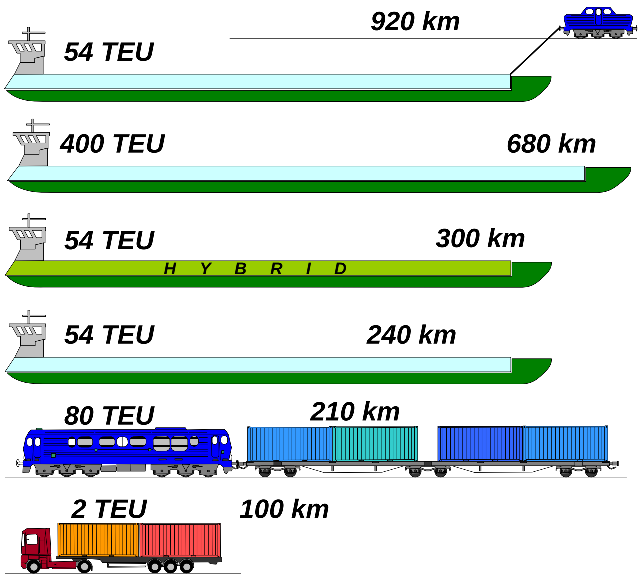

Figure 14. Efficiency of utilization of 1 liter of diesel for transport of 1 ton of cargo through various means of transport.

Based on the data presented, it can be said that the most advantageous situation happens when transporting goods using a large barge (400 TEU) with a capacity of about 10,000 tons. However, such a vessel, due to its size, can navigate only on waterways meeting category VIb criteria. Unfortunately, such inland roads are not currently located in Poland (class Vb at most).

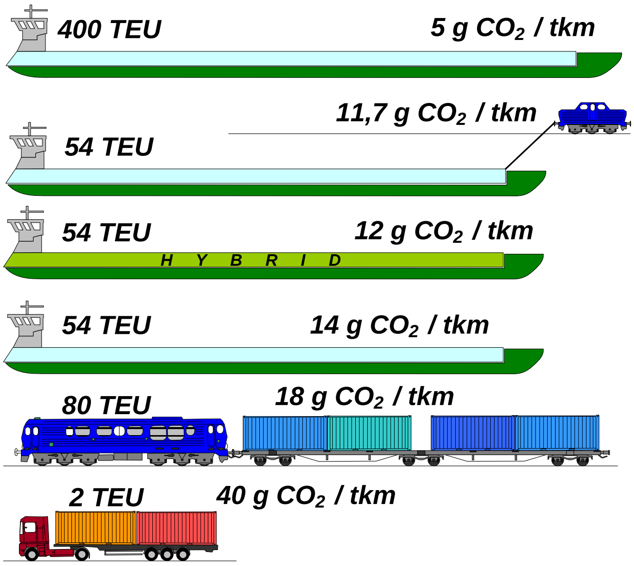

Figure 15. CO2 emissions by different means of transport in grams per tonne-kilometer.

More preferably, the situation would be for a system in which such a barge (400 TEU) would be powered by an electric propulsion system or pulled by an on-shore mule powered from overhead traction wires. However, the suggested solution would require building along the waterway a whole electric network along with the tracks. The conducted tests on a small barge (54 TEU equivalent) showed that the hybrid system produced 20% better results than the identical diesel fueled barge [21]. Of course, the barges move much slower than trucks or trains, but at the same time the cost of transport calculated without transshipment is the lowest compared to other intermodal transport systems.

4 PROPOSED ELECTRIC BARGE DRIVE SYSTEM

For the propulsion of the barge, it is proposed to use a hybrid electric propulsion system. Considerations for the application of the propulsion system were made for a barge model with a displacement of about 1850 tons (54 TEU). Model study of barge boat hull resistance was performed using DELFSHIP software (Fig.16) [19].

For the assumed geometric shape of the hull, the required tow capacity required to overcome barge resistance at a given swim speed was determined by the dependence:

$$P_T = R \cdot V \tag{1}$$

where:
P_T - towing power [kW]
R - barge resistance [kN]
V - barge speed [m/s]

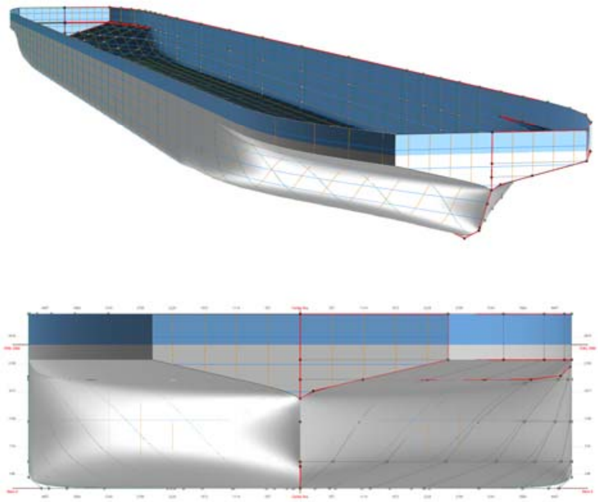

Figure 16. Design of hull barge realized in DELFSHIP [19].

The total value of barge resistance consists of resistance values related to its speed of movement, geometric dimensions and hull shape. These factors affect the hydrodynamic resistance of the hull against water (R_{AH}), the wave resistance and residual resistance (R_R), and the aerodynamic resistance of surface elements of the hull (R_A)

$$R = R_H + R_R + R_A \tag{2}$$

Knowing the value of towing power and resistance,one can determine the power output of the electric motor used to drive the unit. To determine the power output of the power unit, it is necessary to know the efficiency of the transmission system, which consists of the efficiency of the hull barge (0,6 ÷ 1), efficiency of the shaft line (0,9 ÷ 0,99), rotational efficiency (0,95 ÷ 0.99) and the free running screw efficiency (0.35 ÷ 0.75).

$$P_{EM} = \frac{P_T}{\eta \cdot \eta_H} = \frac{P_T}{\eta_S \cdot \eta_R \cdot \eta_{RP} \cdot \eta_H} \tag{3}$$

where:
P_{EM} – power output of electric powertrain [kW]
P_T – towing power [kW]
η – drive train efficiency
η_H – barge hull efficiency
η_S – shaft efficiency
η_R – rotational efficiency
η_{RP} – free running propeller efficiency

In order to properly select the power of the electric drive system, the efficiency of the various power transmission components must be taken into account (Fig.17). For the vessel under consideration, the electrical power of the propulsion system will be approximately 840 kW, with a maximum speed of 22 km/h. When choosing the propulsion system power, it is important to keep in mind that the barge should move at a safe speed, adapted to the existing navigational and atmospheric conditions. Barge speed cannot pose any danger to other ships or waterway users. For this reason, the speed with respect to the edge of the waterway is the most commonly used, and is set for rivers and canals at the level of 5-8 km/h (upstream) and 10-12 km/h (downstream). On other reservoirs such as lakes or lagoons, the speed may be higher and reach up to 15 km/h. In situations where the boat's power train will not have sufficient power, travel upstream will not be possible and, in addition, such a craft would pose a risk to crew members and other units moving in that area.

It should be noted that for the barge propulsion system with the use of electric mule in Polish conditions (maximum current of the fastest river in Poland - Vistula, during the rains is 10 km/h, with the average state of about 6 ÷ 7 km/h). The power needed to move the barge in these conditions would be about 4.5 times smaller and on the order of 180 [kW].

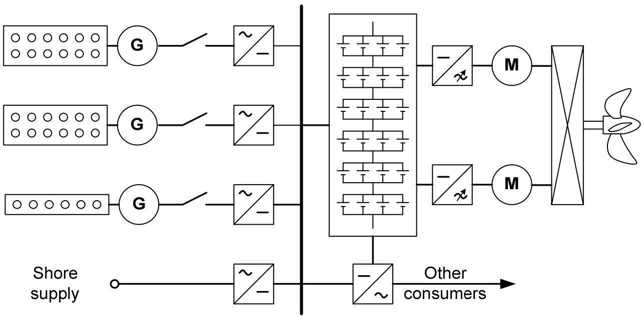

Figure 17. The structure of the hybrid Diesel-Battery-Electric-Propeller barge.

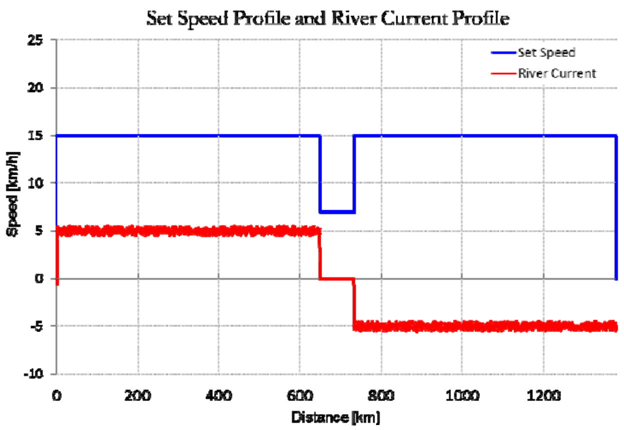

Figure 18. Assigned predetermined barge speed profile for the test route section.

Figure 19 shows the results of energy consumption associated with the motion of the barge on a given test route for Diesel-Propeller (DP); Diesel-Battery-Electric-Propeller (DBEP), and Electric Mule (EM).

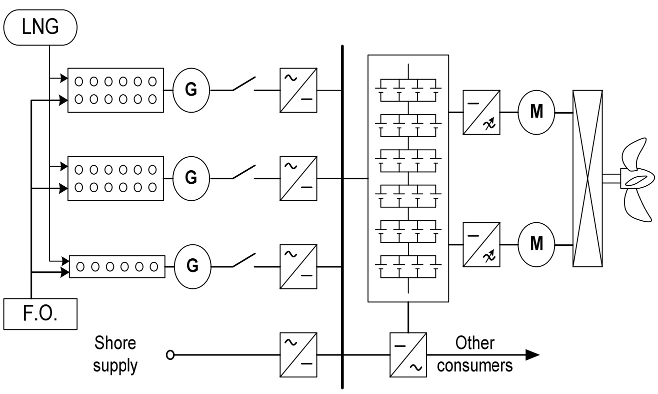

Figure 19. Plot of energy released from fuel for various powertrain configurations on the same route test.

Figure 20 shows the CO2 emissions associated with the motion of the barge on a given test route depending on the powertrain tested.

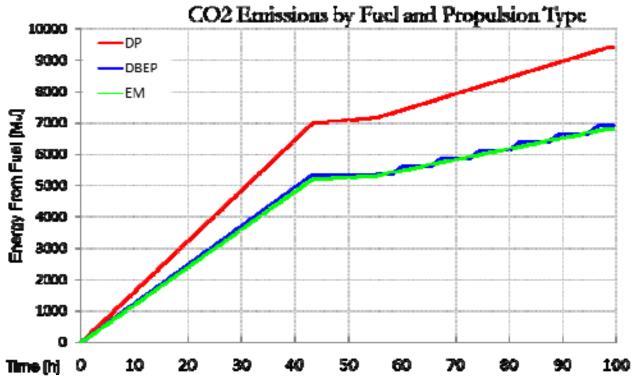

Figure 20. Plot of CO2 emissions by fuel for various powertrain configurations on the same route test.

Figure 21 shows the costs associated with the motion of the barge on a given test route depending on the powertrain tested: DP, DBEP, EM.

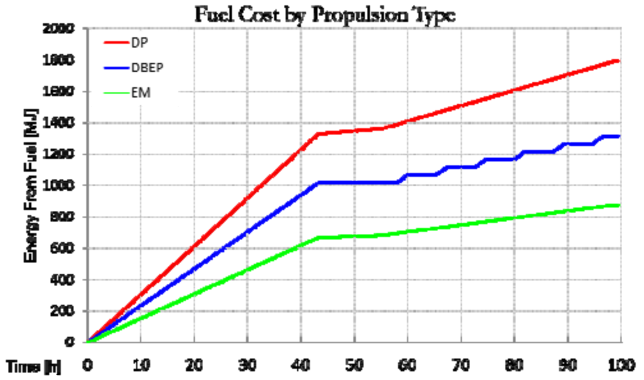

Figure 21. Plot of fuel cost for various powertrain configurations (DP, DBEP, EM) on the same test route.

Figure 22 shows an example of the energy flow parameters of the Diesel-Battery-Electric-Propeller hybrid drive system during the cruise on the test route.

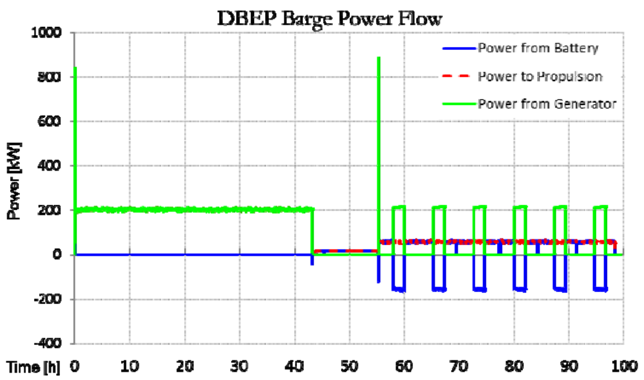

Figure 22. Plot of power flow in the DBEP powered barge while cruising the modelled test route.

Figure 23 illustrates some of the parameters associated with the barge propeller speed that translates into the inland barge speed over ground on the test route for the Diesel-Battery-Electric-Propeller hybrid drive.

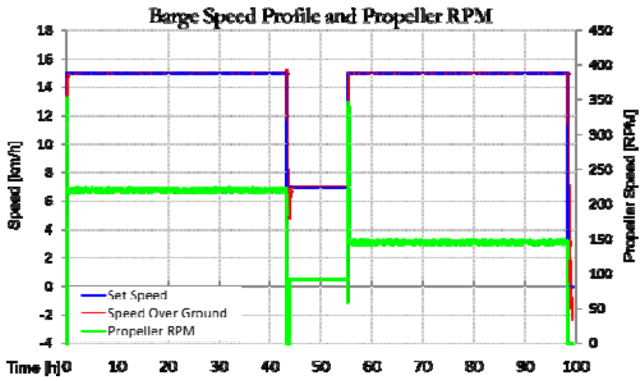

Figure 23. Plot of set speed, actual speed and propeller RPM in DBEP powered barge while cruising the modelled test route.

Figures 24 and 25 illustrate the electrical parameters connected with the hybrid propulsion DBEP of battery pack, such as voltage, state of charge, battery current, propulsion power.

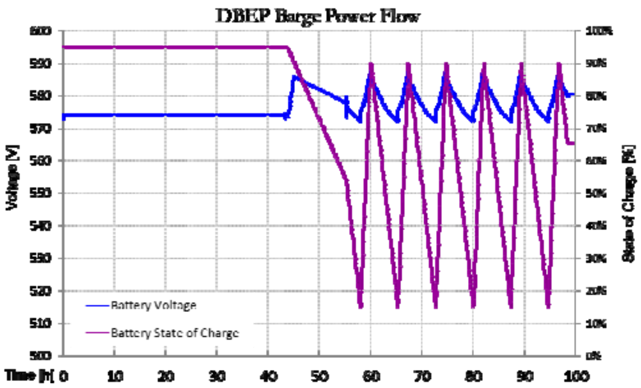

Figure 24. Plot of voltage and state of charge of battery pack of the hybrid propulsion DBEP

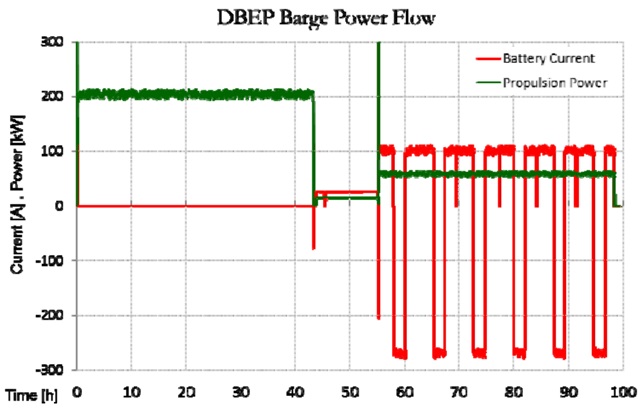

Figure 25. Plot of battery current and propulsion power of the hybrid propulsion DBEP

5 CONCLUSIONS

- The results of energy efficiency analyzes show that the smallest energy consumption in the intermodal transport group can be achieved by barge transport. In addition, these coefficients could be further improved by using hybrid or electric propulsion systems on board or with land mules.
- The use of a hybrid diesel engine (Diesel-Battery-Electric-Propeller) is beneficial for the versatility of the use of the barge in various water bodies. Using a battery pack can help reduce energy consumption, especially when operating downstream of river, or using an electric mule.
- The use of a hybrid propulsion system for barges is beneficial for protecting the environment by significantly limiting greenhouse gas emissions and the energy required to drive the barge. In addition, the use of a battery pack to reduce the GHG emissions during maneuvering, maneuvering in quiet areas, and other areas where gaseous emissions and engine noise are undesirable.
- The use of Electric Mule reduces the cost of transportation of goods on barges. Considering the relatively high CO_2 emission indices (798 kg CO_2/MWh [17]), using EM, this GHG can be reduced by about 25% compared to conventional flue systems.
- Inland water transport is ideally suited for the carriage of non-fast-moving, moisture-insensitive and bulk loads.
- The disadvantage of inland waterway transport in Poland is the poor quality of waterways, lack of infrastructure, and dependence on water conditions and hydrometeorological conditions (freezing in winter, low water levels during the summer).
- To make full use of the inland waterway transport potential in Poland, many costly investments in infrastructure and maintenance of waterways are required. However, this investment can launch a powerful potential present in Polish waterways and turn to economic, tourist, social and environmental growth in a quick period of time.

REFERENCES

[1] MGMiŻŚ, Założenia do planów rozwoju śródlądowych dróg wodnych w Polsce na lata 2016-2020 z perspektywą do roku 2030. Monitor Polski, Dziennik Urzędowy Rzeczypospolitej Polskiej, Poz. 711, Uchwała Rady Ministrów z 14.06.2016r., http://isap.sejm.gov.pl/

[2] Ministerstwo Rozwoju, Założenia do planów rozwoju śródlądowych dróg wodnych w Polsce na lata 2016-2020 z perspektywą do 2030 roku, http://ungc.org.pl/wp-content/uploads/2016/04/26042016_Prezentacja_ Ministerstwo_Rozwoju.pdf, (04.2016).

[3] Ratification of the Convention, in the opinion of the Polish expert 3.0 AGN Jacob Stonawski. www.polska-3-0.pl, (11.2016).

[4] Rozporządzenie Rady Ministrów z 07.05.2002r. w sprawie klasyfikacji śródlądowych dróg wodnych. Dz.U. Nr 77, Poz.695, załącznik 1÷3.

[5] Główny Urząd Statystyczny, Transport wodny śródlądowy w Polsce w 2015 r., http://stat.gov.pl/ (08.2016).

[6] DeDecker K., Trolley canal boats. Low-Tech Magazine, www.lowtechmagazine.com, (12.2009).

[7] Geschichte des Oberleitungsbusses. www.wikiwand.com, (02.2017).

[7] Le tunnel de Mauvages. www.bordabord.org, (12.2009).

[8] Sheller A., Le tunnel fluvial de Mauvages : un ouvrage de 4 877 mètres, accessible qu'aux plaisanciers et aux bateaux de commerce. www.allboatsavenue.com, (12.2013).

[9] Le tunnel de Riqueval et son toueur à Bellicourt. www.petit-patrimoine.com (11.2016).
[10] Inland Waterway Transport. European Commission, Energy and Transport DG, ISBN 92-894-4344-8, 2003.
[11] Piekarski L., Annex D, Statistical Approach to Inland Waterway Transport. European Conference of Ministers of Transport. ISBN 92-821-1354-x, ECMT 2006.
[12] Binnenschiff und Umwelt, Das Verkehrssystem Binnenschiff / Wasserstraße ist umweltfreundlich, kostengünstig und sicher, www.wsv.de/Schifffahrt/Binnenschiff_und_ Umwelt/index.html, (25.09.2014).
[13] Nicholas L., Do CSX Trains Really Move 1 Ton of Cargo 400 Miles on 1 Gallon of Fuel?, The Center for Transportation and Livable Systems (CTLS). www.ctls.uconn.edu, (28.02.2013).
[14] Holly A., The Nation's Freight Railroads Now Average 480 Ton-miles-per-gallon. Assciation of American Railroads. www.aar.org, (22.04.2010).
[15] Fuel consumption by trucks - Specifications www.truckmania.pl/content/view/168/6/
[16] Wasilewicz W., Research electricity consumption for the purpose of traction. Przegląd kolejowy elektrotechniczny nr. 9/1974.
[17] The National Centre for Emissions Management (KOBiZE). CO2 Benchmark for Energy End-use. www.kobize.pl (02.2017)
[18] Dünnebeil F., Lambrecht U., Fuel efficiency and emissions of trucks in Germany - An overview. IFEU-Institute Heidelberg 2012
[19] Delftship Marine Software. www.delftship.net
[20] Papanikolaou A., Ship Design. Springer Netherlands 2014. DOI 10.1007/978-94-017-8751-2
[21] Bach R., Reduzierung des Dieselverbrauchs und der CO2-Emission durch Diesel-direkten Hybridantrieb. (04.2015)
[22] Flämig H., Luft- und Klimabelastung durch Güterverkehr. www.forschungsinformationssystem.de (03.2016)
[23] Mittelweseranpassung Das Großmotorgüterschiff setzt neue Maßstäbe. www.nba-hannover.wsv.de
[24] Gierusz W., Łebkowski A., The researching ship "Gdynia". Polish Maritime Research, Vol. 19, 2012, p.11-18.
[25] Gierusz W., Simulation model of the shiphandling training boat "Blue Lady". IFAC Conference on Control Applications in Marine Systems Location. IFAC Proceedings Series, 2002, p.255-260.
[26] Gierusz W., Tomera M., Logic thrust allocation applied to multivariable control of the training ship. Control Engineering Practice, Vol. 14, Issue 5, 2006, p.511-524.
[27] Lisowski J., Computational intelligence methods of a safe ship control. Procedia Computer Science, Vol. 35, 2014, p.634-643.
[28] Binnenschiff. https://de.wikipedia.org/wiki/Binnenschiff
[29] Specific CO2 emissions per tonne-km and per mode of transport in Europe, 1995-2009. www.eea.europa.eu
[30] Woolford R., McKinnon A., The Role of the Shipper in Decarconising Maritime Supply Chains. Chapter 1, Current Issues in Shipping, Ports and Logistics. Asp, Vubpress, Upa, 2011. ISBN9054878584.