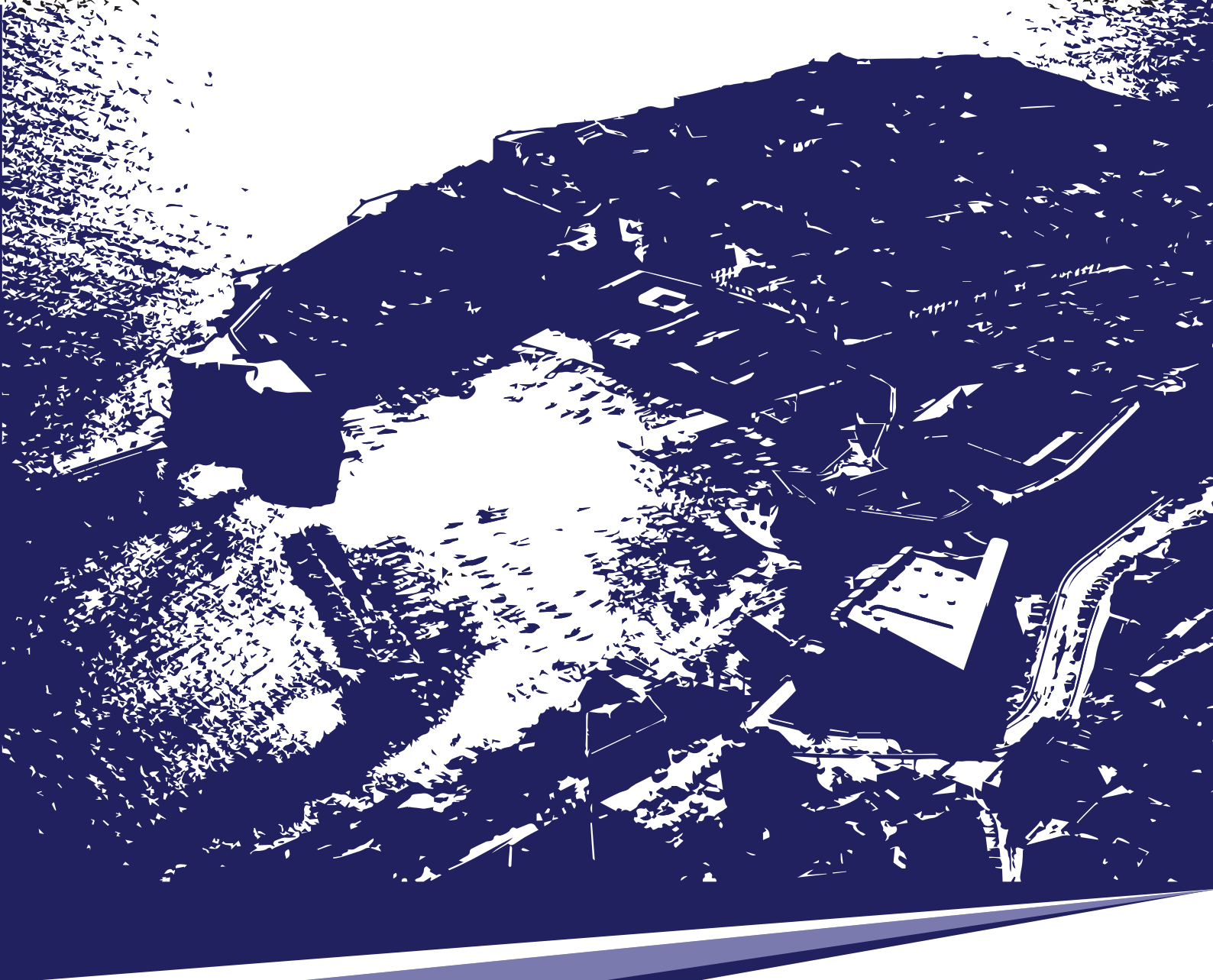




NAŠE MORE 2025

4th International Conference of Maritime Science & Technology

CONFERENCE PROCEEDINGS



SVEUČILIŠTE
U DUBROVNIKU
UNIVERSITY
OF DUBROVNIK

Dubrovnik, 18 – 19 September 2025

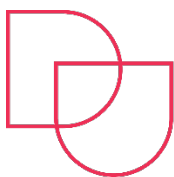
University of Dubrovnik
Faculty of Maritime Studies

4th International Conference of Maritime Science & Technology

NAŠE MORE 2025

CONFERENCE PROCEEDINGS

**Faculty of Maritime Studies
University of Dubrovnik**



**SVEUČILIŠTE
U DUBROVNIKU
UNIVERSITY
OF DUBROVNIK**



**UNIVERSITY
OF DUBROVNIK
FACULTY OF
MARITIME
STUDIES**

Dubrovnik, Croatia

18 – 19 September 2025

PUBLISHER

University of Dubrovnik, Faculty of Maritime Studies

EDITORS

Srđan Vujičić, Faculty of Maritime Studies, Croatia

Nermin Hasanspahić, Faculty of Maritime Studies, Croatia

Miho Kristić, Faculty of Maritime Studies, Croatia

CHAIR

Srđan Vujičić, Faculty of Maritime Studies, Croatia

VICE CHAIR

Nermin Hasanspahić, Faculty of Maritime Studies, Croatia

PROGRAMME COMMITTEE

Alen Jugović, University of Rijeka, Faculty of Maritime Studies, Croatia

Anamarija Falkoni, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Andrea Russo, University of Split, Faculty of Maritime Studies, Croatia

Antun Asić, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Aura Rusca, Universitatea Politehnica Bucuresti, Romania

Daniela Gračan, University of Rijeka, Faculty of Tourism and Hospitality Management, Croatia

Dejan Žagar, University of Ljubljana, Faculty of Maritime Studies and Transport, Slovenia

Dinka Lale, University of Dubrovnik, Faculty of Electrical Engineering and Applied Computing, Croatia

Edvard Tijan, University of Rijeka, Faculty of Maritime Studies, Croatia

Florin Rusca, Universitatea Politehnica Bucuresti, Romania

Heikki Koivisto, Satakunta University of Applied Sciences, Finland

Huanxin Wang, Dalian Maritime University, China

Igor Petrović, University of Montenegro, Faculty of Maritime Studies Kotor, Montenegro

Ivica Krmek, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Jakša Mišković, University of Split, Faculty of Maritime Studies, Croatia

Juraj Bukša, University of Rijeka, Faculty of Maritime Studies, Croatia

Lea Vojković, University of Split, Faculty of Maritime Studies, Croatia

Luka Drobilo, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture

Luka Vukić, University of Split, Faculty of Maritime Studies, Croatia

Ljiljana Peričin, University of Zadar, Maritime Department, Croatia

Maja Uran Maravić, University of Primorska, Faculty of Tourism Studies – Turistica, Slovenia

Maro Ćorak, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Martina Hrnić, University of Dubrovnik,

Mate Barić, University of Zadar, Maritime Department, Croatia

Mate Jurjević, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Mateusz Gil, Gdynia Maritime University, Poland

Miho Baće, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Miho Kristić, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Mislav Maljković, University of Split, Faculty of Maritime Studies, Croatia

Nikola Vladimir, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture
Petra Amižić Jelovčić, University of Split, Faculty of Law, Croatia
Renato Oblak, University of Rijeka, Faculty of Maritime Studies, Croatia
Rino Bošnjak, University of Split, Faculty of Maritime Studies, Croatia
Senka Šekularac-Ivošević, University of Montenegro, Faculty of Maritime Studies Kotor, Montenegro
Srđan Vukša, University of Split, Faculty of Maritime Studies, Croatia
Špiro Ivošević, University of Montenegro, Faculty of Maritime Studies Kotor, Croatia
Tatijana Dlabač, University of Montenegro, Faculty of Maritime Studies Kotor, Croatia
Zlatko Kljajić, University of Split, Faculty of Maritime Studies, Croatia

ORGANISING COMMITTEE

Vujičić Srđan, Conference Chair and President of the Organizing Committee, University of Dubrovnik, Faculty of Maritime Studies, Croatia
Hasanspahić, Nermin, Vice-president, University of Dubrovnik, Faculty of Maritime Studies, Croatia
Ana Perić Hadžić, University of Rijeka, Faculty of Maritime Studies, Croatia
Anamarija Falkoni, University of Dubrovnik, Faculty of Maritime Studies, Croatia
Andrea Vučur, University of Dubrovnik, Croatia
Davorka Turčinović, University of Dubrovnik, Croatia
Dinka Lale, University of Dubrovnik, Faculty of Electrical Engineering and Applied Computing
Ivan Peronja, University of Split, Faculty of Maritime Studies, Croatia
Katarina Banović, University of Dubrovnik, Croatia
Luka Grbić, University of Zadar, Maritime Department, Croatia
Marijana Lujo, University of Dubrovnik, Croatia
Maro Ćorak, University of Dubrovnik, Faculty of Maritime Studies, Croatia
Martina Hrnić, University of Dubrovnik, Croatia
Mate Jurjević, University of Dubrovnik, Faculty of Maritime Studies, Croatia
Matthew John Rooks, Kobe University, Faculty of Maritime Sciences, Japan
Miho Klaić, University of Dubrovnik, Faculty of Maritime Studies, Croatia
Miho Kristić, University of Dubrovnik, Faculty of Maritime Studies, Croatia
Minna Keinänen-Toiviola, Satakunta University of Applied Sciences, Finland
Peter Vidmar, University of Ljubljana, Faculty of maritime studies and transport, Slovenia
Stjepo Hladilo, University of Dubrovnik, Croatia
Tatijana Dlabač, University of Montenegro, Faculty of Maritime Studies, Montenegro
Tonči Biočić, University of Dubrovnik, Faculty of Maritime Studies, Croatia
Yusuke Mori, University of Tokyo, Japan

INTERNATIONAL SCIENTIFIC COMMITTEE

Aleksandar Sladkowski, Silesian University of Technology, Faculty of Transport, Poland
Alessandro Farina, University of Pisa, Department of Civil and Industrial Engineering and University Centre of Logistic Systems, Italy
Ana Bratoš Cetinić, University of Dubrovnik, Department of Applied Ecology, Croatia
Anamaria Bjelopera, University of Dubrovnik, Faculty of Electrical Engineering and Applied Computing, Croatia
Andrzej Grzadziela, Polish Naval Academy, Poland

Bojan Bešković, University of Ljubljana, Faculty of Maritime Studies and Transport, Slovenia

Branko Glamuzina, University of Dubrovnik, Department of Aquaculture, Croatia

Computing, Croatia

Darijo Mišković, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Elen Twrdy, University of Ljubljana, Faculty of Maritime Studies and Transport, Slovenia

Francesc Xavier Martínez de Osés, Universitat Politècnica de Catalunya, Barcelona Tech, Nautical Science and Engineering Department, Spain

Gong Xiang, School of Naval Architecture and Ocean Engineering, Huazhong University of

Igor Nesteruk, Institute of Hydromechanics, National Academy of Sciences of Ukraine, Ukraine

Irina Makarova, Kazan Federal University, Russia

Ivana Palunko, University of Dubrovnik, Faculty of Electrical Engineering and Applied Computing, Croatia

Ivica Đurđević-Tomaš, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Ivica Pavić, University of Split, Faculty of Maritime Studies, Croatia

Ivona Milić-Beran, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Jakša Mišković, University of Split, Faculty of Maritime Studies, Croatia

Josip Kasum, University of Split, University Department for Forensic Science, Croatia

Jozef Gnap, University of Žilina, The Faculty of Operation and Economics of Transport and Communications, Slovak Republic

Kevin Cullinane, University of Gothenburg, Sweden

Kiên Đăng Xuân, Ho Chi Minh City University of Transport, Vietnam

Leszek Chybowski, Maritime University of Szczecin, Szczecin, Poland

Marijana Pećarević, University of Dubrovnik, Department of Aquaculture, Croatia

Maro Ćorak, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Maro Jelić, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Martin Lazar, University of Dubrovnik, Faculty of Electrical Engineering and Applied

Mate Jurjević, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Miho Klaić, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Nermin Hasanspahić, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Nguyen Duy Trinh, Ho Chi Minh City University of Transport, Vietnam

Nikolai Nikolaevich Maiorov, St. Petersburg State University of Aerospace Instrumentation (SUAI), Russia

Ondrej Stopka, Institute of Technology and Business in České Budějovice, Department of

Peter Monka, Technical University of Košice, Faculty of Manufacturing Technologies in Prešov, Slovak Republic

Rudolf Kampf, Faculty of Business in České Budejovice, Czech Republic

Science and Technology, China

Smiljko Rudan, University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Croatia

Srđan Vujičić, University of Dubrovnik, Faculty of Maritime Studies, Croatia

Transport and Logistics, Czech Republic

Vlado Frančić, University of Rijeka, Faculty of Maritime Studies, Croatia

Wang Huanxin, Dalian Maritime University, China

TECHNICAL EDITOR

Davorka Turčinović, University of Dubrovnik, Croatia

GRAPHIC DESIGN & EDITING

Katarina Banović, University of Dubrovnik, Croatia

LANGUAGE EDITOR

Martina Hrnić, University of Dubrovnik, Croatia

CLASSIFICATION OF ARTICLES

Ana Pujo, University of Dubrovnik, Croatia

The papers are peer-reviewed by international experts.

ISBN 978-953-7153-81-6

CONTENT

Ivana Baćović, Miroslav Vukičević, Špiro Ivošević EVALUATING RECYCLING POTENTIAL OF ZINC IN THE MONTENEGRIN MARITIME SECTOR	1
Tonći Biočić, Nermin Hasanspahić, Miho Kristić, Srđan Vujičić COMPARATIVE ANALYSIS OF BULK CARRIERS PORT STATE CONTROL INSPECTIONS	13
Pallab Das, Prasheet Mishra, Vik Patra CHARTING NEW WATERS: EXPLORING LEGAL AND POLICY GAPS IN MARITIME WELFARE AND SEAFARERS' RIGHTS	22
Joško Dvornik, Srđan Dvornik FUEL GAS SUPPLY SYSTEM OF THE ME-GI TWO-STROKE SLOW-SPEED DIESEL ENGINE IN THE LNG TANKER	31
Vlado Frančić, Marko Strabić, Nermin Hasanspahić, Lovro Maglić INTERNATIONAL SAFETY MANAGEMENT CODE IN MARITIME EDUCATION AND TRAINING	42
Georgi Iliev, Bozhidar Dyakov, Miroslav Atanasov PORT INFRASTRUCTURE AS A DETERMINANT OF CARGO HANDLING EFFICIENCY AND DEMURRAGE RISK	51
Nikolay Ivanov, Igljika Ivanova-Slavova IMPLEMENTATION OF ARTIFICIAL INTELLIGENCE IN THE RAILWAY TRANSPORT AND ITS EFFECT ON PORT EFFICIENCY	59
Igljika Ivanova-Slavova, Nikolay Ivanov EFFECT OF INTRODUCING ARTIFICIAL INTELLIGENCE IN LOGISTIC SYSTEMS AND PROCESSES, POSSIBILITIES FOR DEVELOPMENT AND IMPROVEMENT	68
Alen Jugović, Nika Mandarić, Juraj Bukša, Marko Paliaga DIGITALIZATION AND SMART PORT INNOVATIONS IN COASTAL MARINAS FOR SUSTAINABLE NAUTICAL TOURISM: A CASE STUDY OF ACI CLUB INITIATIVES	75
Alen Jugović, Renato Oblak, Dea Aksentijević, Dorian Mičetić IMPACT OF BLACK CHARTER ON NAUTICAL TOURISM IN THE REPUBLIC OF CROATIA	87
Alen Jugović, Renato Oblak, Federica Gulja, Marin Donadić INFLUENCE OF COUNTY PORT AUTHORITIES ON MARITIME PASSENGER TRAFFIC IN THE REPUBLIC OF CROATIA	97
Radosław Kiciński, Tomasz Pawlak ADVANCED MANUFACTURING METHODS IN THE SHIPBUILDING INDUSTRY	107
Roomet Leiger, Pentti Kujala, Kristine Carjova, Alexander Staritsyn, Samuli Hanninen, Ulla Pirita Tapaninen METHANOL AND AMMONIA AS ALTERNATIVE FUELS FOR ICEBREAKING OPERATIONS IN THE NORTHERN BALTIC SEA	117
Roman Mamuladze, Guladi Tkhilaishvili, Manuchar Loria, Meri Gabaidze TRANSFORMATION OF MARITIME LOGISTICS AND SUPPLY CHAINS IN MODERN GEOPOLITICAL CHALLENGES (STRATEGIC ROLE OF GEORGIA)	133

Tahir Mavrić, Martin Čalasan, Ilija Knežević, Nemanja Pudar, Tatijana Dlabač, APPLICATION OF IOT TECHNOLOGY FOR REAL-TIME PERFORMANCE MONITORING OF SHIPBOARD PV SYSTEMS	143
Prasheet Mishra, Vik Patra, Saswat Ranjan Barik, Pritam Pattanaik A SMART SHIP COLLISION AVOIDANCE FRAMEWORK USING AI	152
Seçil Oğuz SAILING INTO THE GAP: EXPLORING BRANDING IN INDUSTRIAL CLUSTERS AND THE MISSING MARITIME LINK	159
Riina Otsason, Tomi Thomasson, Jarkko Rahikainen, Ulla Tapaninen DECARBONIZATION OF ESTONIAN FERRY LINES – CHALLENGES AND OPPORTUNITIES	169
Vinko Pavić, Ivan Mislov, Mate Barić, Nina Kostović ENHANCING JUNIOR DECK OFFICERS PERFORMANCE THROUGH SIMULATOR TRAINING	179
M. Rajeswari MARITIME FINANCE ADAPTATION (MAR FIN ADAPT): A BLENDED FINANCE APPROACH TO MARITIME CLIMATE RESILIENCE AND SUSTAINABILITY	187
Daisy Romanini, Esther Rodriguez, Dimitrios Dalaklis, Fabio Pinelli, Marinella Petrocchi CLOUD SERVICES AND MARITIME CYBERSECURITY IN THE BALTIC SEA REGION	202
Peter Sandell ADJUSTING THE MASTER OF MARITIME MAN-AGEMENT PROGRAMMES TO THE UPCOMING ERA OF AUTONOMOUS VESSELS IN FINLAND	212
Iryna Shvetsova FROM CLASSROOMS TO GLOBAL CONNECTIONS: THE IMPACT OF EXTRA-CURRICULAR ACTIVITIES ON GMP COMPETENCY BUILDING	221
Tatjana Stanivuk, Duje Bratim, Ivan Karin, Ladislav Stazić ANALYSIS OF THE CMMS DATABASE	231
Tomislav Sunko, Mihael Dedo, Lovro Strnad, Vilim Đura INTEGRATION MODEL OF AUTONOMOUS UNDERWATER VEHICLES AND UNMANNED AERIAL VEHICLES FOR COMBATING ILLEGAL, UNREPORTED AND UNREGULATED FISHING	243
Lea Vojković, Ana Kuzmanić Skelin, Irena Čovo Baučić, Josipa Vujević SITUATIONAL AWARENESS AMONG SEAFARERS IN CONDITIONS OF INFORMATION OVERLOAD ON THE NAVIGATIONAL BRIDGE	256
Marina Zanne, Milutin Lakićević, Giuseppe Borruso, Francesca Sinatra THE DECARBONIZATION OF SEAPORTS: AN OVERVIEW OF SELECTED MEASURES	264
Reza Ziarati, Heikki Koivisto, German de Melo Rodriguez, Janusz Uriasz, Lakhvir Singh, Amireshan Barzegarsedigh, Vanessa Makar, Aris Chronopoulos OPTIMISM – ONLINE PROGRAMME FOR TRAINING ON INTERNATIONAL MANAGEMENT OF ISM CODE	273

THE DECARBONIZATION OF SEAPORTS: AN OVERVIEW OF SELECTED MEASURES

Marina Zanne

University of Ljubljana, Faculty of Maritime Studies and Transport
Portorož, Slovenia
E-mail: marina.zanne@fpp.uni-lj.si

Milutin Lakićević

PhD student
University of Montenegro, Faculty of Maritime Studies
Kotor, Montenegro
E-mail: milutin.lakicevic@edu.ucg.ac.me

Giuseppe Borruso

University of Trieste, Department of Economics, Business, Mathematics and Statistics
Trieste, Italy
E-mail: giuseppe.borruso@deams.units.it

Francesca Sinatra

PhD student
University of Trieste, Department of Economics, Business, Mathematics and Statistics
Trieste, Italy
E-mail: francesca.sinatra@phd.units.it

UDK 656.615:504.5
656.615:620.92

Abstract

Ports are considered critical infrastructure as they play an important role in international trade and overall economic growth. There are around 4,000 ports worldwide, of which around 1,200 are located in Europe alone. Ports around the world face the same challenge of providing competitive services while ensuring that the negative impact on the environment is minimized, with the environmental problem being particularly acute in peri-urban ports. While the majority of maritime transport emissions are generated during shipping, ships' auxiliary engines run during port calls to keep the ship's systems running. Ships in port usually contribute more than half of all port-related emissions. The remaining emissions come from the port itself. The aim is to reduce port emissions by 90% by 2050. Ports are already working hard to reduce their environmental footprint and gain the support of local communities. They are applying a combination of soft and hard measures, such as reduced charges for greener ships or a truck arrival booking system and other digitalization approaches, as well as offering alternative fuels for ships and shore power (cold ironing), purchasing sustainable cargo handling and other terminal equipment, using renewable energy sources, developing electrical micro grids, etc. These measures represent a major financial, infrastructural and operational challenge, at least initially. This paper presents measures (examples of best practices) that ports have implemented to achieve cleaner operations with an indication of the cost of implementation.

Keywords: seaport, decarbonization, electrification, renewable sources, cost

1. INTRODUCTION

Maritime transport is considered the most energy-efficient and environmentally friendly mode of transporting large quantities of cargo. It is of crucial importance for world trade, with around 12 billion tons of cargo transported over sea annually. However, without remedial actions, maritime transport emissions could increase by 130% by 2050 compared to 2008 levels [1]. On the other hand, International Maritime Organization (IMO) wants to achieve net zero carbon dioxide (CO₂) emissions from maritime activities by 2050 with 40%

reduction by 2030 and 70% by 2040 compared to 2008 baseline levels [2]. The aim is to reduce also port emissions by 90% by 2050 [3].

Ports play a vital role in economic and social development for the regions they are in, which is evident through above-average employment rates and wages, higher-than-average net migration and motorization levels etc [4]. At the same time, ports pose environmental and human well-being challenges from three primary sources: port operations, ships calling to the port, and the traffic in the port's proximity [5]; in average ships account for around 60% of port emissions, around 30% of emissions come from land transport and remaining around 10% from the terminals [6]. Besides climate changing emissions, ships also emit local pollutants such as sulphur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter (PM), which can affect human health. In fact, emissions from shipping are leading to around 265,000 premature deaths worldwide every year on the other [7].

Ports are adopting green initiatives to foster an environmentally friendly development while still ensuring safe and efficient operations [8]. In recent years, they are getting more engaged in decarbonization of the maritime sector as a whole [9]. The concept of decarbonization in the maritime sector extends beyond the CO₂ or greenhouse gas (GHG) emissions. It encompasses the mitigation of a broader spectrum of pollutants, including above mentioned NO_x, SO_x, as well as other harmful emissions ([10]; [11]). Achieving decarbonization in shipping is a complex and time-consuming process that necessitates changes in technology and operational practices ([12]; [13]). The process of decarbonization is impeded by a range of economic barriers (e.g. limited access to capital, high implementation and hidden costs) as well as non-economic challenges (e.g. policy and technical issues). These difficulties are further emphasized by the sector's international nature and the involvement of a large array of stakeholders [14].

The aim of the paper is to present the economic aspect of several operational and technological measures that ports can take to decarbonize their operations. These measures are given an approximate cost and timeframe for implementation.

The paper is structured into four chapters. The introductory chapter presents the problematics addressed in the paper. A short description of methodology applied is described in the second chapter. The third chapter is the core chapter of the paper delivering a literature overview on the port decarbonization measure. Conclusions are given in the fourth chapter.

2. METHODOLOGY

The literature review was done by searching the Science Direct database with the following syntaxes: ("decarbonization of ports" or "port greening" or "port decarbonization") and "cost" and ("on shore power supply" or "cold ironing" or "electrification" or "renewable energy" or "alternative fuels") and "cost" and "port". After removing duplicates and irrelevant papers, the core corpus of 133 contributions remained for the analysis. The focus was given to more recent publications. During the analysis additional relevant papers, reports and web sites emerged which helped to comprehensively address the research question: What are current measures to decarbonize seaports and at what price they come?

VosViewer was used to present the most frequently used words in the analyzed corpus of 133 contributions, mostly scientific papers and book chapters. After applying the thesaurus to combine similar keywords into a single keyword, 18 keywords with at least five occurrences emerged as can be seen in Figure 1. These keywords were divided into five clusters. The VosViewer visualization presents a network of interconnected terms related to green ports, decarbonization and shipping, organized into color-coded clusters.

The blue cluster centralizes around the term decarbonization. This cluster emphasizes strategies and technologies aimed at reducing carbon emissions in maritime operations (wider than ports). Red cluster is about green ports and sustainability. It focuses on port-level initiatives to enhance environmental performance and integrate clean energy solutions. The green cluster addresses the broader environmental impact of

shipping and explores alternative fuels and emission reduction strategies. The yellow cluster focuses on clean fuel innovations for maritime applications both for shipping and ports. The purple cluster is linked to multiple clusters and represents the overarching shift from fossil fuels to sustainable energy sources, bridging various aspects of maritime and port decarbonization.

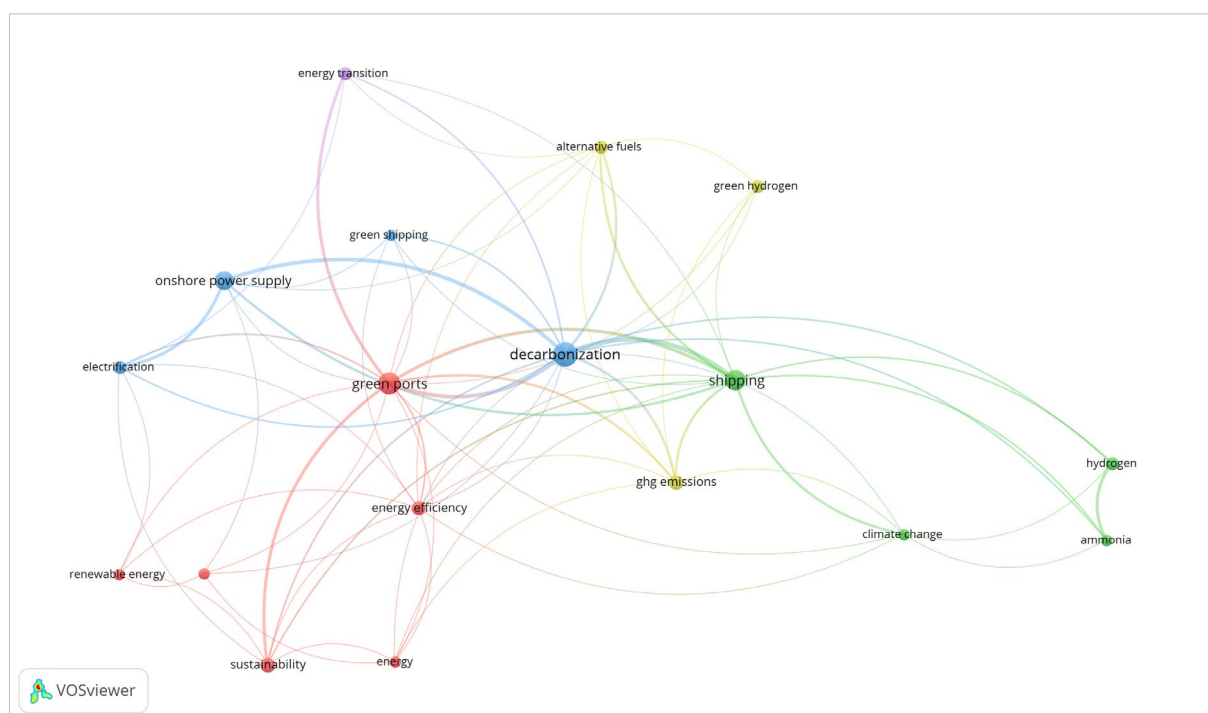


Figure 1 The co-occurrence of keywords in literature corpus

Source: Authors

3. DECARBONIZATION OF SEAPORTS

Maritime transport consumes large amounts of energy; in fact, the energy demand of international shipping (including ports), increased on average by 1.6% annually between 2000 and 2015 [12] and last data shows that International shipping activities consume about 300 Mtonne of fuel per year [15]. In addition, global maritime trade grew by 2.4% in 2023 and it is expected to grow by 2%, with containerized trade potentially increasing by 3.5%, in forthcoming years [16]. With the increased number of ships visiting the ports, maritime emissions are expected to increase. Therefore, changes must be made urgently.

The IMO green initiatives, the IMO Initial Strategy on the reduction of GHG emissions from ships from 2018 and its upgrade from 2023, emphasize the need to reduce emissions in shipping, extending beyond open sea operations to include emissions from ships in ports [17].

Different emission control strategies can lead to reduction of emissions of greenhouse gases or emissions of local pollutants from shipping; however, current solutions cannot address all air pollutants simultaneously or at a reasonable cost [18]. Ports have more sources of emissions than only ships; ports host warehouses, buildings, cargo handling equipment or even industry [19] which makes decarbonization process even a greater challenge.

Nowadays ports place significant emphasis on both monitoring and improving their environmental performance [20]. For example, The Port Authority of Bari together with DBA Group developed a platform that aims to link the environmental pollutants generated in the port area to port traffic, weather conditions and road viability [21]. In addition, in the past decades, a large number of actions and projects has been carried out to reduce the environmental footprint of port areas, especially in the European Union (EU) [22].

Decarbonization of seaports has become a critical step toward reducing global GHG emissions from shipping in general. Around 7% of CO₂ emissions from the shipping are generated at berths in the ports of the European Economic Area [23]. As the EU has set the goal of reducing greenhouse gas emissions by at least 55% by 2030 and becoming climate-neutral by 2050, therefore European ports are facing sustainability and energy challenges, requiring changes to port functions, supply chain systems and business models [24].

Port decarbonization is the process through which a port achieves carbon neutrality and reduces other harmful emissions. This is accomplished by reducing CO₂ emissions from all port activities to near-zero levels, while any surplus CO₂ should be captured through carbon sinks or sequestered [25]. Ports can change operational strategies or apply new technologies and energy management systems to address the problem of emissions [12]. Similar like in shipping, also in ports emission abatement technologies often necessitate trade-offs between cost, performance, and environmental impact [26].

3.1. Operational measures to decarbonize seaports

Operational measures are relatively quick and rather cheap to implement. Although they usually yield quick results, these improvements are not significant in terms of decarbonization of ports and are as such not enough to achieve carbon neutrality of the ports. These can be for example the implementation of differentiated dues in relation to the environmental performance of ships to attract cleaner ships ([27]; [28]), improvement of coordination and synchronization between ship and ports [29] and the definition of speed reduction zones for ships within the port aquatorium to directly reduce emissions ([30] ; [31]), trucks appointment system ([32]; [33]) as well as simplification [34] and automation of port entry/exit procedures ([35]; [36]) or longer gate opening hours and peak pricing strategies [37] to avoid congestion and trucks idling in and outside the port area, the installation of LED lighting to achieve energy savings [38] or eco-driving trainings to reduce fuel consumption. The most expensive amongst operational measures can be the promotion of low carbon hinterland transport as it usually necessitates also infrastructure investment [39].

It is difficult to monetise these measures, as they vary from case to case. Some of these measures do not imply any extra costs for ports, for example reduced speed in port aquatorium or better coordination between ships and ports; in fact, these measures can have positive impacts not only for air emissions in port area but also for shipping companies in form of reduced costs. Some measures can affect port's revenues instead of its costs; for example, the Port of Koper offers 5 to 10% discount on port fees for the arrival of cleaner ships based on Environmental Ship Index (ESI) with the maximum one-off discount being EUR 1,000 (interview) or promotion of modal shift in hinterland transport, but only if all necessary infrastructure is already built. On the other hand, truck appointment systems and other port-gate related measures imply certain investments and higher operating costs (e.g. additional employees), but result in higher productivity and in less congestion (probably also in higher support from local community). Also LED lighting initially assumes investments but given the fact the energy consumption significantly drops the payback period is short. Increased safety is usually an added value of the implementation of LED lighting,

3.2. Technological measures to decarbonize seaports

It is estimated that the global fleet of 100,000-120,000 Container handling equipment (CHE) in ports around the world emit 10-15 million tons of CO₂ per year; this is equivalent to the annual emissions of Slovenia [40]. The electrification of port equipment and vehicles is therefore a common approach to achieving improved energy efficiency and reduction of energy consumption and emissions in relatively short time. Usually, it takes from two to four years to start the operation with new equipment after the investment decision has been made. Electrification offers zero-emission performance [26]; however, studies show that in average electric rubber-tired gantry crane (e-RTG) achieves 86.6% energy savings and a 67.8% reduction in CO₂ emissions in comparison to diesel RTG [41]. Vujičić et al. [42] quantified several other positive impacts of electrification of cargo handling equipment on container terminals; besides lower global warming potential (4.1 times), acidification potential (6.3 times), eutrophication potential (8.6 times) and photochemical ozone creation (7.5

times) are also much lower in comparison to standard diesel powered RTG. The replacement of diesel-powered cranes, trucks, and other handling equipment with electric alternatives requires high investment, but savings on fuel and maintenance occur during their lifespan [4]. Cost per unit for electric cable reel RTG cranes are marginally higher when compared to diesel units (as declared by Yuntai [43] currently in average around \$2 million; however, prices are expected to be equalized after market demand allows electric equipment to be produced on a large scale [44]. Wei and Giuliano[45] estimated capital costs of \$6.9 billion in 2019 value needed for the electrification of port equipment and vehicles in Los Angeles and Long Beach ports in the period from 2020 to 2045 and predicted a macroeconomic loss between \$5.3 and 10 billion in gross state product due to relatively high electricity prices and high capital costs.

On-shore power supply (OPS) or cold ironing (CI) is an electrification alternative in the maritime sector used to reduce shipborne emissions by switching from diesel powered auxiliary generators to electricity when a ship berths at a port [46]. In 2020 there were 36 OPS installations in 31 EU ports [47], with the port of Zeebrugge being the first one to install it back in 2000. This technology is currently considered underutilized due to the high investment cost associated with shoreside installation and ship retrofitting [48]. Although Abu Bakar et al. [48] claim there are unclear benefits for ships and ports, studies show that the OPS reduces port emissions of CO₂ by 48 to 70%, SO₂ by 3 to 60%, NO_x by 40 to 60%, black carbon emissions by 57 to 70% [49] providing wider environmental and human health benefits. OPS installation is therefore expected to be unavoidable in the long term for all port operators due to stringent emission policies; by the Regulation (EU) 2023/1804 ports of core TEN-T network will need to provide OPS to container and passenger ships.

OPS usage reduces CO₂ emissions and emissions of local pollutants compared to berthing without OPS. The capital investment required for the OPS installation is estimated at approximately EUR 7.4 million, assuming the port's existing power grid meets the necessary standards. Considering the substantial external cost savings, estimated at around EUR 1.3 million annually, the total OPS-related expenditure is expected to be fully amortized within roughly seven years [50].

If supported by renewable energy, OPS and electrification make even more sense. In any case, transition to renewable energy can reduce the port's carbon footprint and enhance its resilience and sustainability. In addition, renewable energy sources in combination with an energy storage system can ensure a high degree of energy self-consumption [51]. Currently the average cost is \$1.3 million per megawatt (MW) of electricity-producing capacity by wind turbine, but the cost varies around the world [52]. The price of photovoltaics is similar but can increase due to various factors. For example, in the port of Koper the installation of solar power plant is ongoing, and it should produce sufficient electricity to make the port energy self-sufficient, even when the OPS will be installed (interview).

In recent years, also the zero-carbon fuel, such as hydrogen, is considered more often together with the electrification process [53]. In fact, the REpowerEU plan launched in May 2022 prioritizes combining electrification with low-carbon hydrogen for a green energy shift in EU [54]. In February 2024 Kobe-Osaka international port corporation started cargo handling operations using a hydrogen-fueled RTG crane as the first port ever [55]. In the port of Valencia, they are testing several different hydrogen powered cargo handling machines. Currently green hydrogen prices range from \$5 to over \$12 per kilogram, depending on the production method used and delivery cost; however, the target price of 1\$ per kilogram is set for 2031 [56]. Hydrogen produced from fossil fuels is cheaper, but as such has a very high carbon footprint.

Kavakeb et al. [57] stated that intelligent automated vehicles contribute to vehicle routing optimization and in this way enhance energy efficiency of the ports. In the future, the digital twin (DT) is likely to make a significant contribution to reducing emissions in and around the port as they enhance efficiency and streamline logistical processes [58]. DT is a modern concept; an upgrade of the digital model and digital shadow, providing bidirectional dynamic link between the physical object or system and its digital representation. It is meant to improve threat detection, achieve energy savings and cost reductions, provide increased performance, and finally enhanced collaboration [59] by real-time monitoring and management of cargo, equipment, and environmental conditions [60]. However, due to port's complexity, the creation of

digital twin is time consuming and expensive; but once operating it can achieve up to 30% cost savings on logistics operations [61].

4. DISCUSSION AND CONCLUSIONS

The decarbonization of seaports is a multifaceted challenge that requires a combination of operational, technological, and strategic measures. This paper has highlighted that while operational measures, such as differentiated port dues, truck appointment systems, or eco-driving initiatives, are relatively low-cost and quick to implement, their impact on overall emissions is limited. These measures serve as important first steps but are insufficient on their own to achieve carbon neutrality. Technological interventions, particularly the electrification of port equipment and the implementation of OPS, offer more substantial emission reductions. However, they bear significant capital costs and infrastructural demands. The analysis shows that despite high upfront investments, technologies like OPS and electrification of terminal equipment can yield long-term savings and environmental benefits, especially when powered by renewable energy sources. The integration of renewable energy and energy storage systems further enhances the sustainability and resilience of port operations.

Emerging solutions such as hydrogen-powered equipment and digital twins represent the next steps in port decarbonization. Although promising, these technologies are still in the early stages of deployment and require further development.

From an economic perspective, the transition to low-carbon port operations involves trade-offs between environmental performance, financial feasibility, and operational efficiency. Achieving substantial decarbonization in seaports is possible but demands a tailor-made strategic mix of short-term operational improvements and long-term technological investments.

REFERENCES

- [1] IMO, "Fourth IMO greenhouse gas study 2020," London, 2021.
- [2] IMO, "Strategy on reduction of GHG emissions from ships," 2023.
- [3] EIT, "A practical guide to decarbonising ports - Catalogue of innovative solutions," Eindhoven, 2023.
- [4] M. Zanne and E. Twrady, "The significance of cargo operations in ports for sustainable port-city coexistence," in *IAME conference proceedings*, Athens, 2019.
- [5] OECD, *Environmental impacts of international shipping*. OECD, 2011. doi: 10.1787/9789264097339-en.
- [6] C. Ducruet and G. Gueguen Hallouët, "How to decarbonise commercial ports," Polytechnique insights. Accessed: Jun. 22, 2025. [Online]. Available: <https://www.polytechnique-insights.com/en/columns/energy/how-to-decarbonise-commercial-ports/>
- [7] N. Mueller, M. Westerby, and M. Nieuwenhuijsen, "Health impact assessments of shipping and port-sourced air pollution on a global scale: A scoping literature review," *Environ Res*, vol. 216, p. 114460, Jan. 2023, doi: 10.1016/j.envres.2022.114460.
- [8] K. A. Abood, "Sustainable and green ports: Application of sustainability principles to port development and operation," in *Ports 2007*, Reston, VA: American Society of Civil Engineers, Mar. 2007, pp. 1–10. doi: 10.1061/40834(238)60.
- [9] H. N. Psaraftis and T. Zis, "Shipping decarbonization and green ports," *Maritime Transport Research*, vol. 3, p. 100068, 2022, doi: 10.1016/j.martra.2022.100068.
- [10] S. Terpilowski and S. Sopco, "Why understanding CO₂, NO_x, and SO_x emissions in shipping and ports is important." Accessed: Jun. 25, 2025. [Online]. Available: <https://port-xchange.com/blog/co2-nox-and-sox-emissions-in-shipping-and-ports/>
- [11] D. Christopher Selvam *et al.*, "The role of biodiesel in marine decarbonization: Technological innovations and ocean engineering challenges," *Results in Engineering*, vol. 25, p. 103974, Mar. 2025, doi: 10.1016/j.rineng.2025.103974.
- [12] Ç. Iris and J. S. L. Lam, "A review of energy efficiency in ports: Operational strategies, technologies and energy management systems," *Renewable and Sustainable Energy Reviews*, vol. 112, pp. 170–182, Sep. 2019, doi: 10.1016/j.rser.2019.04.069.
- [13] UNCTAD, "Review of maritime transport 2023: Towards a green and just transition," Geneva, 2023.

- [14] P. Ghaforian Masodzadeh, A. I. Ölçer, F. Ballini, and A. Christodoulou, "A review on barriers to and solutions for shipping decarbonization: What could be the best policy approach for shipping decarbonization?," *Mar Pollut Bull*, vol. 184, p. 114008, Nov. 2022, doi: 10.1016/j.marpolbul.2022.114008.
- [15] E. Fridell, "Emissions and Fuel Use in the Shipping Sector," in *Green Ports*, Elsevier, 2019, pp. 19–33. doi: 10.1016/B978-0-12-814054-3.00002-5.
- [16] UNCTAD, "Review of maritime transport 2024: Navigating maritime chokepoints," Geneva, 2024.
- [17] R. Sun, W. Abouarghoub, E. Demir, and A. Potter, "A comprehensive analysis of strategies for reducing GHG emissions in maritime ports," *Mar Policy*, vol. 171, p. 106455, Jan. 2025, doi: 10.1016/j.marpol.2024.106455.
- [18] M. Zanne, J. Palčič, and M. Lakićević, "Trade-offs in meeting the MARPOL Annex VI requirements with the focus on costs," in *TOMS* (to be published).
- [19] D. Pivetta, A. Tafone, S. Mazzoni, A. Romagnoli, and R. Taccani, "A multi-objective planning tool for the optimal supply of green hydrogen for an industrial port area decarbonization," *Renew Energy*, vol. 232, p. 120979, Oct. 2024, doi: 10.1016/j.renene.2024.120979.
- [20] Z. Zhang *et al.*, "Digitalization and innovation in green ports: A review of current issues, contributions and the way forward in promoting sustainable ports and maritime logistics," *Science of The Total Environment*, vol. 912, p. 169075, Feb. 2024, doi: 10.1016/j.scitotenv.2023.169075.
- [21] DBA Group, "DSS Line ISMAEL: Environmental impact monitoring and prediction in ports [Internet]. 2019 ," 2019. Accessed: Jun. 28, 2025. [Online]. Available: https://sustainableworldports.org/wp-content/uploads/gravity_forms/3-bd84b5b5f37889d5e2375dc98f054b49/2019/07/DSS-Line-Environmental-monitoring-and-prediction.pdf
- [22] M. Mazzarino, L. Braidotti, and G. Borruso, "A Review of Best Practices to Reduce the Environmental Footprint of Port Areas in the Adriatic Region," in *2021 21st International Conference on Computational Science and Its Applications (ICCSA)*, IEEE, Sep. 2021, pp. 168–173. doi: 10.1109/ICCSA54496.2021.00031.
- [23] K. Jacobs, "European ports becoming 'fit for 55,'" Brussels, 2022.
- [24] G. Attanasio, C. Battistella, and E. Chizzolini, "The future of energy management: Results of a Delphi panel applied in the case of ports," *J Clean Prod*, vol. 417, p. 137947, Sep. 2023, doi: 10.1016/j.jclepro.2023.137947.
- [25] T. T. N. Minh, H.-T. H. Hoang, H. S. Nam, A. S. Alamoush, and P. A. Duong, "Revisiting port decarbonization for advancing a sustainable maritime industry: Insights from bibliometric review," *Sustainability*, vol. 17, no. 10, p. 4302, May 2025, doi: 10.3390/su17104302.
- [26] K. Xu, M. P. Brito, and P. Beullens, "Multi-criteria feature selection on maritime emission abatement alternatives," *Research in Transportation Business & Management*, vol. 59, p. 101288, Mar. 2025, doi: 10.1016/j.rtbm.2025.101288.
- [27] T. Lee and H. Nam, "A Study on Green Shipping in Major Countries: In the View of Shipyards, Shipping Companies, Ports, and Policies," *The Asian Journal of Shipping and Logistics*, vol. 33, no. 4, pp. 253–262, Dec. 2017, doi: 10.1016/j.ajsl.2017.12.009.
- [28] A. Mjelde *et al.*, "Differentiating on port fees to accelerate the green maritime transition," *Mar Pollut Bull*, vol. 149, p. 110561, Dec. 2019, doi: 10.1016/j.marpolbul.2019.110561.
- [29] M. Lind, N.-B. Andersen, R. Ward, R. T. Watson, M. Bergmann, and T. Andersen, "Synchronization for port effectiveness," Göteborg, 2019.
- [30] Y.-T. Chang, Y. Song, and Y. Roh, "Assessing greenhouse gas emissions from port vessel operations at the Port of Incheon," *Transp Res D Transp Environ*, vol. 25, pp. 1–4, Dec. 2013, doi: 10.1016/j.trd.2013.06.008.
- [31] A. Linder, "Explaining shipping company participation in voluntary vessel emission reduction programs," *Transp Res D Transp Environ*, vol. 61, pp. 234–245, Jun. 2018, doi: 10.1016/j.trd.2017.07.004.
- [32] F. Schulte, E. Lalla-Ruiz, R. G. González-Ramírez, and S. Voß, "Reducing port-related empty truck emissions: A mathematical approach for truck appointments with collaboration," *Transp Res E Logist Transp Rev*, vol. 105, pp. 195–212, Sep. 2017, doi: 10.1016/j.tre.2017.03.008.
- [33] Z. Jin, X. Lin, L. Zang, W. Liu, and X. Xiao, "Lane Allocation Optimization in Container Seaport Gate System Considering Carbon Emissions," *Sustainability*, vol. 13, no. 7, p. 3628, Mar. 2021, doi: 10.3390/su13073628.
- [34] I. Motono, M. Furuichi, T. Ninomiya, S. Suzuki, and M. Fuse, "Insightful observations on trailer queues at landside container terminal gates: What generates congestion at the gates?," *Research in Transportation Business & Management*, vol. 19, pp. 118–131, Jun. 2016, doi: 10.1016/j.rtbm.2016.04.001.
- [35] S.-L. Chao, "Efficient port gate automation," *Automation and Optimization*, vol. 74, pp. 30–31, 2017.
- [36] I. de la Peña Zarzuelo, M. J. Freire Soeane, and B. López Bermúdez, "Industry 4.0 in the port and maritime industry: A literature review," *J Ind Inf Integr*, vol. 20, p. 100173, Dec. 2020, doi: 10.1016/j.jii.2020.100173.
- [37] A. Maguire, S. Ivey, M. M. Golias, and M. E. Lipinski, "Relieving congestion at intermodal marine container terminals: Review of tactical/operational strategies ," in *51st Annual Transportation Research Forum* , Arlington, Virginia: Transportation Research Forum, Mar. 2010, p. 207280.

- [38] A. Dolamič, "Ekonomski vidik izboljšanja okoljske učinkovitosti delovanja pristanišč / The economic aspect of environmental performance improvement in ports (unofficial translation)," Faculty of Maritime Studies and Transport, Portorož, 2018.
- [39] J. S. L. Lam and T. Notteboom, "The greening of ports: A comparison of port management tools used by leading ports in Asia and Europe," *Transp Rev*, vol. 34, no. 2, pp. 169–189, Mar. 2014, doi: 10.1080/01441647.2014.891162.
- [40] Systemiq and ZEnMo, "Reaching a tipping point in battery-electric container handling equipment," 2023.
- [41] Y.-C. Yang and W.-M. Chang, "Impacts of electric rubber-tired gantries on green port performance," *Research in Transportation Business & Management*, vol. 8, pp. 67–76, Oct. 2013, doi: 10.1016/j.rtbm.2013.04.002.
- [42] A. Vujičić, N. Zrnić, and B. Jerman, "Ports sustainability: A life cycle assessment of zero emission cargo handling equipment," *Strojniški vestnik – Journal of Mechanical Engineering*, vol. 9, no. 59, pp. 547–555, Sep. 2013, doi: 10.5545/sv-jme.2012.933.
- [43] Yuntai, "Rubber-Tired Gantry (RTG) Crane for Container Handling," Yuntai Crane. Accessed: Jun. 28, 2025. [Online]. Available: <https://www.ythoist.com/gantry-crane/rubber-tired-gantry-crane.html#>
- [44] EPRI, "Electric cable reel rubber-tired gantry cranes: Costs and benefits," Palo Alto, 2010.
- [45] D. Wei and G. Giuliano, "Estimating the economic impacts of cargo handling equipment electrification: A case study of the San Pedro Bay ports," *Research in Transportation Business & Management*, vol. 59, p. 101281, Mar. 2025, doi: 10.1016/j.rtbm.2024.101281.
- [46] N. N. Abu Bakar, N. Bazmohammadi, H. Çimen, T. Uyanik, J. C. Vasquez, and J. M. Guerrero, "Data-driven ship berthing forecasting for cold ironing in maritime transportation," *Appl Energy*, vol. 326, p. 119947, Nov. 2022, doi: 10.1016/j.apenergy.2022.119947.
- [47] EMSA, "LNG bunkering & OPS," Sustainable ports. Accessed: Jun. 28, 2025. [Online]. Available: <https://www.emsa.europa.eu/sustainable-ports/lng-bunkering-ops.html>
- [48] N. N. Abu Bakar, N. Bazmohammadi, J. C. Vasquez, and J. M. Guerrero, "Electrification of onshore power systems in maritime transportation towards decarbonization of ports: A review of the cold ironing technology," *Renewable and Sustainable Energy Reviews*, vol. 178, p. 113243, May 2023, doi: 10.1016/j.rser.2023.113243.
- [49] P.-H. Tseng and N. Pilcher, "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*, vol. 17, pp. 83–91, Dec. 2015, doi: 10.1016/j.rtbm.2015.09.001.
- [50] A. Innes and J. Monios, "Identifying the unique challenges of installing cold ironing at small and medium ports – The case of aberdeen," *Transp Res D Transp Environ*, vol. 62, pp. 298–313, Jul. 2018, doi: 10.1016/j.trd.2018.02.004.
- [51] A. Buonomano, G. F. Giuzio, R. Maka, A. Palombo, and G. Russo, "Empowering sea ports with renewable energy under the enabling framework of the energy communities," *Energy Convers Manag*, vol. 314, p. 118693, Aug. 2024, doi: 10.1016/j.enconman.2024.118693.
- [52] D. Blewett, "Wind turbine cost: How much? Are they worth it in 2025?," Weather Guard. Accessed: Jun. 29, 2025. [Online]. Available: <https://weatherguardwind.com/how-much-does-wind-turbine-cost-worth-it/>
- [53] Y. Lu, S. Fang, T. Niu, and R. Liao, "Energy-transport scheduling for green vehicles in seaport areas: A review on operation models," *Renewable and Sustainable Energy Reviews*, vol. 184, p. 113443, Sep. 2023, doi: 10.1016/j.rser.2023.113443.
- [54] N. Namazifard, P. Vingerhoets, and E. Delarue, "Long-term cost optimization of a national low-carbon hydrogen infrastructure for industrial decarbonization," *Int J Hydrogen Energy*, vol. 64, pp. 583–598, Apr. 2024, doi: 10.1016/j.ijhydene.2024.02.324.
- [55] N. Hakirevic Prevljak, "First cargo handling operations using a hydrogen-fueled rubber-tired gantry (RTG) crane have begun in Japan." Accessed: Jun. 28, 2025. [Online]. Available: <https://www.offshore-energy.biz/japan-first-cargo-handling-ops-using-hydrogen-fueled-rtg-begin/#:~:text=NYK%20starts%20operating%20hydrogen%20fuel%2Dcell%20ready%20cranes&text=In%20February%20this%20year%2C%20Japan's,Oita%20factory%20in%20April%202023.>
- [56] L. Jennnifer, "DOE Sets Eyes on Cutting Clean Hydrogen Cost, \$1/Kilo by 203," Carbon credits. Accessed: Jun. 28, 2025. [Online]. Available: <https://carboncredits.com/doe-sets-eyes-on-cutting-clean-hydrogen-cost-1-kilo-by-2031/#:~:text=Currently%2C%20hydrogen%20produced%20by%20electrolysis,with%20a%20significant%20carb on%20footprint.>
- [57] S. Kavakeb, T. T. Nguyen, K. McGinley, Z. Yang, I. Jenkinson, and R. Murray, "Green vehicle technology to enhance the performance of a European port: A simulation model with a cost-benefit approach," *Transp Res Part C Emerg Technol*, vol. 60, pp. 169–188, Nov. 2015, doi: 10.1016/j.trc.2015.08.012.
- [58] F. Hakimi, T. Khaled, M. Al-Kharaz, A. C. Foahom Gouabou, and K. Amzil, "Towards a digital twin modeling method for container terminal port," *Procedia Comput Sci*, vol. 246, pp. 3113–3121, 2024, doi: 10.1016/j.procs.2024.09.361.

- [59] R. Klar, A. Fredriksson, and V. Angelakis, "Digital twins for ports: Derived from smart city and supply chain twinning experience," Aug. 2023, doi: 10.1109/ACCESS.2023.3295495.
- [60] Seatrade Maritime News, "Transforming maritime ports with Digital Twins." Accessed: Jun. 28, 2025. [Online]. Available: <https://www.seatrade-maritime.com/maritime-transportation/transforming-maritime-ports-with-digital-twins>
- [61] M. Bhaskaran, "Driving efficiency and transparency in ports with digital twin technology," Shippeo. Accessed: Jun. 28, 2025. [Online]. Available: <https://www.shippeo.com/blog/driving-efficiency-and-transparency-in-ports-with-digital-twin-technology>