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ANALYSIS AND EVALUATION OF FERRY SERVICES IN THE BALTIC SEA REGION IN THE CONTEXT OF ENVIRONMENTAL SOLUTIONS

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Abstract: This paper discusses the opportunities for reducing the emissions of substances dangerous to the environment as a result of switching from traditional ferry drives to electric propulsion systems. The research carried out included the analysis and evaluation of the technical solutions that are currently used in mixed passenger/vehicle vessels operating in the Baltic Sea Region (BSR). A comparative analysis of the impact of internal combustion engines and environmentally-friendly alternatives was also performed. The objective of the paper was to analyse and evaluate the organisation of ferry services in the BSR in the context of the propulsion systems used in ferries. The technical solutions currently used in the vessels under review were identified, as well as the possibilities offered by electric propulsion.

Keywords: sea ferries, electric drive, natural environment, e-mobility

1. INTRODUCTION

Maritime transport is one of today's best-developing transport modes. It creates trade routes between different economies and offers an extremely important link in global supply chains. In view of its daily activity, experts are continuously implementing innovative ecologistics solutions to maximise the environmental friendliness of maritime transport.

The current advances in technology enable the creation of new solutions that not only reduce exhaust emissions, but are also more efficient and resilient. It is worth noting that the problem of exhaust emissions is becoming global, and out of all available sources of urban pollution, transport equipment ranks first (Deja et al., 2021).

Electric propulsion has emerged as one of the solutions to minimise the emissions of dangerous exhaust gas from vehicles, being more and more often adopted across all transport modes. Transport vehicles with hybrid or electric propulsion are widespread around the world. Norway is one of the leaders in the shift of maritime transport vessels (sea ferries, to be more precise) from internal combustion engines to electric propulsion systems. In 2017, it introduced a high number of electric road transport vehicles, and subsequently focused on maritime transport as well. During a study visit as part of the ELMAR project in 2018, selected passenger ferries and mixed passenger/vehicle vessels were identified and analysed (Forkiewicz and Wolski, 2018).

2. CHARACTERISTICS OF ELECTRIC PROPULSION

Along with the development of civilisation, people have been placing a strong emphasis on technology advances, including on electric propulsion systems. An electric propulsion system results in silent and zero-emission engine operation. What makes it even more innovative is that in the braking process, the energy used is likely to be recovered and reused by recirculating to the battery. Processes supporting the improvement of the natural environment are possible owing to semiconductor components which do not have any interfaces and therefore do not require any maintenance. The block diagram of an electric propulsion system must also include pulse-width modulation or a DC motor control, and further to that, in order to make the system completely environmentally-friendly, control and security devices are also equipped with electrical apparatus. The figure below shows an example of an electric propulsion system in vehicles (Tarkowski and Siemionek, 2010).

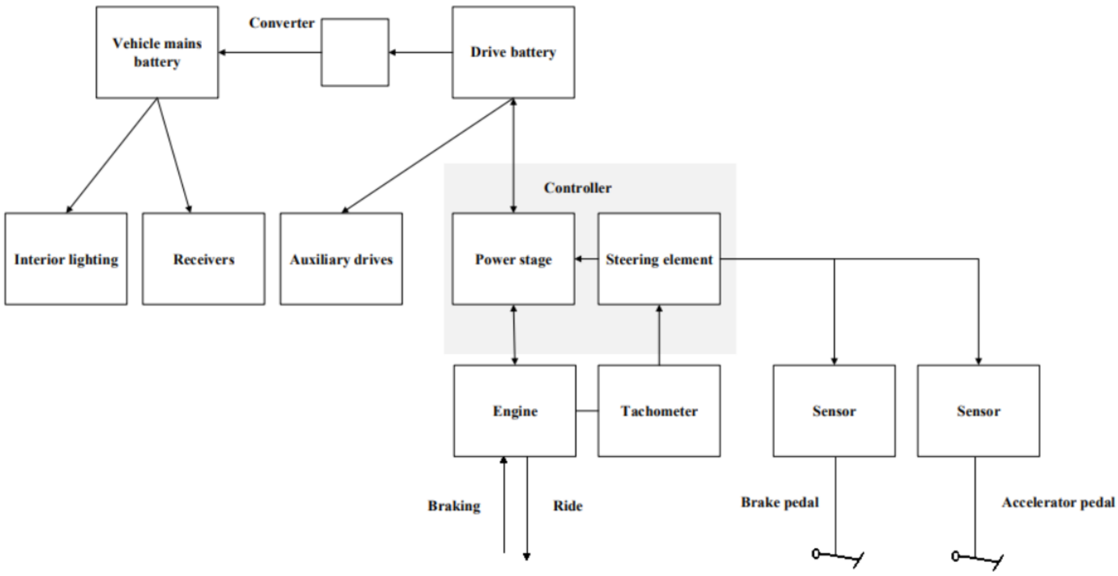

Fig. 1. Block diagram of electric vehicle propulsion [Adapted from: 16]

3. SPECIFICATIONS OF SEA FERRIES

For years, sea ferries have been standing out as a commonly used mode of transport characterised with the capacity to carry large volumes of cargo at low prices. Globally, this transport mode is most commonly identified in the area of three seas: North Sea, Mediterranean Sea, and Baltic Sea (Christowa, 2012). Considering the advancement level and adoption rate of electric propulsion as an innovation, this paper will be dedicated to the analysis of ferry services in the area of the Baltic Sea.

Journeys by ferry have become one of the most popular modes of transport in the area of the countries adjacent to the Baltic Sea. It is noteworthy that there are three main types of ferries (Mańkowska, 2016):

- Passenger ferries,
- Car ferries,
- Train ferries.

Over time, these basic types of ferries have been combined into what is called ‘mixed ferries’, such as (Mańkowska, 2016):

- Car/train ferries,
- Passenger/car ferries,
- Passenger/car/train ferries.

Currently, there are dozens of ferry operators, as shown in Table 1.

Table 1. Main ferry operators in the Baltic Sea

Operator	Number of ferries	Route
St. Peter Line	2	Helsinki to / from Saint Petersburg Saint Petersburg to Tallinn Tallinn to Stockholm Stockholm to Helsinki
Finnlines	5	Lübeck / Travemünde to / from Helsinki Lübeck / Travemünde to / from Malmö Stockholm to / from Turku via the Åland Islands
Viking Line	7	Stockholm to / from Helsinki via the Åland Islands Stockholm to / from Turku via the Åland Islands Helsinki to / from Tallin
Tallink Silja	10	Stockholm to / from Helsinki via the Åland Islands Stockholm to / from Turku via the Åland Islands Helsinki to / from Tallin Stockholm to / from Tallin Stockholm to / from Riga
Eckerö Line	2	Helsinki to / from Tallin
Wasaline	1	Vaasa to / from Umeå
DFDS	9	Paldiski to / from Hanko Kaplica to / from Paldiski Klaipeda to / from Karlshamn Klaipeda to / from Kiel
Stena Line	10	Ventspils to / from Nynäshamn Liepāja to / from Travemünde Gdynia to / from Karlskrona Sassnitz to / from Trelleborg Rostock to / from Trelleborg Kiel to / from Göteborg
TT-Line	6	Świnoujście to / from Trelleborg Rostock to Klaipeda Rostock to Trelleborg Lübeck / Travemünde to Trelleborg
Unity Line	7	Ystad to / from Świnoujście
Polferries	5	Ystad to / from Świnoujście Gdańsk to / from Nynäshamn From Świnoujście to Copenhagen via Ystad
Bornholmslinjen	5	Bornholm to / from Ystad Bornholm to / from Køge Bornholm to / from Sassnitz
Eckerölinjen	1	Grisslehamn to / from Eckerö (the Åland Islands)
Destination Gotland	4	Oskarshamn to / from Visby Nynäshamn to / from Visby

Birka cruises	1	The Stockholm Archipelago (return journey / 'cruise')
Scandlines	6	Rostock to / from Gedser Puttgarden to / from Rødby
Żegluga Gdańska	18	Gdynia to / from Baltiysk (not only in Poland)
Kołobrzeska Żegluga Pasażerska	1	Kołobrzeg to / from Bornholm
Praamid.ee	4	Rohuküla to / from Hiiumaa Virtsu to / from Muhu + Saaremaa
Kihnu Veeteed	8	Tallinn to / from Aegna Laaksaare to / from Piirissaare Munalaid to / from Kihnu Munalaid to / from Manilaid Saaremaa (Triigi) to / from Hiiumaa (Sõru) Rohuküla to / from Vormsi (Sviby)
Tuule Liinid	1	Leppneeme to / from Kelnase
Saimaa Travel	1	Leppävaara to / from Vyborg (and farther to Saint Petersburg)

Source: Adapted from: www.ferryscan.com

Among the aforementioned ferry operators, Stena Line undoubtedly stands out as the one with the highest carrying capacity. The company operates 10 ferries along 6 routes in the Baltic Sea.

Maritime transport in the Baltic Sea area is one of the key pillars of trade in the region. The continuing economic growth has fuelled the development of competition, which currently has a very strong impact on the quality of service offered by sea ferries. Despite the strong development of this mode of transport, growing demand for passenger and cargo transport services is still observed. However, one should note the impact of transport services on the natural environment.

4. THE ENVIRONMENT IN MARITIME TRANSPORT

4.1. LEGAL REGULATIONS

Currently, a focus on environmental protection has become one of the key missions pursed by the transport sector in order to minimise environmental damage. Measures aimed at remedying environmental pollution were taken already in the 20th century by the United Nations (UN), which discussed the issue of implementing solutions to adopt measures in support of environmental protection in its report "The problems of human environment". As regards legal regulations, the first piece of legislation to consider the issue of maritime transport was the International Convention for the Prevention of Pollution of the Sea by Oil of 1954 (Nowosielski and Dąbrowski, 2013).

Today, one of the key documents encompassing all legal acts relating to the prevention of marine environment pollution is the MARPOL Convention (International Convention for the Prevention of Pollution from Ships), originally created in 1973. The current document is a consolidated edition of MARPOL 1973 which includes the Protocol of 1978 and the Protocol of 1997, last amended in 2015. It has the following six annexes (MARPOL, 2015):

- Annex I – Regulations for the Prevention of Pollution by Oil;

- Annex II – Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk;
- Annex III – Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form;
- Annex IV – Prevention of Pollution by Sewage from Ships;
- Annex V – Prevention of Pollution by Garbage from Ships;
- Annex VI – Prevention of Air Pollution from Ships.

The origins of the MARPOL Convention can be traced back to catastrophic offshore events, in particular the Torrey Canyon disaster in 1968 and MT Amoco Cadiz 2 disaster in 1977. The Convention is one of the most important pieces of legislation (along with the London Convention 1972) that governs and lays down the standards to be followed at sea in order to minimise the risk of pollution of the marine environment.

In view of legal regulations applying precisely to the Baltic Sea area, the Convention on the Protection of the Marine Environment of the Baltic Sea Area was drawn up in 1992 in Helsinki. All regulations set out therein relate to measures aimed at maximising the safety and protection of marine areas in the Baltic Sea Region. The Convention lays down the rules of cooperation between all Baltic coastal states which signed it, identifies the potential challenges to the marine environment posed by the transport of hazardous substances, and lists the existing marine environment pollutants originating from land-based sources. Additionally, this legal instrument includes the criteria for the receipt of oily water in seaports in Baltic Sea areas that can be found in the aforementioned MARPOL Convention. The Convention on the Protection of the Marine Environment of the Baltic Sea Area contains the following annexes (Nowosielski and Dąbrowski, 2013):

- Annex I – Harmful substances;
- Annex II – Criteria for the use of Best Environmental Practice and Best Available Technology;
- Annex III – Criteria and measures concerning the prevention of pollution from land-based sources;
- Annex IV – Prevention of pollution from ships;
- Annex V – Exemptions from the general prohibition of dumping of waste and other matter in the Baltic Sea Area;
- Annex VI – Prevention of pollution from offshore activities;
- Annex VII – Response to pollution incidents.

The legal norms discussed above regulate behaviours at sea owing to which maritime transport has become much more sustainable and environmentally friendly. They also contribute to improved safety in the transport of dangerous substances, not only for the environment, but also for ship and sea ferry crews.

4.2. MAJOR THREATS

Out of all available sources of marine pollution, maritime transport equipment ranks first. It makes up an important transport sector within the European Union, with as much as a 38.3% share in the overall cargo transport process in this area. The emissions of dangerous chemicals by maritime transport equipment continue to increase, in particular in areas extending 400 km from the coast line (which is where 70% of all maritime transport pollution is generated), multiplying the problems of air quality, as a result of which hazardous sulphur compounds and particulate matter are released in port and coastal areas (Human Capital, project beneficiary, 2014).

Aside from the aforementioned threat posed by exhaust emissions from maritime vehicle engines, there is a range of other threats associated with maritime transport. Table 2 presents the classification of key sources of marine pollution.

Table 2. Classification of key sources of marine pollution

Source of pollution	Causes of pollution
Industry	Wastewater discharges directly into the sea or indirectly through rivers or the atmosphere.
Municipal services	Wastewater discharges directly into the sea or indirectly through rivers.
Agriculture	Use of pesticides and other chemicals which penetrate into the sea by direct runoff or indirectly through inland waters and the atmosphere.
Navigation	Removal of polluting substances to the sea in connection with regular ship operations, accidental release of polluting substances from ships as a result of environmental disasters, incidents, accidents.
Exploration and production of seabed minerals	Penetration of polluting substances to the sea in connection with regular operations and accidental releases of polluting substances to the sea.
Transhipment factors in ports	Penetration of polluting substances to the sea in connection with regular transhipment operations.
Mobility	Generation of exhaust gases in connection with regular operations which penetrate into the sea as a result of atmospheric exchange.
Operation of subsea pipelines	Accidental release of polluting substances into the sea.
Aviation	Generation of exhaust gases in connection with regular operations which penetrate into the marine environment through the atmosphere.

Source: (Wolak, 2016)

Based on the sources of sea pollution listed in the table above, it can be concluded that huge volumes of harmful chemicals are discharged into the water every day, significantly disturbing the existing ecosystem. It is also noteworthy that oil spills from maritime vehicle operations are an important local threat for the maritime transport environment. This problem is mostly caused by human errors and equipment failures (Wolak, 2016).

Another major problem for the marine environment is posed by pollution introduced into the water from land areas as a result of business and industrial activities, municipal services and farming. All kinds of damage, failures or fires have a strong impact on the environment, including its marine component (Herdzik, 2016).

The threats presented herein have an immense impact on the current state of waters in sea and ocean areas. The problems are becoming global. The legal regulations referred to above allow for a certain reduction of the pollution problem, however they are not enough. Therefore, scientists have been working on innovative ecologistics solutions to bring the risk of the threats materialising down to zero. Ferries featuring built-in electric propulsion systems have turned out to be one of them.

5. ELECTRIC FERRIES IN THE BALTIC SEA AREA

Electricity is coming to the forefront of all energy sources. It offers a perfect alternative to other, more polluting energy sources around the world. Along with the continuing economic and technological development, new trends are emerging that generate demand for electricity. These include, but are not limited to (ATI Küste GmbH):

- Urbanisation and electric mobility,
- Technetronic change: digitalisation, informatisation,
- Use of renewable energy sources,
- Industrial change,
- Education and social change.

Year by year, e-mobility is attracting more and more publicity in the media and worldwide. It is understood as a process of adoption and ongoing upgrading of electric, hybrid and hydrogen-powered propulsion systems aimed at minimising the release of harmful chemicals into the atmosphere from internal combustion engines. It is associated with every transport mode and it not only turns out to be the most environmentally-friendly, but also has become one of the most beneficial options in terms of cost and reliability. E-mobility concepts can be classified into three interrelated areas of activity: electromobility, ecomobility and mobility economics (Burdzik et al., 2017).

Electric ferries have a lightweight and sturdy structure and a modern design. They offer safe and reliable operation, generate no local emissions and are silent. With only slightly higher investment in the vehicle and infrastructure, they are more economical and efficient, and are capable of generating some of the required energy using solar power (provided that adequate technical equipment is available). It is in the nature of ferries that they travel cyclically along the same routes “from socket to socket”, so in technical terms, we can say that a ferry has a fixed travel profile. Examples from the Baltic Sea Area show that a considerable part of existing short-distance ferry services on inland waterways and protected coastal waters can be provided by electric ferries (ATI Küste GmbH).

It can also be proven that the electrification of ferry services on inland waterways has a high potential in terms of both the operation and production of electric ferries. In principle, this fact could speak in favour of ferry services in the Baltic Sea Region, as evidenced by the first successful implementation of e-ferries in Denmark, Norway, Finland and Germany (The BSR electric Project, 2020).

Municipal electric ferries and electric shipping the Baltic Sea Region are becoming a larger and more important element in maritime transport year by year. For a few years, Norway has been the e-mobility leader in this respect, continuing to deploy new electric ferries on its market. The most recent one, the Bastø Electric ferry put into service in March 2021 by the shipping company Bastø Fosen, is now the world’s largest fully electric ferry. It is 139.2 metres long and 21 metres wide, offering enough room for 600 passengers and 200 cars or 24 trucks. The ferry’s batteries have a capacity of 4.3 MWh, and the high-voltage charging systems have a charging capacity of up to 9,000 kW (www.electrive.com).

Obviously, aside from Norway, many other countries on the Baltic coast more and more often launch new electric ferries. In the recent years, many countries have shifted their focus to this type of maritime transport vehicles. This can be observed, for instance, in Denmark, where the Ellen ferry was launched in November 2019, boasting the smallest battery pack of all existing electric ferries (www.elektro.info.pl). Germany has also stepped up its efforts to develop e-mobility in maritime transport. The TT-Line ferry operator has chosen the 'Green Bridge' concept, owing to which it will minimise exhaust emissions from propulsion systems, implementing diesel-electric propulsion in its ferries: Nils Holgersson, Nils Dacke, Peter Pan, Robin Hood, Tom Sawyer and Huckleberry Finn (promy24.com).

6. COMPARISON BETWEEN DIESEL AND ELECTRIC FERRIES

6.1. MIXED PASSENGER/CAR FERRY CRACOVIA OWNED BY PŻB

Polska Żegluga Bałtycka is a Polish ferry operator with a fleet of five ferries travelling between Poland and Scandinavia. Its corporate headquarters are located in Kołobrzeg, while ferry operations are based in Gdańsk and Świnoujście. In 2015, the Mazovia ferry was launched, being the first ferry boat in Poland with a painted bow. The motif of a surfacing fish with scales alludes to *wycinanki*, a popular folk craft originating from the town of Łowicz. Another ferry with a painted bow is Cracovia. Placed in service in 2017, this ferry boasts the image of a whale. Both graphics are marine-themed (polferries.pl). The Cracovia ferry provides services on the route between Świnoujście and Ystad. It was built in 2002, and in 2017 it was purchased by PŻB, which had it refurbished in a shipyard in Szczecin. During the upgrade, the ferry gained a new cafeteria and café in the bow section, and the bow was painted. The ferry is capable of accommodating 650 passengers, 64 cars and ~98 long trucks + 26 short trucks. The technical parameters of the ferry are as follows (polferries.pl):

- Length: 180 m;
- Width: 24.30 m;
- Draft: 6.5 m;
- Load line length: 2,196 m (64 cars and ~98 long trucks + 26 short trucks)
- Operating speed: 16.7 knots;
- The ferry meets the requirements of all applicable conventions and IMO recommendations, as well as any other requirements applicable to shipping services.

Table 3 provides a summary of all parameters of the Cracovia ferry.

Table 3. List of parameters of the M/f Cracovia ferry

Parameter	Measurement
Name	M/f Cracovia
Ferry type	Passenger/car
Shipyard	Stocznia Szczecińska "Wulkan"
Operations (start)	2017
Operator	Polska Żegluga Bałtycka
Route	Świnoujście – Ystad Ystad – Świnoujście
Travel time	1h 30 minutes
Length	180 m
Width	24.30 m
Moulded depth	9.60 m
Number of passengers	650
Number of cars	64
Number of trucks	98
Maximum speed	23.25 knots

Travelling speed	22.8 knots
Propulsion	Internal combustion engine
Power of main engine	23,760 kW

Source: (Polska Żegluga Bałtycka corporate materials)

6.2. THE AMPERE MIXED PASSENGER/CAR FERRY OWNED BY NORLED

Norled is a ferry operator based in Norway, operating a fleet of around 80 ferries. A few years ago, the company started a transition to electric-powered ferries, and owing to that it won a contest of the Norwegian Ministry of Transport for the most environmentally friendly mixed passenger/car ferry in 2011. The prize-winning Ampere ferry is fully electric. It is powered by batteries installed in the transport vehicle, which are recharged at berth from the land side power grid. The ferry operates on a 5.6 km crossing between Lavik and Oppedal in 20 minutes and can carry 120 cars, 8 trucks and 350 passengers at a time (Forkiewicz and Wolski, 2018).

The Ampere is a catamaran with two hulls, 80.8 metres long and 20.9 metres wide. Its battery pack claims 10 m^3 of space, has a weight of 10 tonnes and a lifetime of up to 10 years. It can store one million Watts of energy. While the ferry boat is at berth, batteries are charged from a land side power supply using clean energy obtained from regional hydro power plants (Forkiewicz and Wolski, 2018). A detailed list of technical parameters is provided in Table 4.

Table 4. List of technical parameters of the Ampere ferry

Parameter	Measurement
Name	Ampere
Ferry type	Passenger/car
Shipyard	Fjellstrand AS
Operations (start)	2015
Operator	Norled AS
Route	Lavik – Oppedal Oppedal – Lavik
Travel time	20 min
Length	80.80 m
Width	20.80 m
Moulded depth	6 m
Number of passengers	350
Number of cars	120
Number of trucks	8
Maximum speed	14 knots
Travelling speed	10 knots
Propulsion	Electric
Power of main engine	2 x 450 kW

Source: (Forkiewicz and Wolski, 2018)

6.3. ENVIRONMENTAL INSIGHTS FOR BOTH FERRIES

E-mobility in maritime transport offers a chance for a better tomorrow to the marine environment, which is an advantage for the life cycle of the society as a whole. The continuously growing economy is putting more and more pressure on the adoption of the latest innovations aimed at minimising the emissions of harmful exhaust gases from all kinds of transport vehicles. With regard to maritime transport, in the recent years, different countries have focused on a transition to hybrid or totally electric propulsion

systems. A question arises – is the internal combustion system very different from the electric-powered system?
Based on the M/f Cracovia and Ampere ferries which are discussed above, a comparative analysis was carried out from the perspective of environmental protection, as shown in Table 5.

Table 5. Comparative environmental analysis of the M/f Cracovia and Ampere ferries

Element of the analysis	M/f Cracovia ferry	Ampere ferry
Type of supply	Internal combustion engine	Electric
Source	Low-sulphur diesel oil	Electricity
Engine	4x 5940 Wartsila	Lithium-ion battery (rechargeable)
Noise generated by the ferry	High	Low
Environmental insights about the company	PŻB's ferries are environmentally friendly and they operate in compliance with the regulations of the International Maritime Organization and current EU legislation applicable to ports. The company also intends to implement electricity supply from land to ship. The ISM Code (International Management Code for the safe operation of ships and for pollution prevention) has been deployed on its ferries, improving the safety of navigation and contributing to better environmental protection.	The company invests in the construction of hulls and superstructure, which are shaped to guarantee energy savings of approx. 9.1% at 10 knots. Aside from the construction of the ship, the company has also thought about minimising the energy consumption of on-board systems. The operation of electric ferries produced by Norled opens up such possibilities as lower exhaust emissions and saving a million litres diesel oil annually. This results in both environmental and economic benefits (low cost of operation and maintenance).

Source: Adapted from (Forkiewicz and Wolski, 2018) and (Polska Żegluga Bałtycka corporate materials)

In their transport policies, both Polska Żegluga Bałtycka and Norled consider the context of environmental protection. However, as shown by the comparative analysis of the Cracovia and Ampere ferries in the table above, Norled is the leader that has made a considerable difference in the area of protection of the marine environment. This could be attributable to the fact that Norway puts e-mobility first in its economy. Polska Żegluga Bałtycka is also doing its best to maximise its environmental friendliness, as demonstrated by its plans to convert their ferries to electric power in the future, while currently they are fuelled by low-sulphur diesel oil. Environmental aspects are also gaining ground in Poland, and Polish transport companies are making plans to switch their water transport vehicles to green power in the future.

7. CONCLUSIONS

Electromobility is becoming more and more popular and desirable year by year, which includes seagoing vessels, in particular in special areas where emissions of noxious substances to the atmosphere must be restricted. The MARPOL 73/78 Convention classifies the Baltic Sea as one of such special areas. The use of electric propulsion on seagoing vessels may result in a range of environmental benefits, such as:

- minimising noise in seaports;
- reducing the emissions of dangerous chemicals into the atmosphere;
- possibilities of using renewable energy sources;
- development of education and social change with respect to environmental protection;
- popularisation of maritime transport as an environmentally-friendly mode of transport characterised with the capacity to carry large volumes of cargo at low prices.

Currently, more than 100 ferries are operated in the Baltic Sea Area. Based on the comparative analysis of the M/f Cracovia and Ampere ferries in the area of environmental protection, the following conclusions were reached:

- year by year, the aspect of environmental protection is becoming more and more crucial to maritime carriers operating in special areas;
- noise emission restrictions in seaports force the use of certain technical solutions in vessels which include the use of alternative power supplies (such as electric propulsion);
- electric ferries generate less noise, which is particularly important for port cities.

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