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Decarbonizing waterborne transport in a developing country: Challenges and opportunities

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ABSTRACT

Human-induced greenhouse gas emissions make climate change faster. Following the Paris Agreement, Bulgaria, alongside the international community, has put efforts into decarbonizing its energy industry, manufacturing, service, and transport. This paper studies possible paths to decarbonize waterborne transport in a developing country – Bulgaria, using a systemic approach. It considers the organization and operation principles of Bulgarian inland and maritime transportation, e.g., the main shipping routes, fleet, available infrastructure, and Bulgarian obligations to the European Union and the International Maritime Organization. We analyzed the energy demands and the preferred alternative energy sources of the local shipping industry based on the available multi-source data. To further widen our perspective, the study considered the Bulgarian energy industry and provided insights into alternative energy sources that are available or can be developed within a reasonable time. The study recommends promising measures to decarbonize Bulgarian waterborne transport – using plug-in batteries and biodiesel for inland shipping, and biodiesel for maritime shipping. The findings and the design of the study are transferable as they can be applied to decarbonizing shipping in developing countries, particularly in Europe.

1. Introduction

Although the present global temperature of the planet is in one of the coldest states in its history, modern humans have never lived in a warmer climate (Judd, et al., 2024). Anthropogenic activity resulted in climate change occurring faster compared to the preindustrial period because of significant greenhouse gas emissions. Bulgaria, alongside the international community, has signed the Paris Agreement to concentrate its efforts on minimizing human-induced impact on the climate by significantly reducing greenhouse gas emissions. The International Council on Clean Transportation reports that shipping emitted in 2023 about 2.3 percent of global anthropogenic CO_2 or 989 million tonnes of CO_2 equivalent emissions, calculated using tank-to-wake method and 100 years horizon of global warming potentials (Mao et al., 2025), which is more than the corresponding emissions for Germany but less than for Japan (European Commission, 2024). According to the European Commission (Mao et al., 2025), waterborne transport is one of the most environmentally efficient transport modes, yet still responsible for about 13.5 percent of European greenhouse gas emissions from transport. In 1999, Corbett et al. demonstrated that about 70 percent of SO_X and NO_x emissions from ships occur in coastal areas, negatively affecting the health of humans and animals (Corbett et al., 1999).

Considering this issue, the International Maritime Organization (IMO) has adopted its ambitious greenhouse gas reduction strategy, aiming at meeting the target of net-zero emissions by 2050 (International Maritime Organization, 2025). IMO emphasized that the target can be achieved only with the coordinated effort of the global community and proposed its Net-zero Framework. It offers specific mandatory emission limits with different levels of compliance combined with penalties and rewarding economic measures. Another international shipping organization – the World Association for Waterborne Transport Infrastructure (PIANC) – coordinates the efforts to develop reliable infrastructure for zero-emission energy sources for ships (InCom, 2023). IMO and the shipping industry demonstrated a unique level of international cooperation and developed effective tools for advancing sustainable transportation under the United Nations, which is not typical for other transport modes.

Although green fuel technologies for shipping could potentially be

Abbreviations: IMO, International Maritime Organization; TEN-T, Trans-European Transport Network; TEU, Twenty-foot Equivalent container Units; EU, European Union; GT, Gross Tonnage; NPF, National Policy Frameworks.

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applied worldwide, the most feasible fuel can differ depending on local operational specifics, availability of raw materials, funding, and production and supply infrastructure. Correspondingly, it is reasonable to develop different recommendations for decarbonizing shipping in developed and developing countries, considering significantly different circumstances.

Bulgaria is a developing country and a maritime nation connected to the western coast of the Black Sea. With its strategic location in Europe, close to Asia and Africa, the country has access to the primary international shipping routes. An alternative route to transport Ukrainian grain through the Bulgarian sea and inland ports has emerged after Russia did not extend the grain deal initiative in 2023. Besides, according to Eurostat (European Commission, 2024), Bulgaria is one of the leaders in European inland navigation, ranked 6th out of 27 European Union (EU) countries in tonnes of cargo transported by inland waterways over one kilometer. The important role of inland navigation in the country indicates the high energy efficiency of the local transport sector in Bulgaria. Further development of reliable and sustainable waterborne transport will significantly contribute to decarbonizing Bulgaria. Considering that the development of sustainable shipping requires international efforts, it is important to coordinate its decarbonizing strategy with countries on the Danube, especially neighboring Romania, and countries on the Black Sea.

However, some researchers point out that the Bulgarian shipping industry suffered from the consequences of negative events in the period from 2020 to the present (e.g., the COVID pandemic and the war in Ukraine), resulting in an economic crisis (European Climate, 2024). Although significant efforts have been made by Bulgarian research institutions to develop and test some pilot prototypes of advanced decarbonizing technologies for shipping (Georgiev et al., 2021); (Pencheva et al., 2019) , practical applications and corresponding infrastructure are limited. The issues of regulations for decarbonizing shipping in Bulgaria are highlighted in (Nozharov, 2022). Some relevant existing research developments contributed to sustainable inland and maritime shipping in general. For example, Parvasi et al. demonstrated the competitiveness of electric inland Ro-Ro ships in Western Europe (Parvasi, 2025). Georgiev and Garbatov statistically studied energy needs and carbon emissions of container shipping in the Black Sea (Georgiev and Garbatov, 2024). Radmilović and Dragović emphasized the importance of pushed barges for inland navigation in Europe (Radmilovic and Dragovic, 2007). Sønnervik et al. studied the favorable strategies for decarbonizing the Norwegian fishery fleet (Sønnervik et al., 2024).

A systemic analysis of how to improve the attractiveness, energy efficiency, and sustainability of waterborne transport in Bulgaria, considering the regional specifics, is needed but currently absent in the literature. The findings and the design of the study are transferable as they can be applied to decarbonizing shipping in developing countries, particularly in Europe.

This paper studies possible paths to decarbonize waterborne transport in Bulgaria, answering the following research questions.

- How are Bulgarian inland and maritime transportation organized and operated?
- What are the energy demands and preferred alternative energy sources of local shipping?
- Is the Bulgarian energy industry ready to support the application of alternative energy sources on ships?
- What are the most promising measures to decarbonize Bulgarian shipping, considering the existing constraints of the fleet, port infrastructure, and the energy industry?

The remainder of the paper is organized as follows. Section 2 reviews the principles of Bulgarian waterborne transportation, considering inland and maritime shipping. Section 3 reviews the Bulgarian energy industry and assesses its readiness to support the application of alternative energy sources in shipping. Section 4 recommends pathways to decarbonize Bulgarian river and maritime transport, considering the present state of shipping and energy industries and Bulgarian obligations to the EU and the IMO.

2. Shipping in Bulgaria: Inland and maritime navigation

National waterborne transportation in Bulgaria is based on inland navigation by the Danube River and maritime navigation by the Black Sea. These transport systems are not directly connected because the Danube River flows into the Black Sea through Romania near the port of Constanța. Bulgarian waterways have a significant role in local and international transportation. Particularly, the Bulgarian inland navigation route is a part of the core Rhine-Danube Corridor of the Trans-European Transport Network (TEN-T), and the Bulgarian maritime connections are included in the core Orient/East-Med Corridor of the TEN-T.

2.1. Maritime navigation in Bulgaria

Fig. 1 a) shows the location of the Bulgarian maritime ports. The primary maritime ports in Bulgaria are the Port of Varna, which handles mainly grain exports, bulk cargoes, and containers, and the multipurpose Port of Burgas, which handles all types of cargo. Although the total cargo turnover of the Port of Varna in 2023 – about 8 million tonnes and 150 thousand Twenty-foot Equivalent container Units (TEU) (The Port of Varna, 2025) – is bigger compared to the Port of Burgas with 7.2 million tonnes and 130 thousand TEU (Antonov, 2025), the latter shows better development dynamics over the years. It has slightly higher infrastructure performance (Zhelyazkova, 2023) and can handle bigger ships with a maximum draft of up to 15 m in 2025, making it the closest deepwater port to the Bosphorus Strait. The EU selected the port of Burgas as a part of the TEN-T core network, while the Port of Varna is only in the third-tier TEN-T comprehensive network. However, the port of Varna remains highly competitive as the most critical grain handling hub in one of the leading grain exporter countries in the world. In 2023, the EU provided significant funding for developing the new sustainable infrastructure of the Port of Varna grain terminal (Bank, 2025). Fig. 1 a) shows five secondary ports supporting local commercial shipping, fishing, and tourism.

Fig. 1 b) and c) show the routes connecting Bulgarian ports with international waterways. The routes are based on the historical data on ship voyages for 2023 (MarineTraffic, 2025). The data is derived from the Automatic Identification System for all ships with a gross tonnage higher than 500, all ships with a gross tonnage higher than 300 involved in international navigation, and all passenger vessels. The most popular international shipping routes from the Port of Varna and the Port of Burgas are passing south-east to the Bosphorus Strait and north-east along the coast to the port of Constanța, the Danube inland navigation system in Romania and Ukraine, and further to the Ukrainian port of Odesa. The port of Burgas also has some prominent direct routes to the Russian, Georgian, and Turkish ports of the Black Sea. According to Fig. 1 b) and c), the local shipping between the Bulgarian ports is very intensive.

The main competitor of the ports of Varna and Burgas is the port of Constanța – the central export hub for the Romanian grain. Besides Constanța, the port of Burgas competes with the port of Thessaloniki in Greece, a part of the TEN-T core network, connecting the region with the rest of the EU. Based on the Eurostat data for 2023, Fig. 2 shows the total gross weight of goods transported in all the Black Sea ports by country (Eurostat, 'Sea transport of goods', 2024). Türkiye is the leading country, with about 515 million tonnes of cargo handled in its ports, while Georgian ports have the lowest total cargo turnover of 13.9 million tonnes. The total cargo turnover of Bulgarian maritime ports is near its maximum since 2012, with about 30 million tonnes of cargo handled.

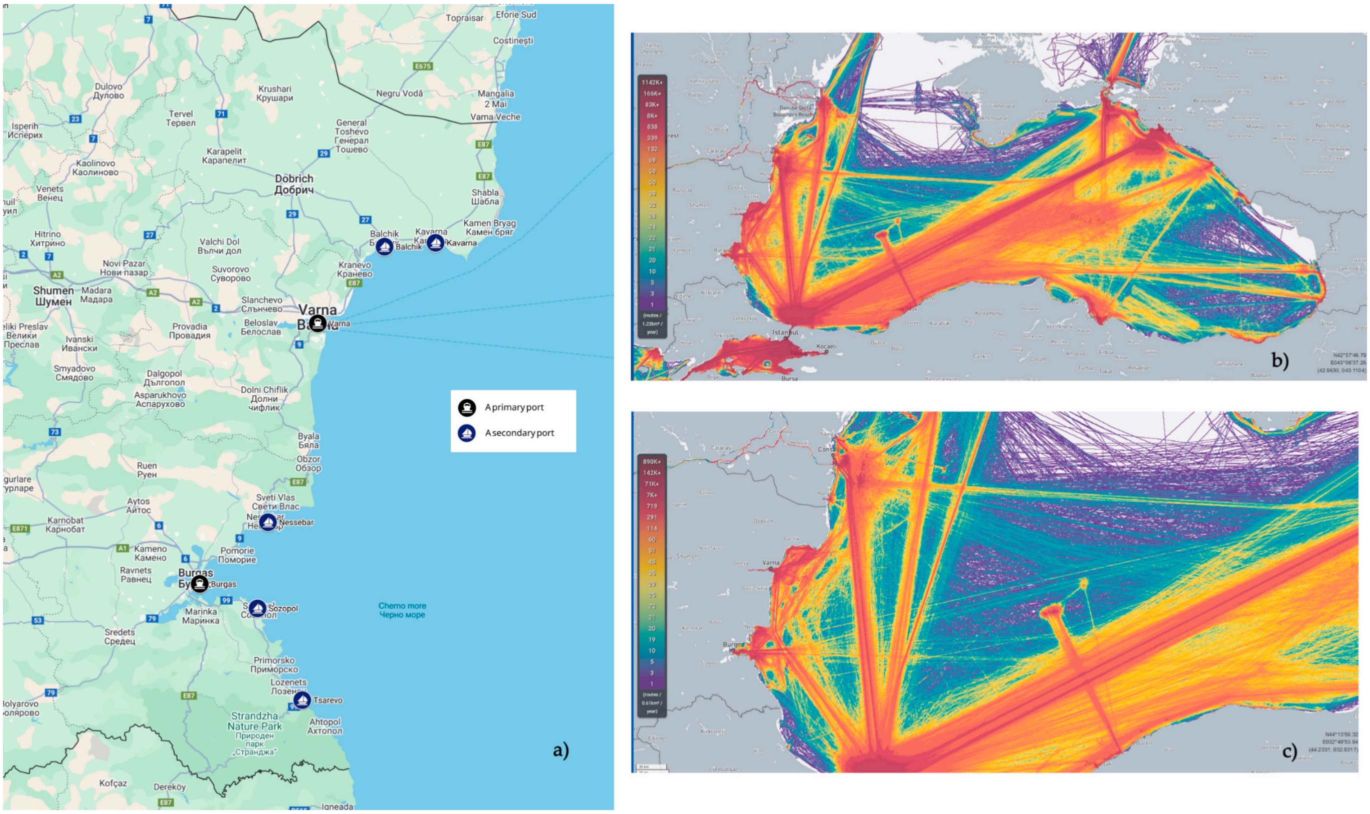

Fig. 1. Maritime navigation in Bulgaria. a) Maritime ports. b) and c) Maritime transportation routes connected to Bulgarian ports on a different scale, obtained using the shipping density data from AIS for 2023.

Fig. 2. The total gross weight of goods transported in all the Black Sea ports by country in 2023.

2.2. Inland navigation in Bulgaria

Inland shipping is often considered the most cost- and energy-efficient mode of transport compared to road and railway transportation (Observatory, 2025); (The United Nations Economic Commission for Europe (UNECE), 2011) . Bulgaria has a well-developed inland navigation system (see Fig. 3) with about 20 %, or 470 km, of the navigable Danube River located in its territory. The Danube, the longest river in the EU, flows from the West to the East and forms most of the northern border of the country. Fig. 3a) shows the location of two primary ports (Ruse and Vidin) and nine secondary inland Bulgarian ports. The ports of Ruse and Vidin – the only Bulgarian inland ports with container terminals – are included in the TEN-T Core Network because of their strategic location near the borders of Serbia and Romania.

Fig. 3. Inland shipping in Bulgaria. a) Bulgarian inland ports. b) Transportation route on the Danube River. Fig. 3 b) is adapted from The Central Commission for the Navigation of the Rhine, 2023.

Besides, four secondary ports – Silistra, Svishtov, Lom, and Oryahovo – are included in the TEN-T Comprehensive Network. The navigable part of the Danube (see Fig. 3 b) passes through and connects the territories of Germany, Austria, Slovakia, Hungary, Croatia, Serbia, Bulgaria, Romania, Moldova, and Ukraine. Fig. 4 shows the top ten EU countries in terms of goods transported by inland waterways in 2023, where Bulgaria holds the 6th place with about 4250 million tonnes of cargo transported over one kilometer. Fig. 4 is based on the Eurostat data (Eurostat, 'Inland waterways transport - Transport - Eurostat', 2024).

According to the Danube Commission data (Danube Commission, 2025) for international inland navigation in 2021, the ports of Ruse and Lom are mainly importing cargoes from the ports of Izmail (Ukraine),

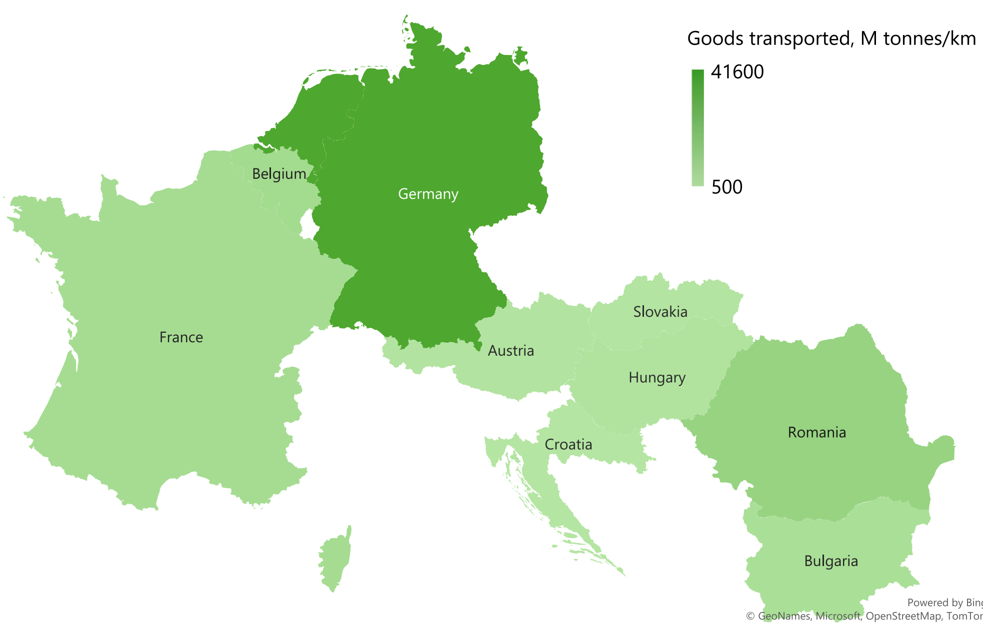

Fig. 4. The top ten EU countries in goods transported by inland waterways.

Linz (Austria), Belgrade (Serbia), and other Serbian ports, when the Port of Vidin is mainly exporting cargoes to Serbian ports. However, the Ruse and Lom ports also export some cargo to the German ports of Kelheim and Regensburg. Danube transportation is dominated by bulk and general cargoes. Besides international importance, inland navigation is significant for the sustainable local distribution of goods between Bulgarian ports.

The Danube inland navigation is complicated by significant irregularity and uncertainty of the transport capacity depending on the season and corresponding water levels (Kalajdzic et al., 2023). During the shallow season in the summer and autumn, vessels must be partially loaded to about 50 percent of the design capacity or less, depending on the temperature, to guarantee a safe draft. According to existing estimations (Dávid and Madudová, 2019), transportation speed on the Bulgarian sector of the Danube is about 9 to 11 knots downstream and about 6 to 8 knots upstream. The most common local mode of transportation is a pushed convoy, consisting of several barges and a pusher boat, which is typical for the centralized model of inland shipping organization (Tarovik et al., 2017).

2.3. Bulgarian fleet and energy demand

According to Eurostat data for 2023 (Eurostat, 'Inland waterways transport - Transport - Eurostat', 2024), the Bulgarian inland fleet includes 34 self-propelled cargo ships with an average payload of about 1600 tonnes and the most common engine power of about 890 kW, more than 90 percent of which have a payload from 1000 to 2999 tonnes. Seventy-four percent of Bulgarian self-propelled cargo ships were built before 1974, or more than fifty years ago. The rest were built between 1975 and 1999, so the newest are already at least twenty-five years old. However, the primary transportation capacity of the Bulgarian inland fleet belongs to 108 non-propelled barges, with an average payload of about 1650 tonnes, more than 90 percent of which also have a payload from 1000 to 2999 tonnes. The non-propelled barges are moved by 25 diesel-fueled pusher tugs with an average power of about 1150 kW, half of which are older than fifty years, and the other half are from twenty-five to fifty years old. The data shows that the self-propelled fleet is significantly older than the pusher tug fleet.

Analysis shows the typical operation mode for Bulgarian inland navigation is when the bulk cargo is transported by a convoy of four barges (see Fig. 5) with 1650 tonnes of goods each, pushed by an 1150 kW powered forty-year-old pusher tug, moving 10 knots downstream and 7 knots upstream. Table 1 provides an energy consumption estimate for such a convoy, which is about 0.016 kWh/tkm. The obtained values align with some existing estimates on energy consumption of small-tonnage waterborne transport (Perčić et al., 2021; M. Bännstrand, A. Jönsson, H. Von Knorring, and R. Karlsson, Study on the optimization of energy consumption as part of implementation of a ship energy efficiency management plan (SEEMP)., 2016; Klein et al., 2020). Considering that Bulgarian inland shipping performance is about 4250 million tkm of cargo transported per year, its total energy consumption can be estimated at 67.15 GWh, corresponding to 13,430 tonnes of diesel fuel with a 200 g per kWh consumption rate. This value must be increased to 74.61 GWh for electricity consumption predictions, considering the energy losses for electrical transmission of about 10 percent, because the existing fleet uses mechanical energy transmission from the engine to the propellers. The estimated energy consumption does not consider the distance traveled without cargo, hotel loads, and port operations.

Fig. 5. A typical inland navigation convoy is made of one pusher and four barges.

Table 1
An energy consumption estimate for a typical Bulgarian inland convoy of one pusher and four barges.

Parameter	Value
Cargo capacity, t	6600
Loading factor	0.7
Power required, kW	1150
Speed average, knots	8.5
Speed average, km/h	15.7
Time to go one kilometer, h	0.064
Energy consumption for a convoy, kWh/km	73.1
Energy consumption, kWh/tkm	0.0158
Energy consumption, kWh/tnm	0.029
Electricity transmission losses	10 percent
Electricity consumption, kWh/tkm	0.0176

Statistics on the maritime Bulgarian fleet are more vague, as in the maritime sector, being registered for a specific flag usually does not indicate belonging to a fleet of that country. The country of registration is generally decided based on the economic considerations of a ship owner. The statistics on vessels visiting the ports of Varna and Burgas are made available by Eurostat (Eurostat, 'Vessels arriving in the main ports by type and size of vessels - quarterly data', 2025), and they are further considered in the study. Table 2 presents the corresponding processed data for the most common ship types and sizes. The uncommon ship

Table 2
Number of ship visits in the ports of Varna and Burgas in 2023 by ship type and size.

Data for the Port of Varna			Data for the Port of Burgas		
Gross tonnage	Ship type	Visits	Gross tonnage	Ship type	Visits
GT2000-2999	Dry bulk	29	GT2000-2999	Dry bulk	33
GT10000-19999	Dry bulk	75	GT10000-19999	Dry bulk	32
GT20000-29999	Dry bulk	82	GT20000-29999	Dry bulk	47
GT30000-39999	Dry bulk	92	GT30000-39999	Dry bulk	48
GT40000-49999	Dry bulk	6	GT40000-49999	Dry bulk	21
GT1000-1999	Tanker	9	GT500-999	Tanker	35
GT3000-3999	Tanker	23	GT1000-1999	Tanker	66
GT4000-5999	Tanker	48	GT3000-3999	Tanker	35
GT6000-6999	Tanker	10	GT4000-5999	Tanker	170
GT7000-7999	Tanker	16	GT6000-6999	Tanker	14
GT10000-19999	Tanker	67	GT7000-7999	Tanker	38
GT20000-29999	Tanker	28	GT10000-19999	Tanker	5
GT1000-1999	General cargo	161	GT20000-29999	Tanker	68
GT2000-2999	General cargo	262	GT50000-79999	Tanker	82
GT3000-3999	General cargo	42	GT1000-1999	General cargo	123
GT4000-4999	General cargo	67	GT2000-2999	General cargo	201
GT5000-6999	General cargo	80	GT3000-3999	General cargo	48
GT7000-7999	General cargo	13	GT4000-4999	General cargo	78
GT10000-19999	General cargo	38	GT5000-6999	General cargo	32
GT10000-19999	Container ship	206	GT7000-7999	General cargo	22
GT20000-29999	Container ship	19	GT10000-19999	General cargo	71
			GT10000-19999	Container ship	114
			GT20000-29999	Container ship	83
	Total	1373		**Total**	1466

categories with few visits per year were combined with the closest representative ship category. Despite having a bigger total cargo turnover than the port of Burgas, Varna has recorded 1373 ship visits in 2023 compared to 1466 visits in the port of Burgas. The primary reason for this is the significant number of small-tonnage tankers with gross tonnage below 6000 arriving at the port of Burgas.

Table 3 provides information on the bunker fuel capacity for the most common types of maritime ships in the ports of Varna and Burgas based on the average data from specialized technical sources (RINA, 2025); (Schiffahrt, 2025) . We calculated the total bunker fuel demand in the ports, considering the bunkering frequency coefficient, the number of visits, and the fuel demand per visit for specific ship types, which is assumed to be 0.5 times the bunker fuel capacity. The bunkering frequency coefficient is assumed to be 0.3, considering the market position of the ports of Varna and Burgas compared to other major Black Sea ports, meaning the average ship bunkers fuel on 30 percent of port visits.

The bunker fuel demand is estimated at 169 610 tonnes in the port of Varna and 200 240 tonnes in the port of Burgas. The total bunker fuel demand in the ports is estimated at 369 850 tonnes, corresponding to the energy demand of 2 055 GWh, assuming a consumption rate of 180 g per kWh typical for maritime ships. This value is about 30 times higher than the demand from Bulgarian inland shipping. Eurostat reports that international maritime bunkers in Bulgaria account for 775 GWh of energy (Eurostat, 'Complete energy balances', 2025), which may be undervalued considering the number of large ships arriving in the port. The obtained numbers on the energy consumption for Bulgarian inland shipping are more reliable than for maritime shipping because they were obtained based on the data on the known transported cargo.

Table 3
An estimate of the bunker fuel capacity for the most common types of ships in the ports of Varna and Burgas.

Type of a ship	Parameters		Type of a ship	Parameters	
Dry bulk	Fuel capacity, t	Fuel capacity, m^3	Container ship	Fuel capacity, t	Fuel capacity, m^3
GT2000-2999	180	200	GT10000-19999	1350	1500
GT10000-19999	1080	1200	GT20000-29999	2160	2400
GT20000-29999	1575	1750			
GT30000-39999	2340	2600			
GT40000-49999	2475	2750			
Type of a ship	Parameters		Type of a ship	Parameters	
Tanker	Fuel capacity, t	Fuel capacity, m^3	General cargo	Fuel capacity, t	Fuel capacity, m^3
GT500-999	90	100	GT1000-1999	122.4	136
GT1000-1999	135	150	GT2000-2999	155.7	173
GT3000-3999	297	330	GT3000-3999	243	270
GT4000-5999	450	500	GT4000-4999	324	360
GT6000-6999	648	720	GT5000-6999	414	460
GT7000-7999	810	900	GT7000-7999	468	520
GT10000-19999	1260	1400	GT10000-19999	1530	1700
GT20000-29999	1530	1700			
GT50000-79999	3150	3500			

3. Bulgarian energy industry: Present energy mix and available alternative energy sources

The Bulgarian transport energy mix is diversified and based on many fuel types. According to Eurostat data for 2023 (Eurostat, 'Final energy consumption in transport by type of fuel', 2025), the total energy consumption of the transport sector is about 3 530 thousand tonnes of oil equivalent or about 41 054 GWh. Fig. 6 shows the distribution of energy consumption in Bulgarian transport, where fossil fuels – gas and diesel oil, motor gasoline, liquified petroleum gases, natural gas, and kerosene – dominate the energy landscape with 94 percent of the total energy consumption. The rest of the energy is divided between the renewables – blended biodiesels (4.4 percent), blended biogasoline (0.6 percent), and electricity (1 percent). Bulgaria has an advanced capacity for biodiesel production. Astra Bioplant – a Bulgarian company located in Ruse and a top-five supplier of biodiesel in Europe, produces about 300 000 tonnes of biofuel per year (Bulmarket, 2025). It has developed supply chains and owns inland port facilities in Ruse. Biodiesel is considered a promising candidate for decarbonizing waterborne transport in Bulgaria.

Another promising and potentially zero-emission energy source is electricity. According to Eurostat (Eurostat, 'Complete energy balances', 2025), Bulgaria produced about 40 250 GWh of electricity in 2023. Fig. 7 presents the distribution of the produced electricity by fuel type, showing about 65 percent or 26 220 GWh of electricity coming from zero- or low-emission sources – renewables, biofuels, and nuclear energy. According to official Bulgarian statistics (Republic of Bulgaria, 2025), the country produced over consumption and exported 7 748 GWh of electricity, which is, according to Section 2.3, much more than required to decarbonize the Bulgarian inland and maritime fleet combined entirely.

4. Discussion: Promising measures for decarbonizing waterborne transport in Bulgaria

Using plug-in battery powering is significantly promising for decarbonizing Bulgarian inland shipping, considering the available reserves of green electricity in the country (see Section 3), ship operation and design features, practical maturity of the technology (Kersey et al., 2022), availability of some charging infrastructure, and corresponding practical experience in Bulgaria. The operation profile of inland shipping fits well with the advantages and constraints of battery powering, which provides the best performance and lowest costs when used on small, low-powered ships in coastal areas with good access to charging facilities (Kondratenko et al., 2025). Besides, the primary transportation mode of Bulgarian inland cargo shipping – the pushed convoy – requires the electrification of roughly every fifth vessel – a pusher tug, when the

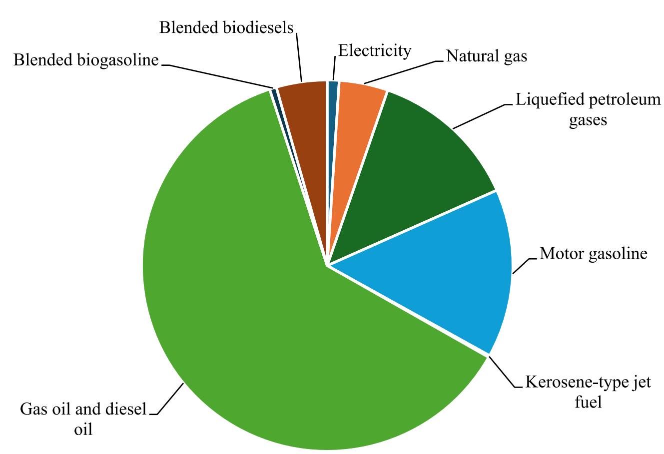

Fig. 6. Energy consumption in Bulgarian transport by type of fuel in 2023.

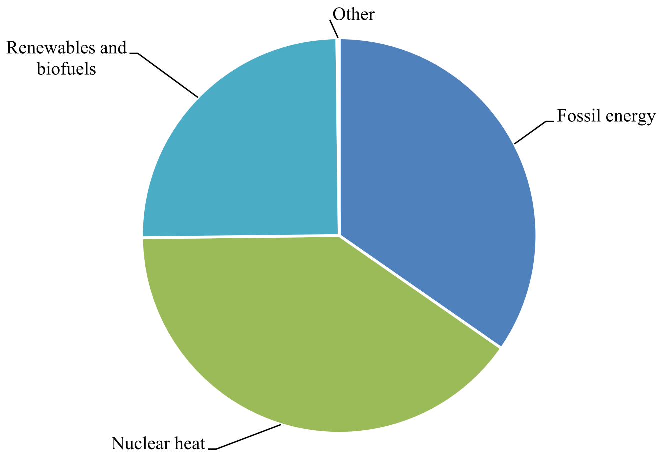

Fig. 7. Production of electricity in Bulgaria by type of fuel in 2023.

remaining four vessels are non-propelled barges and do not require any modifications. Inland shipping in Bulgaria is highly centralized as the number of shipping companies is limited, making it easier and cheaper to organize the transition to plug-in battery-powering due to the scale factor, especially compared to the Western European Danube countries where inland shipping is organized by small private shippers, each owning a few self-propelled cargo ships.

Fig. 8 shows the general arrangement drawing with the design frame numbers of a diesel-powered river pusher tug of project OT-2452 (Morwenna Shipping Company, 2025), built in Hungary in 1989, which is very similar to the ones used in Bulgaria. It is about 52 m long and 12 m wide, with a design draft of 2.25 m. The total engine capacity of the pusher tug with 100 percent load is 1766 kW. Retrofitting or redesigning the ship for battery powering would allow the use of the engine and diesel fuel spaces (see Fig. 8, frames 22–44 and 52–85) and the corresponding vacant weight – 185 tonnes occupied by fuel and about 20 tonnes occupied by the engine set, for the battery arrangement. According to recent data (Kistner et al., 2024), the modern lithium–iron-phosphate battery set can provide about 152 kWh per m^3 and 154.2 kWh energy capacity per tonne. The vessel has much space to arrange the batteries, but the vacant weight of 225 tonnes is the limiting factor, allowing the ship to accommodate about a 34 700 kWh battery set. This energy capacity is enough to cover the length of the Bulgarian part of the Danube without charging. According to the existing estimations, it is also enough for 99 percent of historical trips of pusher tugs recorded for US inland shipping in 2021 (Moon et al., 2025). According to Serbian statistics on the total distance covered by a typical inland cargo ship per month (Kalajdzic et al., 2023), this battery capacity would require charging a battery set from about 2 (in Jan) to 5 (in Oct) times per month. However, these numbers can be higher depending on the traveled distance and safety factor applied to ensure power redundancy. Bulgarian ships will likely need to be charged in parallel with cargo operations at every port visit. The battery set has a very useful advantage over the diesel engine set – it can provide high power of about 1000 kW/t for a period limited by the battery capacity (Papanikolaou, 2020). This feature can allow the pusher tug to perform a broader range of cargo operations by taking more barges in the convoy.

Arranging such a battery set would not cause ship stability and trim issues because of the low center of gravity and favorable weight distribution along the length of a ship. Plug-in battery powering is recommended as the primary choice for the green transition of Bulgarian inland shipping. Researchers from Croatia and the US made the same conclusions for inland shipping in their countries (Perčić et al., 2021); (Moon et al., 2025) .

Efficient operation of plug-in battery-driven ships requires reliable infrastructure for fast battery charging. According to some estimates (Kersey et al., 2022); (Karimi et al., 2020) , charging the 34 700 kWh battery may require from 2 to 12 h or more, depending on the charger performance. Shore-side electricity infrastructure is a part of the mandatory requirements for the public port in Bulgaria and is available in all ports presented in Fig. 3a) (European Union, 'Document 5, 2017). Additional investigation is needed to estimate the optimal performance of the Bulgarian inland waterways charging infrastructure and propose recommendations for modernizing the equipment (Teske et al., 0000). The Bulgarian National Policy Frameworks (NPF) 2018 set the national target of developing shore-side electricity supply points (European Union, 'Document 5, 2017). According to our assessment and the existing data on battery charging stations (Karimi et al., 2020); (Teske et al., 0000) , the charging power of up to 5 MW must be enough for Bulgarian inland ships. The transition of inland shipping to plug-in battery powering can significantly boost the reputation of Bulgaria as a regional leader in supporting sustainable development.

The prospects of retrofitting the existing inland fleet in Bulgaria are limited due to the significant age of the fleet. Half of the pusher tugs were built before 1975 and are at least fifty years old. They must be scrapped soon because they compromise shipping safety, sustainability, and efficiency. The other half is from twenty-five to fifty years old, making it economically unreasonable to retrofit, considering the insignificant residual value of the ships and their ending lifecycle. The

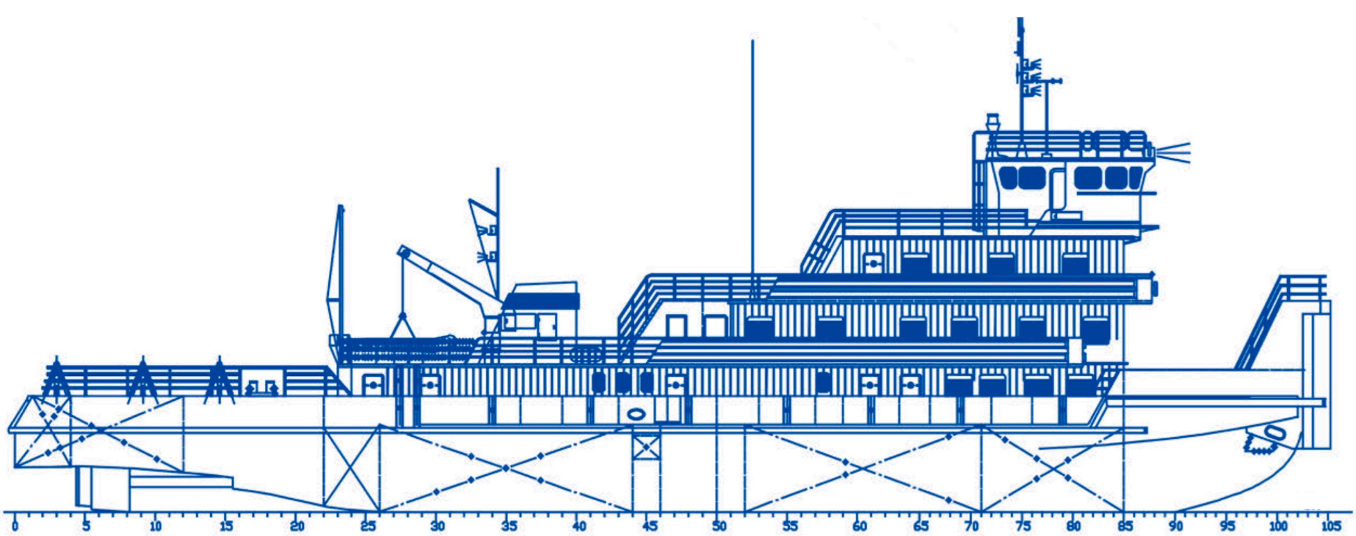

Fig. 8. The general arrangement drawing of a river pusher tug of project OT-2452 (Morwenna Shipping Company, 2025).

intermediary solution can be using biofuel as a drop-in fuel, but to an extent, so this does not slow down the electrification progress. Most vessels are recommended to be replaced before 2035 with new plug-in battery-driven pusher tugs.

Table 2 shows that maritime traffic in Bulgarian ports includes tankers, bulkers, general cargo, and container ships. A recent study (Klein et al., 2020) shows that green ammonia, methanol, and biofuel are the most promising fuels for decarbonizing them. Considering the existing supply chains and green fuel production capacities in Bulgaria, biodiesel is recommended as the primary drop-in green fuel for maritime traffic. The estimated fuel demand from maritime traffic is significant. Further growth of biodiesel production in the country is needed to support the complete transition of maritime cargo shipping, which requires a steady supply of corresponding feedstock. Developing the facilities for producing green ammonia and methanol is promising to diversify the selection of decarbonizing fuels available in Bulgarian maritime ports.

Report (European Union, 'Document 5, 2017) shows that the necessary funds to implement the recommended actions can be sourced from the EU financial instruments, including the Regional Development Fund, EC Regional Policy Operational Programmes, Interreg, and Joint European Support for Sustainable Investment in City Areas.

5. Conclusion

Bulgaria has one of the most developed inland shipping industries in the EU, and much cargo is transported through its Black Sea ports. The country has obligations to the world community to minimize human-induced impact on the climate by significantly reducing greenhouse gas emissions. This study analyzed Bulgarian inland and maritime transportation, looking for opportunities to decarbonize local waterborne transport, considering its technical and operational specifics, energy demands, the capacity of the industry to produce and supply green energy sources, and the available port infrastructure.

The present study demonstrated that biodiesel is a promising candidate for decarbonizing waterborne transport in Bulgaria, considering its practical convenience, advanced infrastructure, and capacity for its production with developed supply chains and port facilities. Moreover, the country produces more than 26 200 GWh of zero- or low-emission electricity per year, with about 7 750 GWh surplus – much more than required to decarbonize the Bulgarian inland and maritime fleet combined entirely.

Considering the shipping specifics, the study identified that plug-in battery energy is the most promising energy source for inland shipping, but biodiesel can be considered an intermediary solution during the transition period before 2035. Biodiesel is recommended as the primary drop-in green fuel for decarbonizing maritime traffic, but developing the production and supply of green ammonia and methanol is promising to diversify the selection of green fuels available in Bulgarian maritime ports.

CRediT authorship contribution statement

A.A. Kondratenko: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **K. Kamberov:** Supervision, Project administration, Funding acquisition. **G. Todorov:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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