Decarbonization of the Maritime Transportation Systems: Recent Progress, Challenges, and Prospects

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Abstract— **Maritime transportation decarbonization plays a pivotal role in eliminating carbon emissions from the transportation sector, one of the significant contributors to global greenhouse gas (GHG) emissions. The maritime transportation industry, traditionally reliant on fossil fuels, is experiencing a rapid transformation by adopting alternative fuels and renewable energy sources to drive sustainable practices in the shipping sector. This paper aims to provide insight into emerging technologies to achieve decarbonization, such as alternative fuels, alternative energy sources (onshore power supply, wind energy, solar energy, fuel cell), and operational approaches (speed optimization, voyage optimization). Moreover, we present these technologies' benefits and challenges, recent progress, and future directions.**

Keywords—decarbonization, maritime transportation, sustainability, alternative fuels, alternative energy sources, shipping emissions

I. Introduction

Greenhouse gas emissions significantly trigger climate change and various environmental problems. Although global emissions decreased by 6% in 2020 due to the Covid-19 pandemic, it is projected to rise dramatically in next three years [1]. Maritime shipping sector plays a crucial role in emitting greenhouse gas emissions. Particularly, port operations (road vehicles, port facility energy usage, non-road mobile machinery) and vessel operations (vessels in port, vessels at sea) play a larger role in air pollution in maritime shipping sector [2]. Considering the emissions of shipping industry including international, domestic, and fishing, there was an increase in GHG emissions by 9.6% from 2012 to 2018 [3]. International Maritime Organization (IMO) introduced an initial GHG strategy in 2018 [4] so as to curb the increase of the shipping emissions. This strategy sets a target of a minimum 50% reduction in total annual GHG emissions from international shipping by 2050 as compared to the levels in 2008 [4]. Some countries have devised plans and strategies to fulfil this purpose [5,6]. For instance, during Cop26, Clydebank Declaration was endorsed by 22 countries to establish a minimum of six green zero emission routes connecting ports by 2025, with the plans for further expansion prior to 2030 [7].

There are numerous benefits of the decarbonization of shipping industry. Besides combatting the imminent threat of climate change and protecting the maritime ecosystems, it can also contribute to reducing air pollution in the environment, which can positively affect the health of people living and commuting near ports.

Due to its the policy-level relevance, the decarbonization of the maritime industry has been increasingly investigated in the recent literature. For instance, Mallouppas and Yfantis [8] highlight the importance of radical technological improvements as well as social pressure and financial incentives in order to reach the aim of IMO. Psaraftis and Kontovas [9] conclude that achieving the target of IMO in 2050 requires taking a huge step forward in terms of energy-saving technologies and alternative fuels. Likewise, Ampah et al. [10] indicate that accomplishing IMO's strategy is an issue that requires effort, and using cleaner alternative fuels can be preferred to decarbonize maritime transportation. Molavi et al. [11] research how the performance of ports regarding operations, environment, energy, and safety can be enhanced via the integration of microgrids.

To decarbonize the shipping industry, it is evident that low-carbon technological improvements are necessary. The aim of this paper is to provide insights into the current state of decarbonization of the shipping industry and to present technological advancements, with a focus on alternative fuels, renewable energy sources, and onshore power supply in the literature to achieve the goal of decarbonization in maritime transportation.

The subsequent sections of this paper are arranged as follows. Section 2 covers emerging technologies to decarbonize the shipping industry, such as alternative fuels and alternative energy sources. Section 3 presents a discussion and provides insight into the benefits and barriers of emerging technologies, the latest progress, and future trends to reduce emissions and enhance sustainability in the maritime sector. Section 4 draws a conclusion.

II. Emerging Technologies for Decarbonization

In this section, we review some of the most promising emerging technologies, such as alternative maritime fuels, renewable energy sources, and onshore power supply to reduce the carbon footprint of the marine shipping industry.

Furthermore, some relevant studies in the literature are presented.

A. Alternative fuels

Switching from traditional maritime fuels to the use of alternative fuels plays a crucial role in reducing emissions in the shipping industry by replacing marine diesel oil and heavy fuel oil with much cleaner energy carriers, like hydrogen, ammonia, liquid natural gas (LNG), biofuels, electricity (via storage), wind, and nuclear. According to Fourth IMO GHG Study [12], heavy fuel oil, one of the significant fuel sources in maritime transportation, decreased by 7% in 2018, while marine diesel oil, LNG, and methanol consumption increased.

Hydrogen is one of the promising sustainable solutions for the shipping sector. It has no carbon dioxide or sulfur oxide emissions and only leads to an insignificant amount of nitrogen oxide [13]. Thus, using hydrogen as a fuel provides environmental benefits for maritime transportation. To this end, Bicer and Dincer [14] conduct a life cycle assessment to investigate the environmental impact of using hydrogen and ammonia instead of diesel and heavy fuel oils in maritime transportation. The results of this study demonstrate that the utilization of ammonia as a dual fuel in ship engines has the potential to result in a reduction of up to 34.5% in total GHG emissions per tonne-kilometer. On the other hand, it is worthwhile mentioning that there are some challenges to adopting hydrogen as a fuel in terms of fuel availability, infrastructure, safety, and energy cost [15].

LNG is another attractive solution to combat climate change and provide environmental benefits in the shipping sector. Livaniou and Papadopoulos [16] compare conventional fuels and LNG by conducting a case study in a Greek port. Their results highlight that LNG is an effective alternative fuel to achieve decarbonization in the ports. Moreover, LNG is a fuel that is accessible globally. The price of LNG is relatively low compared to other alternative fuels, although it is not stable. However, there are some barriers regarding bunkering infrastructure, and its investment can be costly in comparison to other traditional fuels [15].

B. Alternative energy sources

1) Onshore power supply

Onshore power supply (OPS) or cold ironing is a technology that enables ships with the capability to turn off their engines and utilize grid electricity to get power during the berth. According to World Ports Sustainability Report [17], 66 ports in sixteen countries have adopted high-voltage OPS technology. In addition, ESPO Environmental Report [18] highlights that the number of ports providing OPS technology in Europe has increased.

There are some crucial environmental benefits of adopting OPS in the ports. It contributes to mitigating air emissions as well as reducing the noise of ships [13]. Enhancing air quality, thanks to OPS, also profoundly affects the health of people living or commuting in port areas. Stolz et al. [19] conclude that using OPS from the national grids instead of auxiliary engines in some major UK ports would help reduce overall shipping emissions by 2.2%. Likewise, Gutierrez-Romero et al. [20] demonstrate OPS using renewable sources is an approach that helps reduce emissions. According to their study implemented in Cartagena Port, Spain, more than 10,000 tons of carbon dioxide emissions would be reduced annually by implementing OPS technology from renewable energy sources. Wang et al. [21] present a bilevel economic approach to help the decisions of the regulatory agency and port entities so as to increase the adoption of OPS technology and mitigate the ships' emissions at berth. Zhang et al. [22] offer a two-stage model focusing on assessment of berth locations and the optimal scheduling of a port microgrid by using of the OPS technology. The proposed model contributes to improving system efficiency and reliability as well as the reduction in emissions. According to the case study considering tax and economic incentives implemented by Molavi et al. [23], OPS is an effective solution to alleviate emissions.

It is vital to consider some barriers to adopting OPS technology. Tseng and Pilcher [24] address undesirable installation costs, different power requirements based on ship type, size, etc., and the lack of international regulations for its adoption as the challenges for implementing OPS.

2) Solar power

Solar energy is an environmentally friendly option to reduce carbon footprint and fuel consumption. The use of Photovoltaic (PV) cells is one of the ways to convert solar energy into electricity in maritime shipping. Thus, ships can utilize electricity for their operations, such as air conditioning and lighting.

Hussein and Ahmed [25] show that using PV cells provides benefits, such as low maintenance cost, zero emissions and noise, and no difficulties in installation and refurbishment. Karatuğ and Durmuşoğlu [26] propose a new approach to designing an onboard solar system, and they implement a case study to test the layout. Their results demonstrate that the proposed solar design significantly contributes to reducing fuel consumption and GHG emissions. Additionally, high productivity via solar systems is observed in summer compared to the winter season. Perčić et al. [27] conduct a comparative analysis between a diesel engine-powered ship and a ship that integrates PV cells in the Croatian shipping sector. Their results demonstrate that the ship adopting PV cell battery reduced almost €4,653,100 in the total cost and 47.76 kg CO_2-eq/nm in emissions compared with the ship with a diesel engine.

It is worth noticing that meteorology can affect the efficiency of this technology. A simulation-based case study conducted by Park et al. [28] indicates that weather parameters and power production methods of countries affect solar PV's efficiency. Therefore, this technology is a more appropriate investment for ships operating in areas close to the equator [13]. Inclement weather conditions also might have an adverse effect on the efficiency of this technology. Another barrier to adapting solar PV is that it requires a large surface to install and harvest sufficient energy [29].

3) Wind power

Wind power is another promising pathway toward decarbonization in maritime transportation. Wind energy in maritime shipping has been used more widely compared to the past since energy efficiency increases with the advancement of technology (digitalization, automation, sensors, and so on) and emission reduction targets [2]. It is estimated that this technology can help mitigate carbon emissions by 1-50% [30] in the shipping sector.

Wind power generation and wind-assisted propulsion are some of the representative ways to harness wind power in vessels. Wind-assisted propulsion technology is much more energy-efficiency as compared to wind power generation [31]. Using wind turbines to generate power is also effective in reducing and eliminating emissions.

However, there are also barriers to using wind power in the maritime sector. The speed ratio of vessels affects the efficiency of wind power. For instance, race boats can benefit from wind power more efficiently than cargo ships [29]. Trip duration, wind speed, wave height, seasonal variations, optimization of routes, and trade pattern are other indicators affecting the performance of wind-assisted ship propulsion systems [32]. There are some economic barriers, including technical risk, hidden cost of the technology for the widespread adoption of wind power [33]. Moreover, Talluri et al. [34] provide an evaluation approach from an economic and environmental perspective for wind-assisted propulsion systems. Based on the assessment, the efficiency of the vertical installation of two wind turbines on the ship's deck is affected by the environment and routes.

4) Fuel cells

Fuel cells are a maturing technology that generates electricity by harnessing chemical energy in the fuel. There are different types of fuel cells categorized according to electrolyte used, such as alkaline fuel cells, proton exchange membrane fuel cells, solid oxide fuel cells, molten carbonate fuel cells [35]. Because of increased energy efficiency and high-power density, the usage of hydrogen in fuel cells is probably an attractive solution for the future [36]. On the other hand, Perčić et al. [37] conclude that fuel cell technology with green hydrogen is an expensive option even though it ranks first in terms of environmental sustainability.

Reduction of emissions, noise and vibration, flexible design, high efficiency, and reduced maintenance are possible benefits of adopting fuel cells in maritime shipping [1, 38]. Despite these advantages, there are challenges of using fuel cells in terms of economic cost (investment cost, stack costs, cost of auxiliary systems and components, etc.), power capacity, safety, operability, durability, reliability in maritime transportation [35].

There are research projects in many countries (ShipFC (2020-2024), Maranda (2017-2022), Nautilus (2020–2024), HyShip (2021–2024), RiverCell (2015–2022), etc.) related to adopting fuel cell technologies [39]. Di Micco et al. [40] conduct a feasibility analysis adopting a fuel cell utilizing a polymer electrolyte membrane and hydrogen instead of a diesel engine in maritime transportation. The fuel cell system on board ships provides an opportunity to have less volume and mass than the diesel engine. İnal and Deniz [41] implement a case study by gathering a chemical tanker's real-life data and comparing the environmental performance of molten carbonate fuel cell with a traditional diesel engine. In addition to achieving a reduction of over 99% in SO_x, PM, and NO_x emissions, there is a significant reduction of 33% in emissions via the fuel cell technology.

Based on the research covering 150 studies in the literature of Bouman et al. [30], potential carbon dioxide emissions reductions are presented in Table I. In addition, it should be noted that some critical barriers to the extensive utilization the alternative energy sources should be considered. Table II summaries benefits and barriers of adopting these technologies in maritime shipping.

TABLE I. POTENTIAL CARBON EMISSIONS REDUCTION [30]

Alternative Energy Sources	Potential CO_2 Emissions Reduction
Onshore Power Supply	3-10%
Solar Power	0.2-12%
Wind Power	1-50%
Fuel Cells	2-20%

C. Operational approaches

1) Speed Optimization

Engine power plays a vital role in vessels' fuel consumption, and the speed of ships considerably affects the engine power. Therefore, speed optimization of vessels during their voyage dramatically contributes to reducing fuel consumption and carbon footprint in sea transportation. Based on the research covering 150 studies in the literature of Bouman et al. [30], speed optimization has the potential to reduce carbon emissions by 1-60%, which is a significant share among other alternative technologies. In addition, one of the outstanding advantages of speed optimization is that it is energy efficient. This is mainly because ships with higher speeds can complete their routes in a shorter time, leading to less energy consumption. These advantages make this approach an attractive option.

It is worth pointing out that there are some drawbacks to adopting this operational approach. According to a research survey [42], key challenges hindering the implementation of speed optimization include operational challenges, conflicts with charter party requirements, technical risks, and safety concerns. Psaraftis and Kontovas [43] review concepts and models for the speed optimization of vessels. Fuel price, the correlation between fuel consumption and payload, market state and the inventory cost of cargos are identified as baseline parameters in speed optimization models [43].

There are some studies in the literature that establish a speed optimization model [44-48]. Tzortzis and Sakalis [44] offer a dynamic optimization method using weather forecasts that minimizes total fuel consumption in order to determine the optimal speed of ships based on the specified route. The outcomes of the case study applied to an actual container ship route indicate a reduction in fuel consumption by 2%. Li et al. [45] develop a speed optimization model for a container ship along a particular route, considering the option of voluntary speed reduction. This model aims to minimize both the fuel consumption of the main engine and the operating cost of the vessel. This research demonstrates that voluntary loss speed and time window considerably have a crucial impact on speed optimization.

Speed regulations can be implemented so as to help reduce fuel consumption and address climate change for future greener ports. Policies related to speed reduction can be regulated depending on whether the regulations might be voluntary or mandatory, covering global or regional scope, determining average or maximum speed, and varying ship size and type [49]. Some organizations have been developing strategies to achieve decarbonization for future greener ports. Emission Control Area (ECA), Vessel Speed Reduction Incentive Program (VSRIP), Virtual Arrival (VA), and carbon tax policy are some of the policies for this purpose. Significant efforts should be made to comply with these regulations, and some environmental-friendly technologies and approaches should be adopted. Han et al. [50] suggest a speed optimization model based on a quantum genetic algorithm to evaluate these policies that aim to enhance sustainability in port areas. They highlight that considering different policies together (VSRIP, ECA, carbon tax) might not provide a better outcome compared to implementing only one policy.

ECA is one of the widely recognized strategies aiming to alleviate greenhouse gas emissions of ships. Some studies present a speed optimization model considering ECAs [51-54].

2) Voyage Optimization

Voyage optimization helps determine the most appropriate routes for vessels to increase energy efficiency, reduce costs, and enhance safety. Many factors, such as weather conditions and sea/ocean currents, can affect the determining of the most efficient routes of vessels.

Selecting the most efficient routes significantly saves fuel consumption and increases the utilization of energy. It is estimated that voyage optimization can potentially reduce carbon emissions up to 48% [30].

Yu et al. [55] present a comprehensive review article about voyage optimization. They conclude that many factors affect the fuel consumption of vessels, including berth allocation, weather conditions, speed of voyage, time period of voyage, fuel price, and policies related to emission control areas.

Some researchers present voyage optimization models in the literature for specific aims such as minimizing emissions, minimizing fuel consumption, maximizing ship safety, or minimizing travel time. Wang et al. [56] offer an approach for optimizing voyages that relies on the utilization of a genetic algorithm and dynamic programming. Based on the case study applied for a chemical tanker, the presented method provides a reduction in fuel and air emissions by 3.4% as compared with the deterministic approaches. Additionally, some studies develop models or approaches that consider both voyage and speed optimization [54, 57].

III. Discussion and Directions of Future Works

This section aims to address the benefits and barriers of emerging technologies, the latest progress, and future trends to reduce emissions and enhance sustainability in the maritime sector.

- For ***alternative fuels***: When considering alternative fuels, it is important to highlight that the extensive adoption of hydrogen requires infrastructural innovations as well as investments. However, adopting alternative fuels significantly helps decarbonize sea transportation. Therefore, necessary infrastructure and investment costs should be considered to enable the massive implementation of this technology for the future low-carbon maritime sector. With the necessary steps taken in terms of fuel availability, infrastructure, safety, and technological advancements, it is likely that there will be an increase in the utilization of hydrogen, LNG, and ammonia as fuels in maritime transportation.
- For ***OPS technology***: reducing air pollution and emissions could make this technology a more attractive and practical solution in the maritime sector in the future. The future of OPS technology looks promising, although further research is needed regarding pricing and operational frameworks, technical advancements, and regulatory policies. The lack of international regulations and varying power requirements depending on ship size and type can be considered crucial drawbacks for the broad-scale adoption of the technology. Therefore, to ensure the widespread adoption of OPS technology on a global scale, it is essential to implement standard regulations covering voltage/power specifications, electrical connectivity, safety, and security issues. In terms of technological progress, integrating smart microgrids into port areas will significantly increase the efficiency of OPS implementation, as power distribution and energy demand can be effectively managed through these grids. Moreover, taking steps to enhance resilience and reliability in port areas, such as improving infrastructure, strengthening cybersecurity systems, and adopting artificial intelligence and the Internet of Things, will considerably contribute to the operational effectiveness of OPS. For example, the Internet of Things can enable remote performance monitoring and control for ship decision-makers, allowing them to regulate power usage and manage operations effectively for OPS.
- For ***renewable generation***: it is critical to mention that solar and wind power are sensitive to weather conditions. Therefore, achieving a high level of efficiency from solar power systems is highly significant. To that end, advanced design solar power systems should be developed to increase energy efficiency. These systems can include innovative designs of photovoltaic cells, solar windows, and smart solar cells. In the coming years, it is likely that cutting-edge designs will be developed, and novel materials will be used for solar power systems.
- For ***speed optimization***: since there are many factors such as ocean/sea currents, severe weather conditions, and policies that affect the speed of vessels, determining the optimal speed of ships might be a challenging problem to handle. On the other hand, technological advancements, data analytics, and machine learning are likely to provide significant guidance in determining optimal ship speeds in

the future. Incorporating large-scale data, including sensor data, records of historical voyages, meteorological data, traffic information, accident data, emission targets, regulations, and fuel prices, can lead to more realistic results in speed optimization. For speed optimization and other crucial issues, the adoption of big data analytics in maritime shipping can provide valuable information to ships' decision-makers. Additionally, the utilization of smart machines that operate similarly to the human brain in big data analytics can shed light on the decarbonization of maritime transportation.

- For ***voyage optimization***: researchers have been solving these problems by establishing deterministic and heuristic approaches through simulation. It is likely that the future of voyage optimization will be driven by data mining and technological advancements. Adopting artificial intelligence technologies and IoT sensors can make a significant contribution to the development of voyage optimization. For instance, adopting advanced technologies, including digital maps, automatic identification systems, and weather forecasting systems, in voyage optimization would provide high energy efficiency. Through these advancements, the efficiency and safety of voyages can be enhanced, and the environmental impact of maritime transportation can be significantly reduced.

In conclusion, it is obvious that the targets set by the International Maritime Organization (IMO) for the decarbonization of maritime transportation have had a positive impact on efforts, studies, and research in this field. It is also worth noting that achieving widespread adoption of environmentally friendly technologies may require further research and measures to overcome existing barriers.

IV. CONCLUSION

Maritime shipping sector is a significant source of GHG emissions that leads to climate change. To help reach the goal set by climate leaders and IMO, the aim of this paper is to offer an overview of emerging technologies such as alternative energy sources, alternative fuels, and operational approaches. The benefits and challenges of adopting these technologies are presented. Additionally, we share some of the future trends related to the transition towards a low-carbon maritime shipping.

TABLE II. BENEFITS AND BARRIERS OF ADOPTION ALTERNATIVE ENERGY SOURCES IN MARITIME SECTOR

Alternative Energy Sources	**Benefits and Barriers**		
	Benefits	***Barriers***	***Reference Studies***
Onshore power supply	-mitigating air emissions -reduction noise of ships	-undesirable installation costs -different power requirements based on ship type, size, etc. -lack of international regulations	[13,24]
Solar Power	-zero emissions and noise -cheap and abundant -low maintenance cost -no difficulties in installation and refurbishment	-zero emissions and noise -cheap and abundant -low maintenance cost -no difficulties in installation and refurbishment -weather conditions might have an effect on the efficiency of the technology - requiring a large area to get sufficient energy	[13,25, 29,58]
Wind power	-mitigating emissions	- trip duration, wind speed, wave height, seasonal variations, optimization of routes, trade pattern are factor affecting the performance of wind power - economic barriers including technical risk, hidden cost of the technology	[30,32, 33]
Fuel Cells	-emission reduction -high efficiency -reduction in noise and vibration -flexible design -reduced maintenance	-economic cost (investment cost, stack costs, cost of auxiliary systems and components etc.) -power capacity -safety -operability -durability -reliability	[1,35, 38]

REFERENCES

[1] DNV, (2021). Energy transition outlook. A global and regional forecast to 2050.

[2] Koumentakos, A. G. (2019). Developments in electric and green marine ships. Applied system innovation, 2(4), 34.

[3] IMO, The fourth IMO GHG Study 2020 Executive Summary, https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20Executive-Summary.pdf (accessed on 13 December 2022).

[4] International Maritime Organization. “Initial IMO GHG Strategy 2018,” [online] Available at: https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx (accessed Jan. 2023).

[5] Esther Whieldon, (2021). “Your climate change goals may have a maritime shipping problem,” [online] Available at: https://www.spglobal.com/esg/insights/your-climate-change-goals-may-have-a-maritime-shipping-problem (accessed Jan. 2023).

[6] European Commission, (2021). “Reducing emissions from the shipping sector,” [online] Available at: https://ec.europa.eu/clima/eu-

action/transport-emissions/reducing-emissions-shipping-sector_en (accessed Jan. 2023).

[7] S&P Global Commodity Insights, (2021). "COP26: 22 countries sign Clydebank Declaration to boost green shipping." https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/111021-cop26-22-countries-sign-clydebank-declaration-to-boost-green-shipping. (accessed Jan. 2023).

[8] Mallouppas, G., and Yfantis, E. A. (2021). "Decarbonization in shipping industry: A review of research, technology development, and innovation proposals," Journal of Marine Science and Engineering, 9(4), 415. https://doi.org/10.3390/jmse9040415

[9] Psaraftis, H. N., and Kontovas, C. A. (2020). "Decarbonization of maritime transport: Is there light at the end of the tunnel?," Sustainability, 13(1), 237. https://doi.org/10.3390/su13010237

[10] Ampah, J. D., Yusuf, A. A., Afrane, S., Jin, C., and Liu, H. (2021). "Reviewing two decades of cleaner alternative marine fuels: Towards IMO's decarbonization of the maritime transport sector," Journal of Cleaner Production, 320, 128871. https://doi.org/10.1016/j.jclepro.2021.128871

[11] Molavi, A., Shi, J., Wu, Y., & Lim, G. J. (2020). Enabling smart ports through the integration of microgrids: A two-stage stochastic programming approach. Applied Energy, 258, 114022. https://doi.org/10.1016/j.apenergy.2019.114022.

[12] IMO (2021), The fourth IMO GHG Study 2020 Executive Summary, https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20Executive-Summary.pdf (accessed on 13 December 2022).

[13] ITF (2018). "Decarbonising Maritime Transport. Pathways to Zero-Carbon Shipping by 2035," International Transport Forum: Paris, France. https://www.itf-oecd.org/decarbonising-maritime-transport. (accessed on 13 December 2022).

[14] Bicer, Y., and Dincer, I. (2018). "Clean fuel options with hydrogen for sea transportation: A life cycle approach," International Journal of Hydrogen Energy, 43(2), 1179-1193. https://doi.org/10.1016/j.ijhydene.2017.10.157

[15] DNV GL, (2020). Energy transition outlook 2020. Maritime forecast to 2050.

[16] Livaniou, S., and Papadopoulos, G. A. (2022). "Liquefied Natural Gas (LNG) as a Transitional Choice Replacing Marine Conventional Fuels (Heavy Fuel Oil/Marine Diesel Oil), towards the Era of Decarbonisation," Sustainability, 14(24), 16364. https://doi.org/10.3390/su142416364

[17] WPSP. (2020). World Ports Sustainability Report 2020. https://sustainableworldports.org/wp-content/uploads/WORLD-PORTS-SUSTAINABILITY-REPORT-2020-FIN.pdf (accessed on 22 December 2022).

[18] ESPO Environmental Report (2022). EcoportsinSights2022. https://www.espo.be/publications/espo-environmental-report-2022 (accessed on 22 December 2022).

[19] Stolz, B., Held, M., Georges, G., and Boulouchos, K. (2021). "The CO2 reduction potential of shore-side electricity in Europe," Applied Energy, 285, 116425. https://doi.org/10.1016/j.apenergy.2020.116425

[20] Gutierrez-Romero, J. E., Esteve-Pérez, J., and Zamora, B. (2019). "Implementing Onshore Power Supply from renewable energy sources for requirements of ships at berth," Applied energy, 255, 113883. https://doi.org/10.1016/j.apenergy.2019.113883

[21] Wang, L., Liang, C., Shi, J., Molavi, A., Lim, G., & Zhang, Y., (2021). "A bilevel hybrid economic approach for optimal deployment of onshore power supply in maritime ports." Applied Energy, 292, 116892. https://doi.org/10.1016/j.apenergy.2021.116892

[22] Zhang, Y., Liang, C., Shi, J., Lim, G., & Wu, Y. (2022). "Optimal port microgrid scheduling incorporating onshore power supply and berth allocation under uncertainty." Applied Energy, 313, 118856. https://doi.org/10.1016/j.apenergy.2022.118856

[23] Molavi, A., Lim, G. J., & Shi, J. (2020). "Stimulating sustainable energy at maritime ports by hybrid economic incentives: A bilevel optimization approach." Applied Energy, 272, 115188. https://doi.org/10.1016/j.apenergy.2020.115188

[24] Tseng, P. H., and Pilcher, N. (2015). "A study of the potential of shore power for the port of Kaohsiung, Taiwan: to introduce or not to introduce?," Research in transportation business & management, 17, 83-91. https://doi.org/10.1016/j.rtbm.2015.09.001

[25] Hussein, A. W., and Ahmed, M. W. (2014). "Solar Energy: Solution to fuel dilemma," International Journal of Research in Engineering & Technology, 2(8), 77-86.

[26] Karatuğ, Ç., and Durmuşoğlu, Y. (2020). "Design of a solar photovoltaic system for a Ro-Ro ship and estimation of performance analysis: a case study," Solar Energy, 207, 1259-1268. https://doi.org/10.1016/j.solener.2020.07.037

[27] Perčić, M., Ančić, I., and Vladimir, N. (2020). "Life-cycle cost assessments of different power system configurations to reduce the carbon footprint in the Croatian short-sea shipping sector," Renewable and Sustainable Energy Reviews, 131, 110028. https://doi.org/10.1016/j.rser.2020.110028.

[28] Park, C., Jeong, B., Zhou, P., Jang, H., Kim, S., Jeon, H., Nam, D., and Rashedi, A. (2022). "Live-Life cycle assessment of the electric propulsion ship using solar PV," Applied Energy, 309, 118477. https://doi.org/10.1016/j.apenergy.2021.118477

[29] Rutkowski, G. (2016). "Study of Green Shipping Technologies-Harnessing Wind, Waves and Solar Power in New Generation Marine Propulsion Systems," TransNav: International Journal on Marine Navigation and Safety of Sea Transportation, 10(4), 627-632. DOI: 10.12716/1001.10.04.12

[30] Bouman, E. A., Lindstad, E., Rialland, A. I., and Strømman, A. H. (2017). "State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping–A review," Transportation Research Part D: Transport and Environment, 52, 408-421. https://doi.org/10.1016/j.trd.2017.03.022

[31] Pan, P., Sun, Y., Yuan, C., Yan, X., and Tang, X. (2021). "Research progress on ship power systems integrated with new energy sources: A review," Renewable and Sustainable Energy Reviews, 144, 111048. https://doi.org/10.1016/j.rser.2021.111048

[32] Chou, T., Kosmas, V., Acciaro, M., and Renken, K. (2021). "A Comeback of Wind Power in Shipping: An Economic and Operational Review on the Wind-Assisted Ship Propulsion Technology," Sustainability (Basel, Switzerland), 13(4), 1880. https://doi.org/10.3390/su13041880

[33] Rehmatulla, N., Parker, S., Smith, T., and Stulgis, V. (2017). "Wind technologies: Opportunities and barriers to a low carbon shipping industry," Marine Policy, 75, 217-226. https://doi.org/10.1016/j.marpol.2015.12.021

[34] Talluri, L., Nalianda, D. K., Kyprianidis, K. G., Nikolaidis, T., and Pilidis, P. (2016). "Techno economic and environmental assessment of wind assisted marine propulsion systems," Ocean Engineering, 121, 301-311. https://doi.org/10.1016/j.oceaneng.2016.05.047

[35] Xing, H., Stuart, C., Spence, S., and Chen, H. (2021). "Fuel Cell Power Systems for Maritime Applications: Progress and Perspectives," Sustainability (Basel, Switzerland), 13(3), 1213. https://doi.org/10.3390/su13031213

[36] DNV GL, (2019). Energy transition outlook 2019. A global and regional forecast to 2050. https://www.dnv.com/Publications/energy-transition-outlook-2019-168414. (accessed on 22 December 2022).

[37] Perčić, M., Vladimir, N., Jovanović, I., and Koričan, M. (2022). "Application of fuel cells with zero-carbon fuels in short-sea shipping," Applied Energy, 309, 118463. https://doi.org/10.1016/j.apenergy.2021.118463

[38] van Biert, L., Godjevac, M., Visser, K., and Aravind, P. V. (2016). "A review of fuel cell systems for maritime applications," Journal of Power Sources, 327, 345–364. https://doi.org/10.1016/j.jpowsour.2016.07.007

[39] Elkafas A. G., Rivarolo, M., Gadducci, E., Magistri, L., and Massardo, A. F. (2023). "Fuel Cell Systems for Maritime: A Review of Research Development, Commercial Products, Applications, and Perspectives," Processes 2023, 11(1), 97. https://doi.org/10.3390/pr11010097

[40] Di Micco, S., Mastropasqua, L., Cigolotti, V., Minutillo, M., and Brouwer, J. (2022). "A framework for the replacement analysis of a hydrogen-based polymer electrolyte membrane fuel cell technology on board ships: A step towards decarbonization in the maritime sector," Energy Conversion and Management, 267, 115893. https://doi.org/10.1016/j.enconman.2022.115893

[41] İnal, Ö. B. and Deniz, C. (2021). "Emission Analysis of LNG Fuelled Molten Carbonate Fuel Cell System for a Chemical Tanker Ship: A Case Study," Marine Science and Technology Bulletin, 10 (2), 118-133. DOI: 10.33714/masteb.827195

[42] Dewan, M. H., Yaakob, O., and Suzana, A. (2018). "Barriers for adoption of energy efficiency operational measures in shipping industry," WMU Journal of Maritime Affairs, 17, 169-193. https://doi.org/10.1007/s13437-018-0138-3

[43] Psaraftis, H. N., and Kontovas, C. A. (2014). "Ship speed optimization: Concepts, models and combined speed-routing scenarios," Transportation Research Part C: Emerging Technologies, 44, 52-69. https://doi.org/10.1016/j.trc.2014.03.001

[44] Tzortzis,G., and Sakalis, G. (2021). "A dynamic ship speed optimization method with time horizon segmentation," Ocean Engineering, 226, 108840. https://doi.org/10.1016/j.oceaneng.2021.108840

[45] Li, X., Sun, B., Guo, C., Du, W., and Li, Y. (2020). "Speed optimization of a container ship on a given route considering voluntary speed loss and emissions," Applied Ocean Research, 94, 101995. https://doi.org/10.1016/j.apor.2019.101995

[46] Yang, L., Chen, G., Zhao, J., and Rytter, N. G. M. (2020). "Ship speed optimization considering ocean currents to enhance environmental sustainability in maritime shipping," Sustainability, 12(9), 3649. https://doi.org/10.3390/su12093649

[47] Du, Y., Meng, Q., Wang, S., and Kuang, H. (2019). "Two-phase optimal solutions for ship speed and trim optimization over a voyage using voyage report data," Transportation Research Part B: Methodological, 122, 88-114. https://doi.org/10.1016/j.trb.2019.02.004

[48] Andersson, H., Fagerholt, K., and Hobbesland, K. (2015). "Integrated maritime fleet deployment and speed optimization: Case study from RoRo shipping," Computers & Operations Research, 55, 233-240. https://doi.org/10.1016/j.cor.2014.03.017

[49] Faber, J. F., Huigen, T., and Nelissen, D. (2017). "Regulating speed: a short-term measure to reduce maritime GHG emissions," CE Delft. https://cedelft.eu/publications/regulating-speed-a-short-term-measure-to-reduce-maritime-ghg-emissions/ (accessed on 02 January 2023).

[50] Han, Y., Ma, W., and Ma, D. (2023). "Green maritime: An improved quantum genetic algorithm-based ship speed optimization method considering various emission reduction regulations and strategies," Journal of Cleaner Production, 385, 135814. https://doi.org/10.1016/j.jclepro.2022.135814

[51] Zhen, L., Hu, Z., Yan, R., Zhuge, D., and Wang, S. (2020). "Route and speed optimization for liner ships under emission control policies," Transportation Research Part C: Emerging Technologies, 110, 330-345. https://doi.org/10.1016/j.trc.2019.11.004

[52] Ma, D., Ma, W., Jin, S., and Ma, X. (2020). "Method for simultaneously optimizing ship route and speed with emission control areas," Ocean Engineering, 202, 107170. https://doi.org/10.1016/j.oceaneng.2020.107170

[53] Sheng, D., Meng, Q and Li, Z. C. (2019). "Optimal vessel speed and fleet size for industrial shipping services under the emission control area regulation," Transportation Research Part C: Emerging Technologies, 105, 37-53. https://doi.org/10.1016/j.trc.2019.05.038

[54] Fagerholt, K., Gausel, N. T., Rakke, J. G., and Psaraftis, H. N. (2015). "Maritime routing and speed optimization with emission control areas," Transportation Research Part C: Emerging Technologies, 52, 57-73. https://doi.org/10.1016/j.trc.2014.12.010

[55] Yu, H., Fang, Z., Fu, X., Liu, J., and Chen, J. (2021). "Literature review on emission control-based ship voyage optimization," Transportation Research Part D: Transport and Environment, 93, 102768. https://doi.org/10.1016/j.trd.2021.102768

[56] Wang, H., Lang, X., and Mao, W. (2021). "Voyage optimization combining genetic algorithm and dynamic programming for fuel/emissions reduction," Transportation Research Part D: Transport and Environment, 90, 102670. https://doi.org/10.1016/j.trd.2020.102670

[57] Wu, Y., Huang, Y., Wang, H., and Zhen, L. (2023). "Nonlinear programming for fleet deployment, voyage planning and speed optimization in sustainable liner shipping," Electronic Research Archive, 31(1), 147-168. doi: 10.3934/era.2023008

[58] Tuswan,T., Misbahudin, S., Junianto, S., Yudo, H., Budi Santosa, A. W., Trimulyono, A., Mursid, O., and Chrismianto, D. (2022). "Current research outlook on solar-assisted new energy ships: representative applications and fuel & GHG emission benefits," IOP Conference Series. Earth and Environmental Science, 1081, 012011. https://doi.org/10.1088/1755-1315/1081/1/012011