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ADVANCED TECHNICAL SOLUTIONS FOR MARINE POLLUTION CONTROL IN THE ADRIATIC SEA

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Summary

The major environmental problems within the maritime sector are atmospheric pollution due to the extensive use of fossil fuels in ship power systems, as well as seawater pollution from various sources (e.g. oil spills, microplastic, acidification, etc.). Due to their negative effect on the environment, human health and marine ecosystem, they should be carefully controlled. The studies on environmental problems of the maritime sector are more focused on atmospheric pollution, mainly thanks to the Paris Agreement. The ships are mostly powered by conventional power systems (diesel engines), and their negative effect on the environment would be lower with the implementation of some measures for emission reduction. In this paper, the outcomes of the research into the advanced technical measures for maritime pollution control are summarized, where the emphasis is put on ro-ro passenger ships engaged in the Croatian short-sea shipping sector. The results of the performed Life-Cycle Assessment (LCA) and Life-Cycle Cost Assessment (LCCA) suggested that conventional power systems should be modernized by ship electrification. This solution is represented as the most cost-effective and the most environmentally friendly solution regarding air pollution reduction. Furthermore, regarding seawater protection, several aspects of the advanced early warning system, that is being developed by the authors, are discussed. Finally, in line with the global trends in the maritime sector, a review on increasing the degree of autonomy of ships is given, as one of the most important topics for the near future.

Keywords: marine pollution; emission reduction; ro-ro passenger ship; alternative fuels; energy-saving device; early warning system.

1. ENVIRONMENTAL PROBLEMS IN THE MARITIME SECTOR

Nowadays, the effect of marine transportation on the maritime environment has become a very important issue for all parties involved in the shipping sector, i.e. shipbuilders, ship owners and operators, public authorities, policymakers, etc. Marine exhaust gas generated by the combustion of fossil fuel in marine engines can be considered one of the major causes of marine environment pollution. Another environmental problem inherent to the maritime sector is seawater pollution, which represents a direct impairment of the marine ecosystem triggered from a variety of sources [1]. Air pollution negatively affects the environment with global warming and acidification on global basis, while the seawater pollution effect on the environment is locally oriented, and affects the ecosystem and the human health for people nearby the pollution source, which is especially destructive if the sea is enclosed, as is the case with the Adriatic Sea.

The environmental protection of the Adriatic Sea needs to be addressed through a dual approach. The first one is air protection by the reduction of the shipping emissions released during the combustion of fossil marine fuel in a ship power system, which refer to the harmful emission of nitrogen oxides (NO_X), sulphur oxides (SO_X), carbon monoxide (CO), carbon dioxide (CO_2), particulate matter (PM), and hydrocarbons [2]. The environmental trends are nowadays moving toward the electrification of the shipping sector, which could ensure zero-emission shipping (at least in the ship operation stage), i.e. navigation without tailpipe emissions.

The second approach in the environmental protection of the Adriatic Sea should be focused on the development of the early warning protection system, which would continuously monitor the real-time data of the seawater quality. Such systems enable on-time actions, which prevent further pollution accidents [3].

Although seawater pollution is a very important problem that needs to be resolved, the current trends and research are focused on the emissions reduction from which the ship exhaust gas is comprised and contributes to the atmospheric pollution, while seawater pollution is mainly investigated from the biological point of view, as a factor affecting marine life.

As mentioned above, the reduction of emissions in all kinds of waterborne transportation (long-distance shipping, short-sea shipping and inland shipping), as well as seawater protection, are very important research topics, and there is a number of projects worldwide targeting particular ship types, navigation areas or the implementation of different technical and operative measures to achieve environmental benefit in a particular sector. This work brings an overview of the research results obtained at the Chair of Marine Engineering of the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, within several competitive ongoing research projects. They are dedicated to the improvement of ship energy efficiency and environmental friendliness for vessels operating in the Adriatic Sea, as well as to the seawater protection in this area.

2. AIR PROTECTION IN THE ADRIATIC SEA

2.1. General about the reduction of CO_2 emissions in the shipping industry

One of the important environmental problems that the global community is facing nowadays is global warming, caused by the increased concentration of anthropogenic Greenhouse Gases (GHGs) in the atmosphere. These GHGs refer to the emission of CO_2, methane (CH_4), nitrous oxide (N_2O) and fluorinated gases in very low concentrations. The GHGs in the atmosphere form a thick layer that prevents energy from the Sun to escape into space. Furthermore, the Earth is warming, which causes various climate changes [4], [5]. The relevant legally binding international treaty on climate change is the Paris Agreement, which entered into force in 2016. It aims at keeping the global temperature rise below 2°C compared to preindustrial levels, requiring a sharp decrease in the global amount of CO_2 emissions, since it is the main GHG [6]. With the UN holding that each sector should reduce the GHGs, the shipping sector is being pushed towards reduction of its Carbon Footprint (CF), which represents a measure of the total amount of CO_2 or CO_2-eq emissions caused by indirect or direct activity, or is accumulated over the life-cycle of a product [7]. The reduction of the CF refers to representing an environmental trend that is the main focus of number of studies on emission reduction in the maritime sector.

In order to reduce the CF of the maritime sector, different technical and operational measures can be implemented [8], [9], Figure 1. Most of these measures refer to the reduction of fossil fuel consumption. In that way, not only CO_2, but also other pernicious emissions released during fuel combustion are reduced.

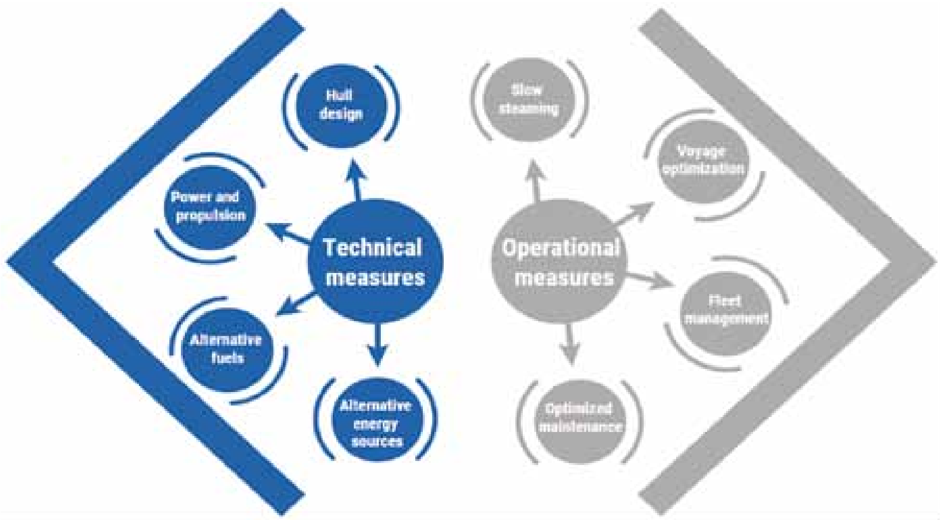

Figure 1. Measures for the CF reduction of the maritime sector [10]

Slika 1. Mjere smanjenja ugljičnog otiska u pomorskom sektoru [10]

Technical measures can be divided into four groups: hull design, propulsion and power, alternative fuels, and alternative energy sources. While some measures refer to the optimization of propeller/trim/hull or the implementation of Energy-Saving Devices (ESDs), the most significant technical measure that might result in a great reduction of shipping emissions is the replacement of conventional ship power system with an alternative one that is powered by cleaner fuel with lower carbon content, or alternative powering options, such as Renewable Energy Sources (RESs) [11].

Among different alternative fuels for maritime purposes, Liquefied Natural gas (LNG) is the most used. Even though it is of fossil origin, it has lower carbon content than diesel fuel, and its use in a dual-fuel engine regularly results in lower CO_2 emissions [12]. Methanol [13] and biofuels [14] are also thoroughly investigated for maritime purposes. However, the ultimate game-changer for the CF reduction of the maritime sector is the implementation of zero-carbon fuels, such as electricity [15] and hydrogen [16]. Their application in a ship power system results in no tailpipe emissions [17].

The potential RESs for maritime purposes include wind energy (e.g. sails, fixed wings, rotors, kites, and wind turbines), solar energy (Photovoltaic (PV) cells), wave energy, etc. [18]. Renewable energy solutions can be used for the ship propulsion or satisfying ship's auxiliary energy needs. The integration of the RESs in the ship power system is a rather case-specific task that should be performed for each vessel separately, simultaneously taking into account its technical characteristics and operating profile (highly dependent on the navigation area and the climate factors, i.e. wind density, insolation, etc.).

Operational measures for the CF reduction include speed reduction, voyage optimisation, fleet management, optimised maintenance, etc. [19]. Among them, slow steaming, i.e. voluntary reducing the operational speed well below the design speed, is highlighted as the most effective and popular measure to reduce fuel consumption, which consequently leads to a reduction in fuel cost and released emissions [20].

Another set of measures form market-based measures. Among them, the implementation of carbon allowance is thoroughly investigated. The carbon allowance refers to a permit for emitting 1 ton of CO_2 [21]. Even though it still has not been implemented in the maritime sector, this additional cost would represent an incentive toward the emission reduction and the implementation of some technical or operative measures to reduce fossil fuel consumption, or completely replace it with alternative fuel with lower carbon content.

The IMO's strategy on the reduction of the GHG emissions represents three levels of ambition for achieving the goal of reduction of the GHGs from international shipping by 50% up to 2050, compared to the 2008 levels [22], Figure 2.

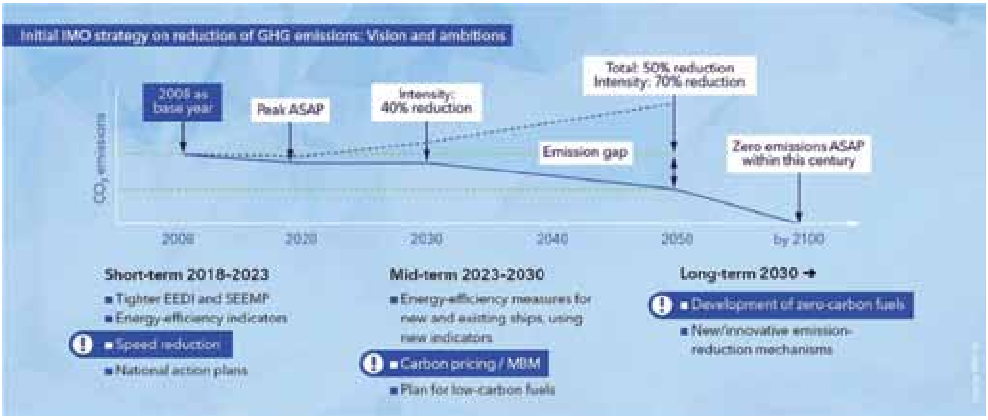

Figure 2. The IMO strategy on the reduction of the GHG emissions [23] (reproduced with permission of Det Norske Veritas (DNV))

Slika 2. IMO-va strategija za smanjenje emisija stakleničkih plinova [23] (slika je preuzeta iz literature uz dopuštenje klasifikacijskog društva Det Norske Veritas (DNV))

The short-term ambition (2018–2023) represents measures for the beginning of reducing the GHGs either by the introduction of energy efficiency regulation (Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP)) or by the implementation of an operative measure of speed reduction. The mid-term ambition (2023–2030) includes the measures of increasing the energy efficiency of ship power system, the implementation of low-carbon fuels and the implementation of carbon allowance in the shipping sector. The long-term ambition (2030–) refers to the development of zero-carbon fuels and innovative emission reduction technology that could achieve the 2050 goal and further zero-emission goal within this century [23].

2.2. The Croatian short-sea shipping sector

Croatia is situated on the East Adriatic coastline, which is very indented and has many islands. Since the islands need to be connected with the mainland by ships, the short-sea shipping fleet counts a great number of ships. The term short-sea shipping fleet refers to the ships that operate between national ports and between a country's ports and the ports of the neighbouring countries [24].

The released emissions during ship operation negatively affect the environment and human health; this is more pronounced for the ships that spend a lot of time near inhabited areas and in ports, which is the case for ships engaged in the short-sea shipping sector (e.g. ro-ro passenger ships) [25], [26]. Ro-ro transport refers to roll on – roll off transport for vehicles transported on and off the ship on their own wheels [27], while ro-ro passenger ship refers to a ship that transports both passengers and vehicles. A typical example of such a ship is a ferry. A major part of the Croatian ro-ro passenger fleet includes outdated vessels with an average age of 29 years powered by diesel engines. A total of 44 ro-ro passenger ships have been identified that operate on the Croatian side of the Adriatic Sea on 27 ferry lines, out of which 24 domestic and 3 international ferry lines, connecting Croatia to Italy and vice versa [10]. In order to determine which ferry lines have a major contribution to atmospheric pollution, the analysis has been performed by following steps presented in Figure 3.

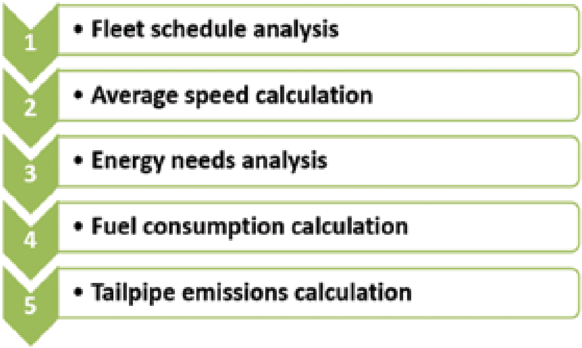

Figure 3. Analysis procedure of the emissions released from the Croatian ro-ro passenger fleet

Slika 3. Postupak analize emisija ispušnih plinova hrvatske ro-ro putničke flote

The mathematical model of the analysis is presented in the study by Perčić et al. [28]. The results are presented in Figure 4 and Figure 5, where annual tailpipe emissions of CO_2, NO_X, SO_X and PM of considered ferry lines are calculated.

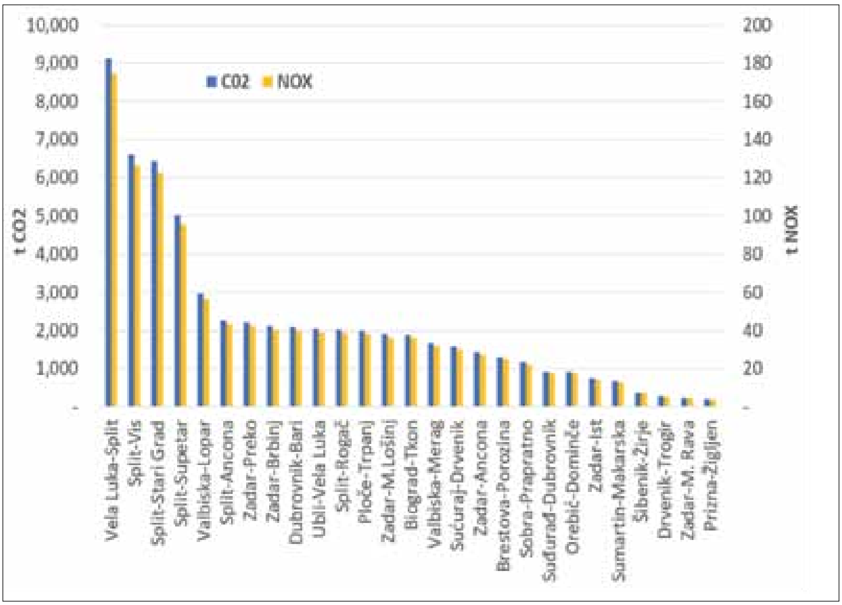

Figure 4. Annual CO_2 and NO_X emissions [29]

Slika 4. Godišnje CO_2 i NO_X emisije [29]

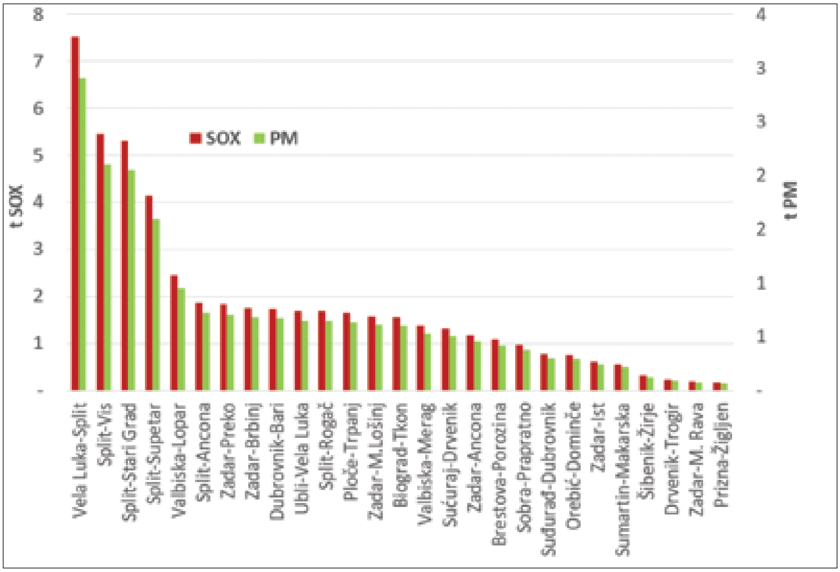

Figure 5. Annual SO_X and PM emissions [29]

Slika 5. Godišnje SO_X i PM emisije [29]

Calculated annual emissions indicated which ships, operating on specific ferry lines, contribute more to the atmospheric pollution and more negatively affect human health. With the application of the CF reduction measures, the tailpipe emissions would be reduced. The implementation of zero-carbon fuels in a ship power system does not generate tailpipe emissions during ship operation, but a great number of emissions are released during the production of such fuels. Since the main aim of the climate policy is to reduce the GHGs at global level, the emissions released through the entire life-cycle of fuel should be investigated by performing the Life-Cycle Assessment (LCA).

This paper illustrates some of the available technical solutions that can be implemented for the CF reduction of the Croatian short-sea shipping sector, whereby the emphasis has been put on the replacement of conventional diesel power systems installed on board selected ro-ro passenger ships.

2.3. Illustrative examples of the selected technical measures

The selected technical measures that offer a reduction of shipping emissions are the replacement of a conventional power system (i.e. diesel engine) with an alternative one, either powered by alternative and cleaner fuel or alternative powering options, such as the implementation of the RESs. Furthermore, the implementation of the ESD has been outlined as a technical measure of CO_2 emission reduction.

2.3.1. The application of alternative fuels in a ship power system

The analysis of the application of alternative marine fuels (electricity, methanol, dimethyl ether (DME), natural gas, hydrogen and biodiesel) has been performed in [28] for three ro-ro passenger ships that operate in the Adriatic Sea. They have been selected based on the route length, i.e. Ship 1 operates on a very short route (Prizna-Žigljen), while Ship 2 (Ploče-Trpanj) and Ship 3 (Split-Vis) operate on medium and long routes, Figure 6.

Figure 6. Selected ro-ro passenger ships and their routes [28]
Slika 6. Odabrani ro-ro putnički brodovi i njihove rute [28]

The most environmentally friendly fuel was identified with an LCA, considering the CO_2-eq emission released during the life-cycle of a power system. The investigated emissions are divided into three groups: Well-to-Pump (WTP) emissions refer to the emissions related to the fuel cycle (raw material extraction, production of fuel and its distribution to the refuelling station), Pump-to-Wake (PTW) emissions refer to the emissions released during the use of the fuel in a ship power system, i.e. ship operation, while Manufacturing emissions refer to the manufacturing of the main element of a power system. Each LCA is performed by means of the LCA software GREET [30], Figure 7.

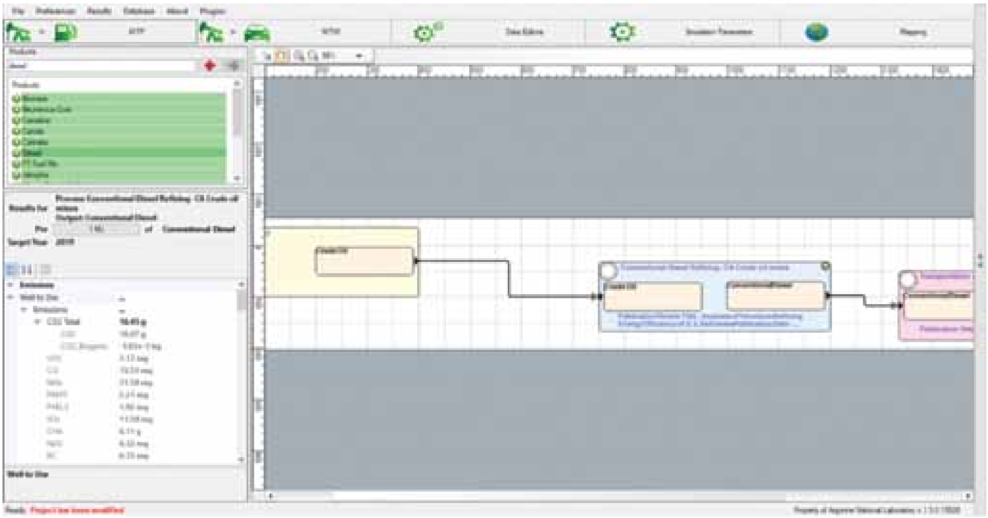

Figure 7. The interface of the LCA software GREET

Slika 7. Sučelje LCA programa GREET

The most cost-efficient power system is indicated by performing the Life-Cycle Cost Assessment (LCCA), which gathers the total costs of a power system, i.e. investment cost, fuel cost, maintenance cost, etc. In this research, the market-based measure of carbon allowance implementation is observed, where the most rigorous implementation scenario, i.e. the Sustainable Development (SD) scenario, is considered.

Both economic and environmental assessments are performed from the lifetime point of view of 20 years. Mathematical models are presented in [28], while the results of the research are shown in Figure 8, whereby D denotes diesel, E denotes electricity, M refers to methanol, the LNG refers to liquefied natural gas, the CNG denotes compressed natural gas, the DME denotes dimethyl ether, the RH represents renewable hydrogen, the FH represents fossil hydrogen, and the BD refers to biodiesel-diesel blend.

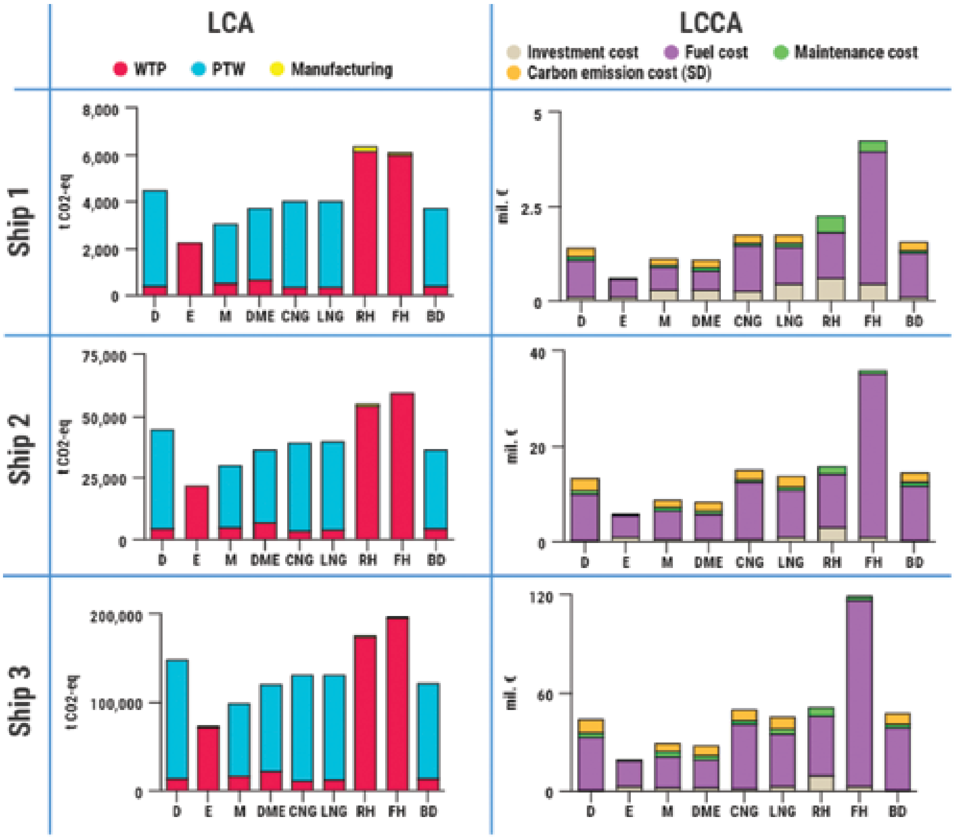

Figure 8. The environmental and economic assessment of different alternative fuels [28]

Slika 8. Ekološka i ekonomska analiza različitih alternativnih goriva [28]

The results indicate that for each considered ship, an electricity-powered ship with only a battery as power source is the most environmentally friendly and the most cost-efficient power system among those considered. On the other hand, a power system constituted of low-temperature fuel cell powered by fossil hydrogen represents the worst alternative option to be implemented in a ship power system.

2.3.2. The utilization of solar energy for ship energy needs

The analysis of different ship power systems (diesel-powered ship, battery-powered ship and PV cells-battery-powered ship) is performed and presented in [31], where the results relate to the ship that operates on the Ploče-Trpanj route, i.e. Ship 2 from Figure 6.

The utilization of solar energy for ship energy needs is accomplished by the installation of the PV cells on the ship deck. However, the selected ship cannot be powered only by solar power. Therefore, a PV system is incorporated into a power system with a battery. Such as in the previous illustrative example, in this research, the LCA and the LCCA are also performed to highlight the most ecological and economic power system. The mathematical model is presented in [31], and the results of the research are presented in Figure 9 and Figure 10.

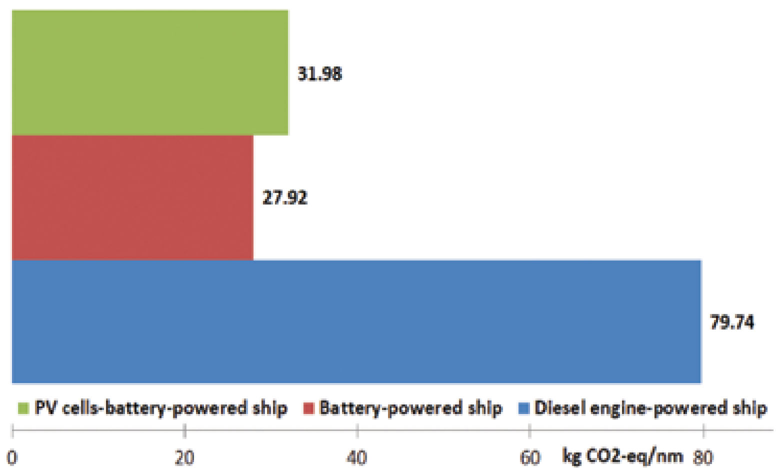

Figure 9. The LCA comparison of selected power systems [31]

Slika 9. Usporedba cjeloživotnih emisija odabranih energetskih sustava [31]

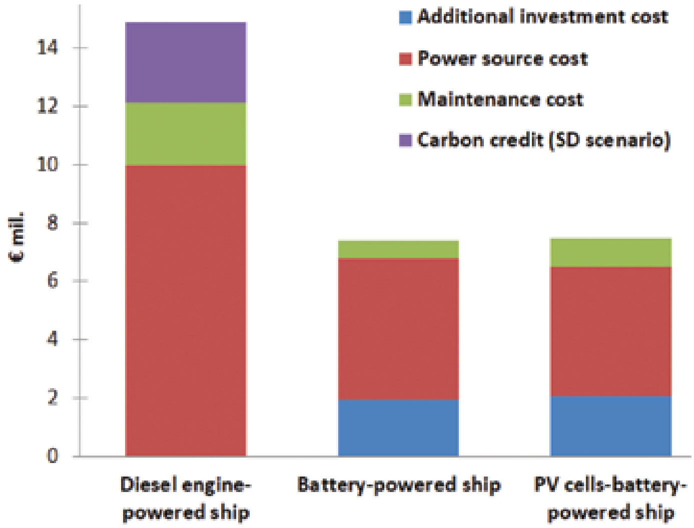

Figure 10. The LCCA comparison of selected power systems [31]

Slika 10. Usporedba cjeloživotnih troškova odabranih energetskih sustava [31]

Both considered alternative power system configurations are presented as a more ecological and cost-effective option than the existing power system configuration with diesel engine installed on board ro-ro passenger ship. Even though the PV cells-battery-powered ship satisfies some of its energy needs with solar energy, which is generated without released emissions, due to the emissions released within the process of PV system manufacturing, the battery-powered ship has a slightly lower CF and slightly lower total costs than the PV cells-battery-powered ship.

2.3.3. The installation of energy-saving devices

Recently, the ESDs have become an attractive and cost-effective measure not only in reducing fuel consumption in the shipping sector, but consequently also in reducing the carbon footprint. The ESDs can be installed both on new buildings and existing vessels in an attempt to increase its fuel efficiency. Compared to all possible improvements with respect to marine propulsion, the ESDs provide one of the least expensive alternatives, although it should be clearly stated that not every ESD can be beneficial for a specific type of ship. Essentially, these devices recover energy losses at the vicinity of the propeller, so for each device to operate properly, there must be a specific type of energy loss present in order for the ESD operational profile to be effective [32], [33].

The commonly accepted classification of ESDs is according to their location with respect to the propeller plane [34], as shown in Figure 11. Zone I (behind the propeller) devices alter the flow before it reaches the propeller by enhancing a radial uniform velocity distribution (duct type) or by adding an additional rotational component to reduce the amount of kinetic energy losses in the propeller wake (pre-swirl stator and other fin type ESDs), or by combining the benefits of both the duct and the fin typed ESD (e.g. Mewis duct). Zone II devices refer to the non-conventional propeller designs, such as contracted and loaded tip propellers, contra-rotating propeller or propeller hub improvements (propeller boss cap fins), which effectively reduce the hub vortex. Finally, Zone III devices aim at recovering energy losses in the propeller slipstream. This usually includes rudder modifications or the unconventional free-to-rotate wheel retrieving rotational kinetic energy from the propeller.

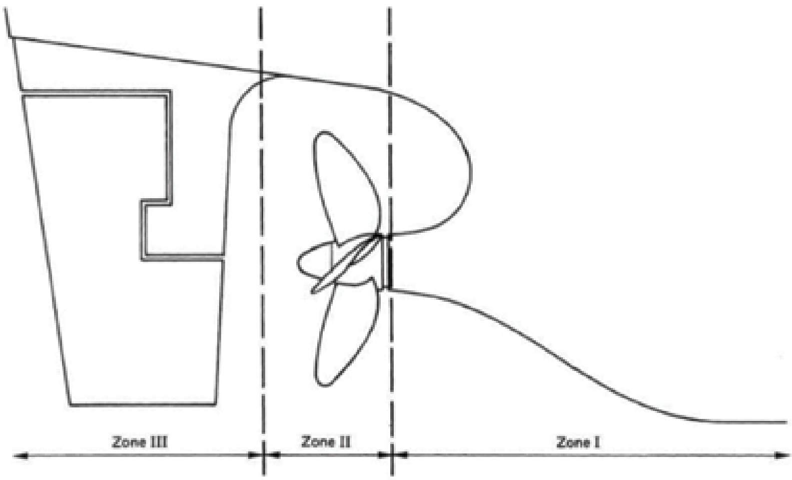

Figure 11. The classification of energy saving devices [34]
Slika 11. Klasifikacija uređaja za uštedu energije [34]

Currently, the most widespread and investigated devices for standard merchant fleet belong to Zone I. One of the first devices is the Wake Equalizing Duct (WED). Numerous authors investigated WED by using numerical methods [35] or experimental analysis [36], with estimated savings ranging even up to 9% in propulsive efficiency. Even commercially available designs are available with the authors in [37], stressing optimum effectiveness if the ship design speed lies between 12 and 18 knots, with a block coefficient larger than 0.6. Similarly, the ESD designed by Mewis [38] – a combination of the duct and Pre-Swirl Stator (PSS) – reports suitable vessel speed under 20 knots, with high block coefficient as the most beneficial with savings from 3 to 9%. Obviously, these ship parameters favour the bilge vortex creation, hence creating necessary energy losses in the ship hydrodynamics, for which these ESDs can be beneficial. Similar savings of 3 to 6% are reported by Kim et al. [39] for the PSS and the PSS-duct combination. There furthermore exist the so-called vortex generators [40], but their benefit should yet be investigated in detail. Overall, devices in Zone I should not be optimized independently, but only together with both the hull and the propeller, while minimizing the flow separation at the ESD surface to reduce the drag from the installation of the device and possible vibration issues.

From the Zone II ESDs, the ongoing development is dedicated to contracted and loaded tip (CLT) propellers. These devices are theoretically explained and investigated in [41]. The CLT propellers shift the load distribution to the propeller tip; this improves the efficiency, but has a negative effect of increasing the pressure pulses on the ship stern surface, which is directly correlated to vibration and noise transmitted to the hull structure. Propeller Boss Cap Fins (PBCF) offer a simple advantage of reducing the hub vortex. The PBCF fuel savings range from 1 to 2% according to recent works in [42]; their safety and simple installation make them one of the prominent ESDs for ship owners. To the contrary, Contra-Rotating Propellers (CRPs) drastically reduce the rotational losses, but their high complexity and cost of maintenance make them suitable for specialized ship types only.

In Zone III, there are numerous rudder modifications to decrease the rotational energy loss, such as Z-twisted rudder with and without the bulb [43], placement of thrust fins on the rudder [44], X-twisted rudder [45], and even bio-mimicking wavy twisted rudder [46]. The range of savings for this type of rudder improvement lies between 2 and 5% in propulsion efficiency. Besides the rudder modifications, one of the most unusual ESDs is the Vane Wheel (VW). The VW is free to rotate after the propeller plane and designed as a turbine on the bottom part of the wing, while the geometry slowly transitions to a propeller blade shape on the outermost part. However, obvious complexities in design, maintenance and cost have not brought this device to prominence [47].

A combination of devices is possible for the optimum fuel consumption, but it should be clear that savings from a single device will not have the same efficiency when combined with another type of the ESD, having in mind their mutual interaction. Furthermore, devices reducing the same kind of energy losses should be assessed in detail before deciding whether their interaction is beneficial – for example, the PBCF combined with the rudder bulb, both of which reduce the hub vortex, is likely to reduce the efficiency of their independent employment. Nonetheless, the evaluation of any ESD still remains an open subject due to scaling effects and uncertain estimation of interaction between the ESD, hull and propeller in real ship operation. Complementary data between experimental analysis and numerical simulations become important here. Due to high turbulence in the region near the propeller plane (i.e. wake field), the use of potential flow models is not recommended. In recent years, substantial progress in the field of the ESDs is owed to the Computational Fluid Dynamics (CFD) simulations. An example of a CFD simulation with propeller and the PSS is shown in Figure 12. Another subject still not fully addressed is the structural integrity of the ESDs. Given their novel design and the relatively complex flow field in which they operate, classification societies do not offer straightforward rules and regulations for their ultimate strength analysis, as well as fatigue. The lack of a clear design procedure initiated a joint project GRIP [48] featuring a thorough investigation of the PSS and the duct type ESD. Overall, given the current increasing regulations on harmful gases, the ESDs design will continue to mature and develop from the perspective of both the hydrodynamic design and the structural safety, while keeping in mind their promising benefit in terms of reduced fuel consumption.

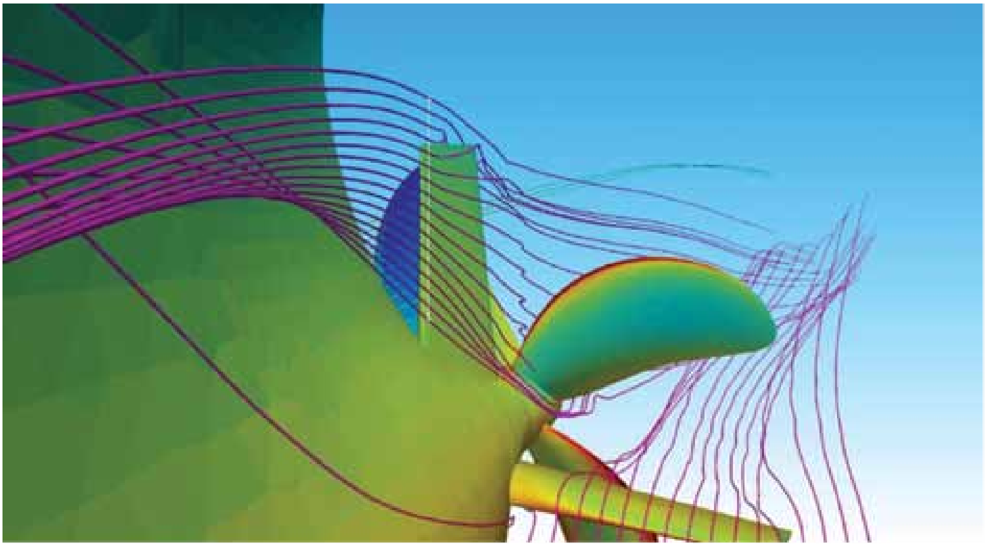

Figure 12. An example of the CFD simulation of flow around the ESD
Slika 12. Primjer CFD simulacije opstrujavanja uređaja za uštedu energije

The illustrative examples of the selected technical measures indicated that an electricity-powered ship with only a battery as a power source is the most ecological and the most cost-effective alternative power system that might replace the diesel engine power system configuration. By implementing the carbon pricing policy in the shipping sector, an electricity-powered ship appears more cost-effective due to the absence of tailpipe emissions.

Similar research as presented in this paper was performed for the Inland navigation fleet in Croatia. In that study, Perčić et al. [49] performed the LCA and the LCCA comparisons of different alternative fuels; the results are illustrated on three different types of ship: cargo ship, passenger ship, and dredger. The study showed that an electricity-powered ship with only a battery as power source represents the most ecological solution for each type of ship. However, the LCCA comparison indicated that an electricity-powered ship is the only cost-effective solution for a passenger ship, while for cargo ship and dredger, the methanol and diesel represent the most ecological solution, while for them, an electricity-powered ship results in very high costs. It is evident that the implementation of alternative fuels depends greatly on the area of navigation, as well as on the type of ship and its exploitation characteristics.

The main limitations of this research are:

- The assumption that the ship is powered by only one power source, and not with two or more power sources included in a hybrid power system. This may be thoroughly investigated by the means of an analysis of such a system and the individual shares of power sources included in it. Its environmental performance and cost-effectiveness can be assessed with optimization methods.
- The focus of the research is only on the atmospheric pollution due to emissions released through the life cycle of a power system. Replacing conventional fossil fuel with alternative fuel represents a feasible measure for the reduction of shipping emissions. While considering different alternative fuels, the toxicity of the fuel for the marine ecosystem in case the ship has an accident and the fuel ends up in the sea should be borne in mind. Therefore, with the replacement of diesel fuel with alternative and non-toxic fuel with low carbon content, seawater pollution and atmospheric pollution would be reduced.
- With respect to the ESDs, it is fair to say that their applicability was not investigated in detail for the Croatian coastal fleet, because at this stage, the emphasis of the research is on the development of hydro-structure mathematical models that will provide full insight into their structural design as a prerogative, while the techno-economic aspects will be addressed in future investigations.

3. SEAWATER PROTECTION IN THE ADRIATIC SEA

In addition to the harmful effect on the marine ecosystem, each seawater pollution problem negatively affects human health and the economy of the considered country as well. Current trends in the area of marine pollution prevention have led to the development of early warning systems with the installation of the multi-parameter probe on-site, and collecting the real-time data of several parameters. The process of establishment of an early warning system contains several steps. The first step is to conclude which parameters give valuable information about water quality level and setting up a repository that will receive and store data from various sources. The network of multi-parameter probes represents one source, a scientific set of data that can be analysed and understood by highly educated personnel. As a future challenge, the goal is to develop an application that can be used by the general public, and therefore raise the awareness of marine pollution issues [3], Figure 13.

Figure 13. The preview of the early warning system developed within the SEAVIEWS project

Slika 13. Sustav ranog upozoravanja na zagađenje razvijen u okviru projekta SEAVIEWS

Some of the tracked parameters include salinity, temperature, pH, dissolved oxygen, total dissolved solids, etc., whose values can indicate that marine pollution occurred. The rise of water temperature can increase the risk of water-borne diseases, as well as contribute to the appearance of oxygen-depleted zones, i.e. “dead zones”, which cause the mortality of marine organisms. Salinity variations due to the inflow of freshwater can also affect the development of marine organisms, especially crustaceans. As a result of the absorption of a larger amount of CO_2 in the ocean and the production of carbonic acid, the acidification affects the photosynthesis of marine plants and prevents crustaceans from developing a strong exoskeleton [50].

4. FUTURE CHALLENGES IN THE COASTAL NAVIGATION – AN INCREASE OF SHIP AUTONOMY

Rapid technological development, wireless communication and monitoring, growing environmental awareness, alternative fuels, and stringent regulations are continuously present in maritime transportation and shipbuilding. The maritime sector is exploring ways to reduce cost and emissions, but at the same time to increase safety and energy efficiency. Autonomous shipping is an emerging topic, where technical, economic, safety, and environmental aspects are still not mature enough to significantly increase the percentage of autonomous vessels in the global fleet. The technologies needed for autonomous navigation already exist, and it is necessary to find the optimal way to combine their safety, reliability, feasibility, and cost-effectiveness. It is also important to investigate what types of ships and which trades are suitable for autonomous shipping.

The autonomous ship contains some form of autonomy, which means that certain tasks are executed without human interference [51]. Autonomy degree increases while human involvement decreases. A fully autonomous ship can perform all the needed tasks by itself. A fully autonomous merchant ship is not likely to be seen in the coming future, but transferring some assignments from crew to autonomous systems and shore is the way to achieve this goal [52]. The path from manned to autonomous ship is shown in Figure 14, indicating that remote control enables unmanned shipping.

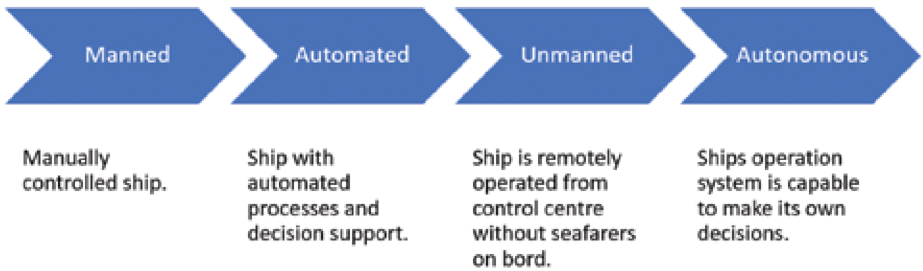

Figure 14. The path from manned to autonomous ship

Slika 14. Put od broda s posadom do autonomnog broda

The transition from manned to unmanned and autonomous shipping is expected to be gradual, with a lot of alternations, testing, and simulations [53]. It is important to precisely define the levels/classes of autonomy. Currently, there are a few classifications of ship autonomy, and they are shown in [53].

The International Maritime Organization has defined the following four Degrees of Autonomy (DoA) related to Maritime Autonomous Surface Ships (MASS) [54]:

1. DoA1, ships with automated processes and decision support, where the seafarers are on board for the operation and control. Some operations may be automated and at times be unsupervised, but with seafarers on board, ready to take control.
2. DoA2, a remotely controlled ship with seafarers on board. The ship is controlled and operated from another location. Seafarers are available on board for taking control and operating the shipboard systems and functions.
3. DoA3, a remotely controlled ship without seafarers on board. The ship is controlled and operated from another location. There are no seafarers on board.
4. DoA4, a fully autonomous ship. The operating system of the ship can make decisions and determine actions by itself.

With the increase in ship automation, the number of crew members has decreased significantly. It is now 18-22 crew members on board commercial ocean-going ships. Although the number of members was constantly decreasing, it is not known whether the number reached the lower boundary or can it be eliminated for most of the vessels with the implementation of an autonomous ship's crew. Apart from human casualties and equipment/vessel damage, maritime accidents cause environmental disasters [55]. In the period from 2011 to 2018, 65.8% of maritime accidents were attributed to human error [56], indicating that if the human action is less involved in ship operations, the number of accidents will probably decrease. An autonomous ship will find its successful commercial usage when it is shown that they are at least as safe as conventional ships [57].

Shore Control Centre (SCC) allows for the transition of the crew from ship to shore. The crew in the SCC supervises and remotely operates a ship; when needed, it takes full control. Sensor fusion on ships is crucial for reliable remote operation. Data collected by multiple cameras, RADAR (Radio detection and ranging), LIDAR (Light detection and ranging), and sonars are transmitted to the SCC to gain situation awareness [58].

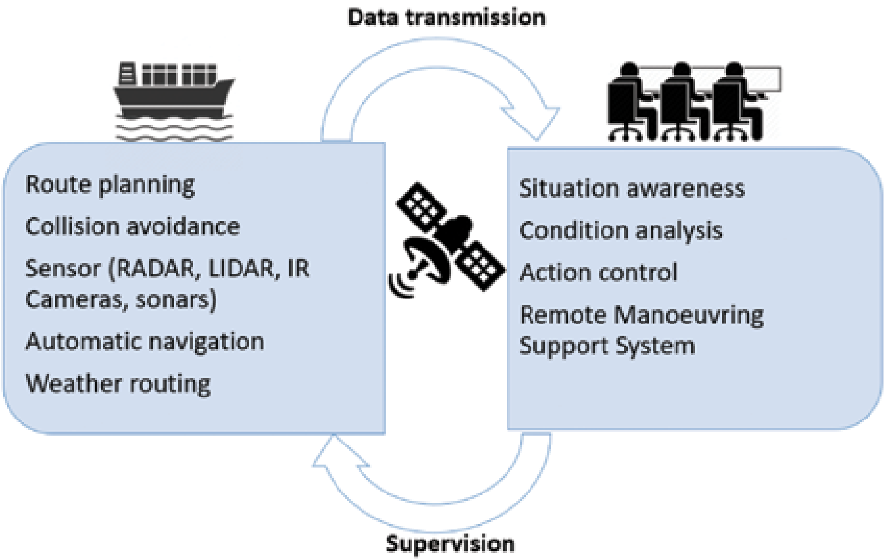

Figure 15. Relation between ship and remote control centre
Slika 15. Veza između broda i centra za daljinsko upravljanje

Essential components needed for autonomous operations are guidance, navigation, and control systems, which are connected and dependable on each other [59]. The guidance system can be classified in path planning [60], [61] (global and local) and replanning, and collision avoidance [62]. Advanced sensing technologies enable a safe navigation system that is classified in state estimation, environmental perception, and situation awareness.

Kretschmann et al. [63] conducted a cost comparison between an autonomous and a conventional Panamax bulk carrier for three scenarios, taking into consideration reduced crew, new port services, improved energy efficiency, and additional capital costs, pointing out that autonomous shipping has the potential to increase profitability and reduce emissions. The application of such a solution in the Croatian coastal navigation is a subject of ongoing research activities, where the authors are developing mathematical models to assess the effect of the increase of autonomy degree on ship total costs and safety.

5. CONCLUSION

The control of marine pollution is mainly focused on air pollution caused by emissions released from the combustion of fossil fuel in a marine engine. By replacing conventional marine fuel, i.e. diesel, with alternative and cleaner fuel, shipping emissions can be reduced. The research presented in this paper refers to the application of some advanced technical solutions, illustrated on ro-ro passenger ships engaged in the Croatian short-sea shipping fleet. The analyses of different alternative fuels and power systems are performed from the environmental and economic points of view. The presented LCA and LCCA comparisons indicated that an electricity-powered ship, i.e. a ship powered by a power system that consists of only a battery as power source that is charged onshore, is the most cost-effective and environmentally friendly solution to replace the conventional power system with diesel as fuel.

Current technological developments have brought significant changes to the shipping industry, encouraging digitalization and automation, which will result in increased autonomy levels and make the shipping sector energy efficient. There is a large number of research projects currently conducted on these topics, bringing autonomous shipping closer to commercial applications.

In this paper, the outcomes of several research projects dedicated to the protection of the Adriatic Sea are summarized. The investigations of the CF reduction of vessels operating in the Adriatic Sea is a mature topic, already offering viable options and guidelines for the modernization of the ro-ro passenger fleet. The investigations of seawater protection and an increase of the level of autonomy are currently in the intermediate stage. Precise modernization directions can be expected in near future.

Future research projects dedicated to the protection of the Adriatic Sea should be oriented toward the increase of energy efficiency and environmental friendliness of other ship types, as for instance fishing vessels, as well as to the development of intelligent solutions for sustainable and environmentally friendly aquaculture.

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NAPREDNA TEHNIČKA RJEŠENJA ZA KONTROLU ONEČIŠĆENJA POMORSKOG SEKTORA U JADRANSKOM MORU

Sažetak

Glavni ekološki problemi u pomorskom sektoru su onečišćenje atmosfere zbog upotrebe fosilnih goriva u brodskom energetskom sustavu te onečišćenje morske vode iz različitih izvora (npr. izlijevanje nafte, mikroplastika, zakiseljavanje itd.). Zbog njihovog negativnog utjecaja na okoliš, ljudsko zdravlje i morski ekosustav, treba ih pažljivo kontrolirati. Studije o ekološkim problemima pomorskog sektora više su usredotočene na onečišćenje atmosfere, što je uglavnom posljedica Pariškog sporazuma prema kojem bi svaki sektor trebao doprinijeti smanjenju stakleničkih plinova. Brodovi su uglavnom pogonjeni konvencionalnim energetskim sustavima s dizelskih motorima, čiji bi negativan učinak na okoliš bio manji provedbom nekih mjera za smanjenje emisija. U ovom radu prikazana su istraživanja o naprednim tehničkim mjerama za kontrolu pomorskog onečišćenja, a rezultati su ilustrirani na ro-ro putničkim brodovima hrvatske priobalne plovidbe. Analize cjeloživotnih emisija i troškova potiču modernizaciju konvencionalnih energetskih sustava elektrifikacijom broda. Ovo je rješenje predstavljeno kao najisplativije i ekološki najprihvatljivije. Uz spomenute mehanizme za smanjenje onečišćenja zraka, u radu je dan osvrt na određena rješenja za nadzor i očuvanje morske vode s naglaskom na sustav ranog upozoravanja razvijen od strane autora u okviru kompetitivnog međunarodnog projekta. Naposljetku, u skladu sa svjetskim trendovima u pomorskom sektoru, dan je osvrt na povećanje stupnja autonomnosti brodova, kao jedne od važnijih tema u bližoj budućnosti.

Ključne riječi: onečišćenje pomorskog sektora; smanjenje emisija; ro-ro putnički brod; alternativna goriva; uređaj za uštedu energije; sustav ranog upozoravanja.

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