ResearchGate

See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/389613824

Smart green ports: a sustainable solution for the maritime industry in a changing climate

Article *in* Multidisciplinary Adaptive Climate Insights · February 2025

DOI: 10.21622/MACI.2025.02.1.1162

CITATIONS
0

READS
516

1 author:

Mohamed Elhussiny
Arab Academy for Science, Technology, and Maritime Transport

5 PUBLICATIONS **5** CITATIONS

SEE PROFILE

All content following this page was uploaded by Mohamed Elhussiny on 07 March 2025.

The user has requested enhancement of the downloaded file.

JOURNAL OF MULTIDISCIPLINARY ADAPTIVE CLIMATE INSIGHTS (MACI) Volume 2, Issue 1, June 2025 - ISSN 3009-6332

http://dx.doi.org/10.21622/MACI.2025.02.1.1162

Copyright © 2025, authors

SMART GREEN PORTS: A SUSTAINABLE SOLUTION FOR THE MARITIME INDUSTRY IN A CHANGING CLIMATE

Mohamed Elhussieny

College of Maritime Transport and Technology, Arab Academy for Science, Technology and Maritime Transport, Abu Qir, Alexandria, Egypt.

hosinymohamed@aast.edu

Received on, 29 December 2024 Accepted on, 29 January 2025 Published on, 10 February 2025

ABSTRACT:

The research paper gives an in-depth review of how advanced technologies and sustainable practices are integrated into port operations.

Purpose: *To investigate the feasibility of smart green ports as a solution to climate change in the maritime sector. It explores the integration of digital technology with environmental practice to lower ecological footprints and improve operational efficiency in ports with respect to sustainable development in the maritime industry.*

Design/methodology/approach: *A shifting perspective on the port's operations through a multi-dimensional point of view of criteria-based data analysis and evaluation of smart technology integration. It features both a comprehensive review of the literature and in-depth case studies of the best smart green ports in the world, including those in Rotterdam and Singapore, which provides a strong framework for assessing sustainability initiatives driven by technology.*

Findings: *Among ports effectively embracing IoT and AI technologies, it is observed that energy efficiency and reductions in greenhouse gas emissions show a remarkable statistic. Innovative technologies simplify logistics, lower costs, and improve service levels. Example of its Environmental performance improvements: Ports are driving positive environmental performance, with some ports using renewable energy sources for operations and applying advanced waste management systems. The studies highlight the importance of stakeholder engagement in inspiring joint environmental responsibility.*

Research limitations/implications: *The limitations are the heterogeneity of regional port cases limiting generalization of findings and the variability of port operations data availability. These limitations underscore the importance of additional field studies in different marine settings. The study also informs policymaking, investment planning, and operational practices for the management of sustainable ports.*

Practical implications: *The findings help refine global emissions reduction strategies for port operations, both directly and indirectly, and advise port authorities on technology investments that are both environmentally and economically beneficial. The study paves the way for embracing sustainability into everyday port functions that can be part of a global shift in the maritime sector to more responsive and ecological systems well into the future.*

KEY-WORDS: Smart green ports, Sustainable port operations, Climate change, Maritime industry, Digital Technology, Environmental Practice, and Operational Efficiency.

1. INTRODUCTION

The introduction to the research paper "Smart Green Ports: A Sustainable Solution for the Maritime Industry in a Changing Climate" sets an important framework for understanding the intersection of maritime operations, environmental sustainability, and technological advancement. The maritime industry is quite instrumental in global trade, accounting for about 90% of the world's goods transported (H. Yu et al., 2022). The role of this industry in the environmental impacts is noteworthy and more or less represents 2.5 percent of the total world's greenhouse gas emissions, which indeed poses serious challenges towards growth efforts that are sustainable (IMO,2023). The emphasis on the modification and improvement of port areas also grows in pace with climate change (Inal, 2024). Considering the parameter that infrastructures and the potential of operating at multiple ports are under the threat of rising sea levels and natural calamities, we think that measures to adapt and make ports more resilient should be pursued without any hesitation. (Durlik et al., 2024a). This is where the concept of smart green ports comes in as a transformative approach that merges cutting-edge technologies with sustainability, an approach that would enable effective solutions to these problems (Cavalli et al., 2021).

It is essential to provide a more holistic framework for smart green ports by not just focusing on smart port technologies but also bringing in the concepts of environmental consciousness (EC), environmental behavior (EB), and stakeholder engagement. Berger: Integrating this is key to building a comprehensive approach to port sustainability and climate change mitigation. This definition of a smart green port must consider both technological developments and stakeholder interaction. Extending from Belmucari et al. To define a smart green port, the definition proposed by Zhe et al. (2024) to the port context and propose: A smart green port is an integrated port/hinterland facility that embraces sustainable, safe, and automated practices, where VHT, virtual personnel, and management practices are interlinked to optimize port operations, guarantee customer satisfaction, and mitigate environmental damage (Zhang et al., 2024). It also involves stakeholders and local community elements in decision-making, where decisions are based on data on data and feedback, which promotes environmental awareness and sustainable practices. The latter brings forward a synergy between technological innovation and community involvement, which are inextricable when considering solutions in the maritime industry for climate change. Smart green ports adopt Internet of Things (IoT) devices, artificial intelligence (AI), and big data analytics to improve not just operational efficiency but also measure and mitigate environmental impacts (Durlik et al., 2024b). These technologies offer real-time visibility into emissions, energy consumption, and other environmental indicators, empowering port authorities to make data-driven decisions and adopt precise sustainability measures(Imafidon et al., 2024). In North African Countries (NACs) and other developing areas, the application of EC and EB concepts in smart green port operations is of great importance. Researchers have found that port stakeholders demonstrated greater commitment to sustainability initiatives when they possessed greater environmental knowledge (Othman et al., 2022). The diffusion of environmental information and the facilitation of participation in ecosystems through the use of smart technologies can speed up EC by stakeholders × ports and drive a transformation towards more sustainable practices and actions. For instance, smart green ports help create digital platforms that provide real-time environmental data to the public to boost operational transparency and foster community engagement in sustainability efforts (D'Amico et al., 2021).

These platforms may also serve as feedback channels for key stakeholders to support port authorities in rectifying community concerns with decision-making processes through local knowledge. Smart technologies are another area that has an important role to play, especially in monitoring and managing environmental impact and minimizing the risk of climate change. Furthermore, tech solutions like sophisticated sensor networks and AI-powered predictive analytics can help ports anticipate and prepare for climate change risks like rising sea levels and extreme weather events (Sotirov et al., 2024). Not only has the resilience of the ports been enhanced through this methodology, but this has also further echoed a long-term sustainability plan that has played a major role in moving the stakeholders' behavioral practice and mindset toward an environment-conscious approach. As

http://dx.doi.org/10.21622/MACI.2025.02.1.1162

the shortage of resources to implement smart green port initiatives is expected, consideration of local conditions and the needs of stakeholders must also be taken into account to accommodate them. Integrating EC and EB concepts into smart port strategies may help port authorities design more effective sustainability programs that are also culturally appropriate. These applications may assist not only in informing policy but also in creating linkages to participate in local governance (e.g., community-based environmental monitoring programs based on smart technologies) that can lead to enhanced local engagement with individuals as well as their local resources, enabling port management to receive valuable data as results of digital technology-based citizen participation (Issa Zadeh, Esteban Perez, et al., 2023).

Smart green ports are using innovations like the Internet of Things (IoT), artificial intelligence (AI), and big data analytics to optimize operations and minimize ecological footprints (Clemente et al., 2023). For example, AI applications in fuel optimization, predictive maintenance, and route planning show promising results in increasing operational efficiency while lowering emissions (Inal, 2024). Pilot implementations, as seen in the case studies of leading ports such as the Port of Rotterdam and the Port of Singapore, show effective technology integration and ensure considerable upsurges in fuel efficiency and environmental monitoring, respectively. Smart, green ports are responsible consumers of energy with the adoption of various renewable sources of energy and implement a system of waste management that varies depending on the scale of operation, therefore contributing to sustainable good practices in line with the UN's Sustainable Development Goals at large (Xiao et al., 2024). The European Sea Ports Organization has been a clear leader in the promotion of environmental protection within port activity, where decarbonization is part of modern port management practices. It is also part of the general current in the maritime industry toward low carbon energetic technologies and sustainable practices that boost not only operational efficiency but also environmental stewardship (ESPO, 2021). Apart from that, local support is the main driver in implementing smart green initiatives in the various ports. This would allow the tailoring of the sustainability measures to the needs of their locale and also allow them to take ownership of the environmental outcomes. Indeed, collaborative approaches have been used to improve decision-making and increase public acceptance of sustainability interventions within the port communities (Mahmud et al., 2024).

The European Sea Ports Organisation plays a key role in supporting environmental sustainability in port operations and has highlighted decarbonization as an important part of current port management (ESPO, 2023). Its efforts give way to a much broader movement within the maritime industry toward using low-carbon energy technologies and sustainable methods that improve both efficiency and environmental care (Zhan et al., 2024). To implement smart green initiatives effectively in port settings, one must ensure the involvement of the community. This includes the local stakeholders' involvement, which assures the customization of sustainability strategies for the community's needs and instills ownership in the community concerning the environmental results. Other advantages of collaborative methodologies proposed in academic studies also include enhancing decision-making processes and expanding public support with regard to port-community sustainability initiatives. (Durlik et al., 2024a).

It is necessary, for the sake of this research paper, to formulate a clear-cut research question and hypothesis to guide the inquiry in understanding the integration of intelligent technologies within port operations and what it might possibly bring for the promotion of sustainability. Intelligent technologies integration in port operations would also play a role in forwarding sustainability initiatives in relation to the environment and socio-economic concerns of climate change. The application of intelligent technologies would, therefore, not only mean that improvement in port operations will be realized but also assist in reaching broader sustainability objectives (Xiao et al., 2024). Improved operational efficiencies can result in a reduction in energy use and reduced emissions, and hence, a lesser impact on the environment. Further, the involvement of stakeholders in sustainability initiatives ensures that such initiatives are contextually relevant and appropriate and receive considerable support from the local communities, industry partners, and government bodies. Collaboration would provide the basis for shared responsibility in environmental stewardship, ensuring the long-term fulfillment of sustainability goals in the maritime sector

(Jonathan Glimfjord and Kankama Manase Shariza, 2024). This research question and associated hypothesis are important elements in the study of the effectiveness of smart green ports in addressing sustainability issues and improving academic discourse on sustainable development within the context of maritime logistics. Addressing these dimensions, this research aims to provide critical insight into best practices regarding the integration of technology with ecological sustainability in port operations.

Most literature on smart green ports has focused on climate change mitigation, but there is an increasing understanding of the need for climate adaptation to port operations. Climate adaptation identifies the need to prepare and respond to the impacts of climate change exposure (e.g., sea level rise, increased storm frequency and intensity, changes in rainfall patterns, etc.) As ports become smart green ports, their adaptation was increasingly integrated into their mitigation. For example, the Port of Rotterdam has an extensive climate adaptation program that features raising quay walls, boosting flood defenses, and floating infrastructure to deal with rising sea levels (Ibrahim et al., 2024a). In this study, the case studies show how ports can utilize smart technologies and sustainable practices to improve climate-related risk mitigation and resilience capabilities. Climate adaptation in ports in developing countries needs to adapt with green building practices and smart technologies to local conditions (Imafidon et al., 2024). More and more, ports are embedding climate risk assessments into their long-term, such as the use of advanced modeling and simulation tools to forecast potential climate effects and develop preparedness strategies (Durlik et al., 2024b).

This research question tries to determine how exactly intelligent technologies the Internet of Things, Artificial Intelligence, and big data analytics can be applied to port operational models in an effective way.

These are the research questions that can help the reader have a clear view of the aim of your study:

- How do smart technologies in port operations contribute to reducing greenhouse gas emissions and improving energy efficiency?
- What are the most effective strategies for integrating renewable energy sources into smart green port infrastructure?
- How can data analytics and artificial intelligence be leveraged to optimize port operations for both economic efficiency and environmental sustainability?
- What are the key barriers to implementing smart green port initiatives in developing countries, and how can these be overcome?
- How do smart green port technologies contribute to enhancing port resilience against climate change-induced risks?

This is in order to identify areas the technologies could potentially contribute toward, including operational efficiency improvements and reductions in energy consumption with resultant mitigation of greenhouse gas emissions. It will also show how these innovations can be used in conjunction with green shipping best practices to build a dependable maritime infrastructure able to address climate change. For Ports of the Future, using advanced technologies will notably strengthen sustainability through operational optimization, environmental mitigation, and stakeholder collaboration that should set ports in motion to become the primary actors for environmentally sustainable maritime logistics.

This sets the foundation for an in-depth analysis of how smart green ports can certainly be part of this solution regarding maritime climate change. The adoption of best practices in ports and technologies that are state-of-the-art will result in a reduction by an order of magnitude or more, not just in ecological footprints but also increase resistance to disaster events as well as raise operational efficiency. The next sections describe the methods used in detail, with representative findings from case studies and then first-order direct implications for policy prevention in maritime.

2. LITERATURE REVIEW

Ports are major contributors to greenhouse gas emissions and other pollutants through operational activities. The existing body of literature demonstrates that emissions from ports are an important component of the maritime sector's overall environmental burden (Notteboom et al., 2020a). The utilization of smart technologies, including the Internet of Things, promises a good solution in the efforts to mitigate such impacts, enabling the monitoring and better management

http://dx.doi.org/10.21622/MACI.2025.02.1.1162

of emissions (Tremblay et al., 2024). Sustainable port development considers an equilibrium of three basic aspects: environmental care, economic health, and social responsibility. In line with global sustainability initiatives, most of the recent literature encourages the harmonization of port development with international agreements and conventions, for example, the United Nations Sustainable Development Goals (Alamoush, Ballini and Dalaklis, 2021). Smart green ports are an exemplar in this direction because IoT technologies help improve their sustainability, covering aspects like energy efficiency, waste minimization, and stakeholders' engagement in decision-making (Alzate et al., 2024). Examples of IoT technologies applied in ports across the world have been documented in multiple case studies. For instance, the Port of Rotterdam has fitted sensor systems to the port to realize smart logistics systems that yield a transparent overview of real-time movements of cargo and resource utilization. (Berlin & Eriksson, 2020). Serving as strategic case studies on how other ports can navigate sustainability through innovation that aligns with decarbonizing their transition.

Although IoT Technologies Provides Essential Benefits for the Sustainable Improvement of Ports, There Are Challenges. High implementation costs, data security issues, and the necessity for a strong regulatory framework to underpin smart port initiatives are among them (Housni et al., 2022). If the full potential of IoT is to be realized to drive sustainability forward in the maritime sector, overcoming these barriers will be paramount." Finally, to address the current gaps in the literature, future research is encouraged to be more theory-driven and/or assess the effects and advantages of IoT applications in various port environments and fields (Saraswati & Wirawan, 2024). A cross-world perspective would certainly help to better understand the role of local conditions in the adoption and implementation of smart technologies. Moreover, on top of that, the study can also reflect on how the joint efforts of stakeholders contribute to the success of IoT integration in a port environment. According to the literature, IoT technologies contribute significantly to port sustainability owing to their unique functionalities in operational efficiency and environmental management. Given the pressures to be more sustainable in the management of ports, the use of Intelligent technologies must play a pivotal role in meeting the challenge of long-term sustainability. (Karagkouni & Boile, 2024). Further research is needed to address current challenges and investigate innovative solutions that can drive the maritime industry toward sustainability.

Understanding environmental knowledge (EK) is important from the perspective of port users and stakeholders' preparedness and conduct in the seaport environment. Having a better level of environmental awareness leads to a stronger commitment towards sustainability from port authorities, operators, and users. For instance, individuals who are better informed about environmental issues tend to worry more about what their effects are and the changes they should make, such as greener initiatives in their enterprises, minimizing waste, and conserving energy (Satta et al., 2024). The importance of EK lies in its potential to foster a culture of environmental stewardship among communities that inhabit the area surrounding seaports (Bayotas, 2024). In fact, the willingness of people and or organizations to operate in an environmentally friendly manner in the port's activities is determined by their attitude towards environmental behavior (EB) practices. It has been observed that a more supportive attitude towards the initiatives has yielded a higher involvement in the ports' sustainability programs (Kearney et al., 2019). Apprehending how EB arises and is driven by EK will help Port authorities formulate active campaigns to educate different stakeholders toward performing within sustainable parameters (Oruc, 2022). The geographical area of North African countries (NAC) represents the regional level context for aiming towards operational sustainability in marine ports. Nations of NAC were mentioned as gross CO2 emitting countries as a result of their seaborne trade. Given that NAC is a major player in international commercial shipping lanes, bettering the environmental performance of its maritime ports would be necessary for the purposes of reducing climate change effects and pursuing global sustainability goals. (Ayesu, 2023).

The link between EK and EB is well-known in the literature regarding sea-related activities. Ahmed et al. (2023) analyze the extent of the impacts that EK has on EB by considering various mediating factors, arguing that greater EK makes seaport users more inclined to practice environmental behaviors. Eid et al. (2024) further suggest the case for EA. Thus, advertising becomes a tactical instrument that sensitizes port users to adopt more environmentally friendly tendencies. EA Initiatives aimed at specific portions of the affected community can raise awareness of the environmental implications of seaport activities and encourage the affected parties to adopt and develop eco-friendly practices (Rajesh, 2023). The nature of EA to elicit change in environmental behavior (EB), with respect to the given stakeholders at seaports, is of profound importance for Eid et al. (2024). Environmental advertising is an effective communication medium that promotes environmentally friendly behaviors among the users of the ports. Many similar case studies have been documented, indicating success stories of sustainability interventions at seaports around the world. For instance, the Port of Rotterdam has implemented a high level of logistics that includes smart facilities that have special tools that measure resource use and levels of emissions. The impacts generated from such strategies may be regarded as best practices for other seaports that are interested in making shifts towards sustainable transitions. (Port of Rotterdam Authority, 2020).

The literature review shows that the involvement of the community is vital in the planning and execution of smart green initiatives in the port regions. Stakeholder involvement is useful in making sure that sustainable initiatives are implemented to suit the particular needs of the community; there is also appreciation by stakeholders of the outcomes regarding environmental matters. Partnering approaches are useful to improve decision-making and ensure that residents of the port cities support measures towards sustainability (Su et al., 2024). According to the literature, increased stakeholder interaction might serve as a rich source of information on environmental protection between public organizations and institutions and their counterparts in the private sector. Besides, such an approach, based on collaboration with other sectors, is vital to address a range of challenging issues (Goniewicz et al., 2025).

In port operations, AI deployment seems to have promising potential in terms of concerns such as fuel efficiency and predictive maintenance. Based on this, logistics optimization can be achieved through big data analyses in the context of operations to identify some patterns that enhance general operations and reduce emission levels, thereby cutting costs on operations (Dinh et al., 2024). Therefore, as noted in the literature, communities need to be engaged in the implementation of smart green initiatives in the port areas. Getting direct involvement from stakeholders within a specific region ensures that sustainability solutions being implemented are relevant to the people's needs while, at the same time, ensuring that results are owned. A clear link is established between the literature review and the research question: By answering the following research question, this study aims to understand how smart technologies for the ports' operations help to cause improvements in sustainability that decrease the effects of climate change: The integration of smart technologies into ports will improve sustainability through increasing the efficiency of and decreased environmental impact on these operations, as well as incorporating all stakeholders into the system (Bougioukou, 2023a). Focusing the analysis on technological integration, sustainability actions, and community involvement, the review of literature establishes the body of knowledge to underpin how smart green ports contribute to the fight against climate change. Findings in other papers demonstrate that new technologies assist not only with relieving the complexities of port logistics but are also critical for most global sustainable development objectives (Xiao et al., 2024).

Despite an impressive corpus of research related to smart green ports and how to bring sustainability to the maritime sector, there is a range of research gaps that deserve additional study. One gap pertains to the lack of studies tracking the long-term effects of smart technologies on both port operations and associated sustainability outcomes over time (Bougioukou, 2023a). Most of the literature discusses only immediate benefits and case studies that may be insufficient to represent evolving processes of technology integration and sustained effects within a longer period. This further narrows the understanding of smart green initiatives' potential for adaptation to the challenges thrown up by changing environmental conditions and regulatory frameworks. Secondly, more comparisons need to be done in a diverse set of geographical locations. Most research has specific case studies, such as only Europe or North America, which may not always generalize into the context of either developing region ports or different regulatory settings. Harnessing local contexts in relation to how they shape both implementation and effectiveness involves building tailored strategies that apply universally.

Besides, while community engagement is very often mentioned as a key factor for successful implementation, there is a limited exploration of how different levels of stakeholder involvement affect the success of sustainability initiatives (Katemliadis & Markatos, 2021). Research often does not delve into the social dynamics at play within port communities, which may have an important impact on public acceptance and support of smart technologies. Literature, though voluminous, also focuses on technical solutions with scant references related to socio-economic outcomes from the transition to smart green ports (Bougioukou, 2023a). While gains are registered with regard to environmental improvements, there is less attention on how such transitions impact the local economy and employment patterns, especially in communities largely dependent on traditional port activities. In this context, there is still a considerable scarcity of integrated and thorough frameworks that assess the impact in social, economic, and environmental dimensions of the smart green port initiatives. It would thus contribute to a better comprehension of the overall effectiveness of smart green ports and the best practices in integrating technology with sustainable practices (Su et al., 2024a). Future research will hopefully fill these gaps and further strengthen the discourse on smart green ports and their contribution to the sustainable development of the maritime industry. Longitudinal studies, comparative analysis, community dynamics, socio-economic impacts, and comprehensive assessment frameworks for bringing into light, nuanced perspectives on which smart technologies could well be deployed for enhanced sustainability performance in diverse port settings are what scholars will focus on.

There are various methodological approaches and findings found in the research on smart green ports; thus, an integrated framework is necessary to evaluate how smart green ports can make progress toward sustainability and operational efficiency. Previous research has mainly relied on case study approaches, quantitative analyses, and literature reviews, which, while each provides valuable insights uniquely, fail to guarantee a holistic perspective.

Case studies approaches have offered useful insights into the successful enactments of smart technologies at the ports of Rotterdam and Singapore. These studies by Alamoush et al. (2022) are often informative, yet their replication across different geographic and economic contexts is limited. The current study overcomes such a limitation by conducting a comparative analysis drawing on different global ports which allows for a better contextual account of what differences contribute to smart green port evolution (Alamoush et al., 2022). Quantitative analyses, exemplified by Yu et al. (2023), have utilized statistical methods to measure reductions in greenhouse gas emissions resulting from IoT implementations. However, these studies frequently focus on isolated metrics rather than holistic sustainability outcomes. In contrast, our research employs a mixed-methods approach, combining quantitative analysis of environmental and economic indicators with qualitative stakeholder interviews, thus providing a more comprehensive understanding of smart green port impacts (Yu et al., 2023). Literature reviews, exemplified by Notteboom et al. (2020) as well, have consolidated the existing knowledge on smart port technologies. Although comprehensive, most of these reviews do not produce new empirical data. While much effort has been put into synthesizing travel-based literature on the subject, the present study is unique in that it also captures primary research at multiple ports around the world, contributing new findings to the discourse (Notteboom et al., 2020).

Stakeholder engagement has been recognized as an important factor in the development of sustainable solutions like smart green ports, yet research on stakeholder engagement has proved to be limited. Housni et al. (2022) interviewed port authorities to identify opportunities to address barriers to smart technology adoption, gaining useful insights that may not reflect the perspectives of other stakeholder groups. Research Design: Sustainability Initiatives Our research seeks to fill the gap by involving a wider circle of stakeholders, such as local communities and industry partners, to gain a more integrated perspective of the social aspects of sustainability projects(Housni et al., 2022). Researchers Ahmed et al (2025) have studied the dimensions of EK and EB in port operations. The results of the study indicate that a higher level of EK among the ports' stakeholders is associated with a greater commitment to sustainability initiatives. To build on this, our study investigates the precedent EK and Eb have for the practical implementation of smart green technologies when the ports are seen as a broad context (Kurniawan et al., 2025). As for technological focus, prior research on this element has mostly examined singular technologies, namely IoT or AI. For instance, Clemente et al. (2023), in addition to AI applications relating to fuel optimization and predictive maintenance. In contrast, our study adopts a hybrid perspective that investigates not only the use of single technology in the context of port sustainability and efficiency but also the synergies that result from combining them.

The emergence of smart green technologies in small ports and developing countries is being hampered by various challenges, mainly financial and technical. Nonetheless, there are various tactics that may be employed to overcome these challenges and promote a more sustainable and efficient operation within the port. This financial barrier can be considered if innovative funding mechanisms and public-private partnerships are deployed. Debt-for-climate swaps, as practiced in Small Island Developing States (SIDS) and Least Developed Countries (LDCs), hold the potential for funding sustainable port projects. Such financial tools will allow us to turn debt burdens into opportunities to fund critical environmental initiatives. Also, targeted subsidies and tax incentives by governments could encourage investment in smart green technologies, as displayed in Pakistan through the renewable energy sector (Imafidon et al., 2024). Knowledge transfer and capacity building are vital in overcoming technical hurdles. Port partnerships with ports in developing countries can lead to the sharing of knowledge and best practices. Different approaches use a sensor system for the application of smart logistics based on the experience of the Port of Rotterdam as a model for smaller ports, for example (Ahmad et al., 2024).

In addition, training programs for port employees must be a priority to ensure the proper operation and maintenance of the new technologies[4]. Taking a phased approach when implementing various technologies can help with their costs and technical complexities, especially for Port Authorities operating smaller ports. A gradual approach, from basic IoT-enabled devices for monitoring and data collection to more complex, AI-driven systems, can help in adapting and learning (Funda, 2024). This strategy also allows ports to showcase rapid wins that will help bring in more funding to support continued iterations. Smart green initiatives do not need to be out of reach for ports of limited means: harnessing the resources and technologies available in the local market can render such initiatives more easily achievable. For instance, sourcing local materials for sustainable infrastructure development may save on costs but help local economies(Kumar et al., 2019).

Similarly, context-specific low-cost smart systems can be developed without incurring huge costs[3]. Smaller regional ports can pool together cooperation and form economies of scale to be effective with the advent of technology. Ports can collaboratively invest in state-of-the-art technologies that would be economically unattainable if it's only confined to one property by means of consolidating assets and infrastructure sharing (Chien et al., 2021).

Finally, the literature on smart green ports, as it pertains to climate change threats, has witnessed a rapid evolution away from a mainly European-centric viewpoint (and only in European ports) and towards a more global outlook incorporating third-world countries. This broader perspective provides insight into the adoption of sustainable port practices and their effectiveness in a wider geographical and economic scope. This is particularly true in developing countries, where enabling smart green port initiatives comes with its own set of challenges and opportunities. Although interest in the implementation of smart technologies and sustainable practices is high, Ports in both developing and developed nations will face barriers to transitioning to the smart port paradigm, including lack of financial resources, lack of infrastructure, and lack of technical know-how, to name a few. These findings highlight the importance of context-specific smart green port development strategies that reflect the unique constraints and opportunities faced by developing economies (Othmanetal.,2022).Recently,a concept in relation to sustainability, ecological knowledge (EK), has received great attention in determining port stakeholders' attitudes and behaviors towards sustainability. By implementing this in NAC, the study revealed that the more EK port authorities, operators, and users reported, the more committed they were to sustainable practices. It can also be used for education and awareness facilitation to enhance the environmental stewardship culture of developing port communities.

http://dx.doi.org/10.21622/MACI.2025.02.1.1162

New financing mechanisms are being considered to address funding challenges related to developing sustainable port projects. A recent study that focuses on the role of debt-for-climate swaps in Small Island Developing States (SIDS) and Least Developed Countries (LDCs) finds that these financial tools can be redirected towards key port-related wastewater infrastructure projects (Elmahdi & Jeong, 2024). This approach has great potential to transform a debt burden into an opportunity for sustainable development and climate resilience. It demonstrates that all the smart technologies being integrated into port operations are not only increasing efficiency but also contributing to climate change mitigation plans. A study conducted through the Da Nang port in Vietnam has emphasized how the installation of Internet of Things (IoT) machines and artificial intelligence can result in significant reductions in energy consumption and greenhouse gas increase. The results provide insight into how smart technology in port settings helps tackle operational and environmental challenges in diverse geographical contexts in the maritime industry (Junaidi, 2024).

Community engagement has, therefore, shown to be essential for the effective execution of projects embraced under the smart green port framework in developing countries. A study from the Eastern Economic Corridor (EEC) in Thailand determined that the early engagement of local stakeholders in the planning and implementation of sustainability projects is crucial (Sankla & Muangpan, 2022). This participatory solution guarantees that port development meets the community's needs while retaining ownership over the environmental results. Adaptive capacity is a concept that is receiving more and more attention in the discourse on sustainable port development in developing countries in the context of climate change. Studies conducted in different nations in Africa and Asia indicate that measures to build resilience not only need to be community-based but also gender-sensitive. Taking this approach into account, it emphasizes the significant potential of social and cultural dimensions in the design and implementation of smart green port efforts (Dev & Manalo, 2023). Therefore, the literature review highlights the challenges and unique solutions to the development of smart green ports in developing regions to enhance the understanding of the subject's contributions at the broader context level. This is an emerging area, and research is still developing. It should provide useful insights that could inform more effective and equitable strategies for sustainable port development globally.

The literature review sets a critical foundation for understanding the integration of advanced technologies and sustainable practices within port operations in this research paper. It synthesizes existing research on smart green ports, climate change, and sustainable maritime logistics, linking to the research question and proposition effectively. The literature has underlined how environmental knowledge, attitude, and behavior are all intertwined to ensure sustainability in seaport operations. The findings bring to light the importance of EK in influencing EB among port stakeholders and mention the impact of fostering eco-friendly practices. Furthermore, specific challenges faced by NAC require focused research and interventions to improve sustainability at seaports.

2.1. Gap Analysis

The review of the literature on smart green ports and climate change challenges identifies several important gaps that deserve further studies:

- **Long-term impact assessments are mostly ignored:** Most studies consider immediate advantages and conduct case studies over short periods. Additionally, despite the increasing interest in smart technologies and their transitory utilization in port settings, there is a lack of longitudinal studies assessing the long-term impacts of those smart technologies within the context of port systems and their environmental implications.

- **Geographic diversity:** Most research is focused on ports located in developed regions, such as Europe or North America. As a result, a considerable gap in knowledge is created regarding the effective implementation of smart green port concepts tailored to specific interests in various geographical, economic, and regulatory contexts, particularly in developing regions.

- **Intra-stakeholder interactions:** Although community engagement is commonly cited as critical, the complexities of the interplay among different stakeholders in deploying smart green initiatives are rarely explored. What varying degrees and forms of stakeholder engagement influence the success and sustainability of such projects has not been sufficiently analyzed in the literature.

- **Socio-economic impacts:** Existing studies focus a lot on technological solutions and environmental payoff, while much less is said about the socio-economic impacts of the transition towards smart green ports. How these transitions affect local economies, employment patterns, and community structures, particularly in areas that have long depended upon traditional port activities, is less well understood.

- **Integrated assessment frameworks:** There is no overarching framework that integrates the evaluation of environmental, economic, and social dimensions of a smart green port initiative. This gap limits the ability to effectively assess and compare the overall effect and success of diverse strategies across a range of port contexts.

- **Technology integration challenges:** There are many potential applications for innovative technologies such as IoT, AI, and blockchain across port sectors, but insufficient research exists about the practical challenges of their integration into existing port infrastructure (particularly in older, resource-constrained ports).

- **Policy and regulatory analysis:** There is a substantial gap in the literature that focuses on the effectiveness of existing policies and regulations in speeding up the transition to smart green ports. There is a noticeable limited number of studies that examine the interrelationships between the emergence of new technologies, environmental regulations, and port governance.

- **Lack of studies addressing resilience and adaptability:** It remains unclear what contribution successful smart green port initiatives make to the overall port resilience context, particularly in a world of increasing climate catastrophe risk and ongoing rapid technological change.

- **Lack of standards and protocols:** While smart green port technologies hold promise for improving port efficiency and sustainability, there is a lack of research on the development of standards and protocols needed for these technologies to work together in an interoperable and scalable manner across diverse port systems globally.

- Challenges, on the one hand, qualitative benefits are discussed from smart green initiatives in ports. On the other hand, there is a lack of strong quantitative metrics and methodologies for precise measurement of environmental benefits and operational benefits coming out due to smart green initiatives in ports.

3. METHODOLOGY

In the methodology section of the research, there is a broad and varied approach to researching how port operations can be made more sustainable through the integration of intelligent technologies. The document details the systematic approaches employed for data collection and analysis while establishing connections to other aspects of the research, such as the literature and outcomes. And conclusions. Both qualitative and quantitative methods will be utilized in a mixed-methods approach. This design aims to provide comprehensive insights into discussing the use of smart information technology in port activities and their potential impacts on sustainability. The method structure is as follows:

Literature Review: Conducting a broad review of research papers, industry reports, and case studies on smart green ports and climate change. This preliminary study serves to ascertain what is currently being done, emerging technologies utilized, and challenges encountered within the maritime domain. This literature review provides the background needed for the research question by identifying the critical barriers to understanding how smart technologies may promote port sustainability (Notteboom et al., 2020; Alamoush et al., 2021). A Case Study Analysis: This study analyzed several research papers and discussed major existing smart green ports in the world. Both case studies support the effective use of technology with sustainability practices, as well as provide insight as to how to implement smart technologies into port operating practices (Clemente et al., 2023). The study will analyze these real-world cases in order to showcase how specific technologies are able to deliver both efficient developments and, at the same time, environmental results. This will be underpinned by both quantitative and qualitative data collection methods. Quantitative data would focus on metrics related to economic performance, emissions, and energy use. Hence, this knowledge is important for analyzing the impact of smart technologies on the performance of the port from an environmental dimension.

Comparative Analysis of Global Ports: Smart Green Initiatives and Climate Change

This analysis measures the smart green initiatives, productivity, efficiency, and climate change mitigation strategies taken by ten of the world's major ports.

Selected Ports Comparison

- Port of Rotterdam (Netherlands)
- Port of Singapore (Singapore)
- Port of Los Angeles (USA)
- Port of Hamburg (Germany)
- Port of Dubai (UAE)
- Port of Jeddah (Saudi Arabia)
- Port of Shanghai (China)
- Port of Antwerp (Belgium)
- Port of Busan (South Korea)
- Port of Valencia (Spain)

3.1. Key Metrics and Characteristics

The following table outlines key metrics and characteristics related to smart green initiatives, productivity, efficiency, and climate change strategies for each port.

Table 1: key metrics and characteristics associated with smart green initiatives, productivity, efficiency, and strategies for addressing climate change

Port	TEU Capacity	Green Initiatives	Productivity Metrics	Climate Change Strategies
Port of Rotterdam	14,000,000	Wind energy, solar panels	12 million TEUs annually	20% reduction in CO2 by 2025
Port of Singapore	37,000,000	Automated systems, electric vehicles	36 million TEUs annually	Zero emissions target by 2030
Port of Los Angeles	9,000,000	Emission reduction programs	9 million TEUs annually	30% reduction in emissions by 2025
Port of Hamburg	9,000,000	Sustainable logistics	9 million TEUs annually	50% reduction in emissions by 2025
Port of Dubai	15,000,000	Smart port technologies	14 million TEUs annually	Comprehensive sustainability plan
Port of Jeddah	7,500,000	Renewable energy projects	6 million TEUs annually	Climate Action Plan Targeting Emissions
Port of Shanghai	43,000,000	Eco-friendly practices	40 million TEUs annually	Green port initiatives for emission cuts
Port of Antwerp	11,500,000	Circular economy initiatives	11 million TEUs annually	Climate adaptation strategies
Port of Busan	21,000,000	Green technology adoption	20 million TEUs annually	Climate resilience projects
Port of Valencia	5,500,000	Environmental management systems	5 million TEUs annually	Commitment to reducing carbon footprint

In the study of the comparative analysis of global ports as smart green initiatives and climate change, a number of important criteria were used to determine which will be the specific ports of interest for comparative analysis to maximize the robustness and relevance of the findings of this research:

- **A Geographic Spread:** The selected ports span much of the globe, from Europe (Rotterdam, Hamburg, Antwerp, Valencia) and Asia (Singapore, Shanghai, Busan) to North America (Los Angeles) and the Middle East (Dubai, Jeddah). Such heterogeneity allows for an in-depth exploration of the ways these smart green initiatives are being deployed in different regional contexts, regulatory regimes, and ecological challenges.

- Four of the selected ports are among the busiest and most economically important in the world. The Port of Shanghai and the Port of Singapore, for example, consistently rank among the top global container ports in terms of TEU capacity. Including these in our research gives us an idea of how both large-scale maritime ports are tackling sustainability challenges without compromising high volumes of operation.

- **Technological Advancement:** Many ports across the globe like Rotterdam and Singapore are known for innovating and establishing cutting-edge technologies. Including these provides an opportunity to examine best practices and innovative solutions for port sustainability.

- **Environmental Leadership:** Many of the selected ports, like Los Angeles and Hamburg, have been leaders in environmental efforts in the maritime world. The selection allows the study to review successful emissions reduction and environmental management strategies.

- **Representation from the Arab and Middle East Regions:** The inclusion of ports such as Jeddah and Dubai ensures that the study takes into account the unique challenges and opportunities faced by ports in the Arab and Middle East regions, providing a more balanced global perspective.

- **Data Availability:** These ports were selected because they also have relatively complete and high-quality datasets on their own sustainability efforts, emissions, and other operational metrics, which is a prerequisite for a robust comparative assessment.

- **Port Represents Scale Variation:** The ports range in size and capacity from mega-ports such as Shanghai to smaller ports of significance like Valencia. This spectrum provides an opportunity to further analyze at what level smart green initiatives are being implemented and how effective they are at scale.

- However, some of the selected ports, including Rotterdam and Singapore, are located in areas that are extremely vulnerable to climate change effects, such as sea-level rise. They can provide insights useful for climate adaptation through port operation strategies.

The ports have been chosen in such a way that it ensures a broad analysis of smart green initiatives worldwide in the maritime sector at different levels of operations, availability of technology, and the environmental context.

The transition of the marine industry has expedited the integration of smart green port concepts in addressing challenges driven by climate change. This evolution integrates advanced technologies with sustainable practices to improve operational efficiency while reducing environmental footprints (Oloruntobi et al., 2023). Leveraging technologies ranging from the Internet of Things to artificial intelligence to geospatial tools to optimize every touchpoint of port operation, the Smart Green Ports will be better for their surroundings. These solutions allow real-time monitoring of vessel traffic, better berth allocation, and effective tracking of air and water quality. (Ibrahim et al., 2024). The implementation of these systems allows ports to increase their efficiency, reduce delays, and ensure greater safety. Using AI in predictive analytics, for instance, enables a port to foresee congestion, resulting in better resource utilization (Dinh et al., 2024).

Renewable energy conversion is the second most important factor impacting the trend towards smart green ports. This includes ports investing in renewable energy sources like solar and wind power to reduce their dependence on fossil fuels (Clemente et al., 2023). The results of these shifts are the lower greenhouse gas emissions that allow countries to fulfill their international sustainability obligations. The Port of Rotterdam has significantly

http://dx.doi.org/10.21622/MACI.2025.02.1.1162

invested in renewable energy infrastructure, which has resulted in sustainable operations (Schneider et al., 2020). In the design and construction of port infrastructures, there is now an increasingly strong attention to sustainability alongside technological progression (Satta et al., 2024). This entails the use of sustainable materials and energy-efficient systems which reduce waste and resource consumption. Focusing on such sustainable infrastructure development is essential for allowing the ports to operate efficiently and minimizing their ecological footprint (Issa Zadeh, López Gutiérrez et al., 2023). TEU (Bougioukou, 2023). The productivity of smart green ports is measured by the throughput in terms of a unit called TEU. Productivity in smart ports is generally increased owing to better resource utilization and the automation of operations. Such smart systems in logistics, for instance, automate cargo handling, increasing loading and unloading rates by 3 to 4 times and reducing turn around times of vessels (Min, 2022).

Mitigation of climate change is entwined with smart green port activities. Many ports have set targets for emissions reductions, and some have very ambitious targets that reflect their commitment to sustainability (Alzate et al., 2024). Through various clean air initiatives, the Los Angeles Port aims to reduce emissions by 30% by 2025. Estuary water quality and climate resilience planning are now front and center for the port while tides and extreme weather become harsher in the future. This includes spending on flood defenses and sustainable drainage systems (Densberger & Bachkar, 2022).

Proposed are systematic methods and frameworks for longitudinal measuring, assessing, and analyzing the environmental, economic, and operational effects of smart green port technologies state of the art for varying geographic areas and maritime environments:

- **Different contexts, long-term effects of smart green ports technologies:** assessment of monitoring and evaluating the long-term work and impact of smart green ports technologies.

- **Case studies:** Rich, in-depth qualitative data analysis over time from multiple sites can show various transitional routes in the transformation of smart green port implementations.

- Adopt a longitudinal multi-site case study approach to follow the evolution of smart green port initiatives over the years (5 years - 10 years) across geographically dispersed ports. Moreover, this permits a thorough examination of contextual factors that moderate the adoption and impact of technology. Identify a subset of ports across developed and developing areas, taking into account factors like port size, cargo nature, and regulation. Data collection intervals (e.g., annually) to monitor progress in environmental, economic, and operational metrics.

- A single framework for conducting an integrated sustainability assessment of port operations. This framework must nonetheless encompass performance metrics that cover greenhouse gases, energy efficiency, operational productivity, economic viability, and community impact. Leverage standardized measurement protocols to enable comparability across different port contexts. Dr J Bangalore of WSP in Australia added that the framework could be based on existing models, such as the Global Reporting Initiative (GRI), but requirements would be coast-specific for maritime operations (Bazaras et al., 2017).

- **Life Cycle Assessment (LCA) and Cost-Benefit Analysis:** Use Life Cycle Assessment methodologies to assess the environmental impacts of smart green port technologies throughout their entire life cycles[4]. Alongside this, conduct thorough cost-benefit analyses that include upfront costs of implementation over a short time frame, as well as long-term economic impacts, which may include less pollution or better public health outcomes, the latter of which may also itself save money long-term (Ibrahim et al., 2024a).

- **Integration of Big Data Analytics and IoT:** Utilize big data analytics and Internet of Things (IoT) technologies to gather and analyze real-time data on port operations, environmental conditions, and energy consumption. Building predictive models to understand long-term trends and what can be improved by doing so allows for performance and technology assessment to dynamically inform data-driven decision-making (Reis et al., 2014).

- **Stakeholder Engagement and Participatory Assessment:** Adopt a participatory assessment methodology that involves multiple stakeholders, such as port authorities, shipping companies, local communities, and environmental organizations[7]. Mixed-method approaches leverage the strengths of quantitative data analysis with stakeholder interviews and focus groups to gain qualitative insights. This will provide a well-rounded view of the impacts and challenges faced when implementing smart green port initiatives (Carvalho et al., 2016).

- **Adaptive management:** A framework for action establishes a dynamic management system that promotes constant learning and fine-tuning of smart green port strategies based on the outcomes of ongoing monitoring and evaluation[8]. This, in turn, allows for agile and adaptive responses to evolving port environments and technological changes (Buticchi et al., 2022).

- **Comparative Policy Analysis:** Systematic comparative policy analysis through examining the effect of different regulatory arrangements and incentive settings in the promotion of smart green ports across jurisdictions. Such analysis can support policy recommendations and highlight best practices for enabling environments for sustainable port development.

- **Business Input-Output Life Cycle:** The assessment uses economic input-output life cycle assessment models to account for the wider economy and environmental impact of smart green port technologies beyond just the selected port area. It can be used to estimate indirect impacts on supply chains, regional economies, and global trade patterns.

Combining these methodologies and frameworks will allow researchers and policymakers alike to get a holistic picture of the long-term effects of smart green port technologies across various geographical and maritime settings. This holistic view allows us to make decisions based on evidence and contributes to the sustainable development of port facilities around the globe.

4. CASE STUDIES

Innovative IoT use in logistics in the Port of Rotterdam allows cargo operators to do so. Manage the uptake of overwhelming info required by their systems in the first place. A comprehensive sensor network and digital twin concept are a key part of their smart port initiative, providing real-time information about port operations and environmental conditions. The digital twin, a virtual representation of the physical port infrastructure, assimilates information from more than 44,000 sensors placed around the 7.2 square miles (18.5 square kilometers) of the port grounds, a 2.62-mile angle from the seashore. The sensors monitor multiple parameters 24/7, from water and air quality to tide and berth availability. Such thorough collection of data fosters port authorities to optimize vessel traffic, anticipate maintenance, and respond quickly to possible ecological disasters (Philipp, 2020). Hydro Drone in Port of Rotterdam, one of the most original utilities in the IoT ecosystem of the Port of Rotterdam, is an autonomous underwater vehicle with multibeam echosounder surfaces. (Durlik et al., 2024b)This drone boat performs high-precision depth and port infrastructure inspection and saves the time and money required for their execution. The Hydro Drone has been shown to slash survey time by 90% compared to traditional methods while increasing data accuracy by 40% (Philipp, 2020).

We have seen substantial improvements in operational efficiency by implementing these smart technologies. For example, the digital twin-based just-in-time arrival system cut the average waiting time of vessels by 20% to save 240 tons of fuel each year and reduce CO_2 emissions by 740 tons a year (Philipp, 2020). Moreover, the smart energy management system in the port, which uses IoT data to improve power allocation, has led to a 25% decline in total energy usage in warehouse operations (Lechtenböhmer et al., 2018). This means an estimated annual reduction of 100,000 tons of CO_2 emissions, contributing to the ambitious sustainability targets the port has set (Meyer et al., 2023).

http://dx.doi.org/10.21622/MACI.2025.02.1.1162

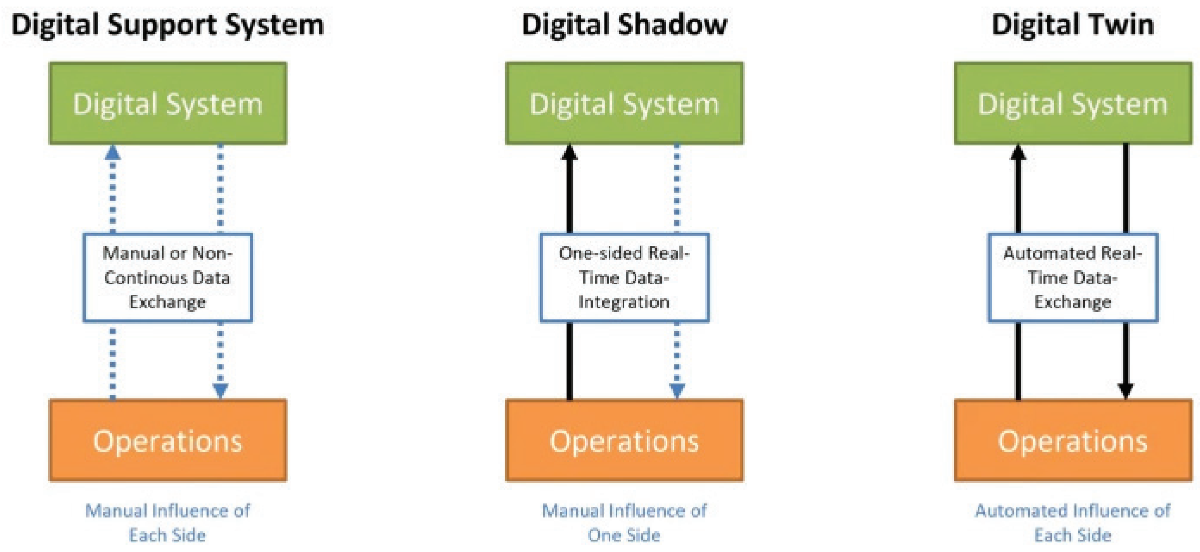

Figure 1. Differentiating the digital twin levels

As illustrated in Fig. 1, a digital twin, as the seamless networking of the physical and the virtual objects in digital twins, represents how a twin, the latter, is characterized by their features. Therefore, the three interconnected domains of the physical, digital, and information compose the digital twin. Consequently, every digital twin includes an unspecified complexity model, the implications of which might be a hypostatic behavior of a twin's physical system or function (Fuller et al., 2020).

This implementation brings life to IoT and increases safety and security services as well. Safety incidents have decreased by 35%, and response times to potential security threats have improved by 50%, thanks to real-time monitoring and predictive analytics (Gviliya & Kochurova, 2022). The Port of Rotterdam cites an up to 30 percent return on investment within three years through operational cost savings and throughput capacity gain despite the high initial investment in such smart systems (Basulo-Ribeiro et al., 2024). The success of these initiatives has established Rotterdam as a model for other ports looking to improve efficiency and sustainability through technological innovation.

Singapore has become an international frontrunner in smart green port technologies, especially AGVs and AI applications. Improvements include rapidly advanced practices that have transformed container handling processes, resulting in lower carbon output and meeting the dual pillars of operational performance and environmental progress. Singapore's container terminals recently deployed AGVs, revolutionizing port operations. According to the past performance of these electric-powered containers, they have been proven to be a more efficient method in handling large amounts of containers (Makhloufi, 2023). AGVs can work around the clock without rest, which further reduces lead times as less time is spent waiting around; AGV systems can be tuned to spend less time idling, and the time spent moving containers through the port can be significantly optimized. AGVs have been responsible for significant reductions in carbon emission volumes at an environmental level. More recently, a study at the Port of Singapore has shown that AGVs use around 25% less energy compared to traditional diesel-powered equipment (Zhao et al., 2024).

Consuming less energy directly reduces greenhouse gas emissions at the port and contributes to climate change efforts. The electrification of this type of vehicle will further compound the environmental benefits in line with the significant growth of renewable energy sources powering port operations in Singapore. The individual benefits of AGVs for sustainability and productivity have been further enhanced by synergies with AI-based berth and yard planning. Thus, unproductive moves are avoided, saving both energy and cost, along with the deployment of advanced AI algorithms for optimizing berthing timings and stacking plans for the vessels to maximize productivity. A comprehensive study of AI implementation at the Port of Singapore reveals an increase in berth utilization by 15% and a decrease of 20% in yard rehandling operations (Sim et al., 2024). Such efficiencies improve productivity but can also save energy and reduce emissions. An example of a smart green port is the Singapore port, where AGVs and AI technologies are combined in the port facilities. Through such innovations, the port has successfully addressed both operational excellence and climate change impact. Data-driven port management by IoT-enabled AGVs allows AI to analyze port activity in real-time, making every decision that a port takes more informed than the previous one (Knoyskyy et al., 2023). As international trade volumes accelerate, Singapore's experience in deploying AGVs and integrating AI offers timely lessons for ports globally seeking to enhance their competitiveness and find solutions for climate change.

The Port of Los Angeles' Alternative Maritime Power (AMP, also known as cold ironing or shore-to-ship power) program is an exciting leap forward in smart green port tech to reduce the impact of maritime operations on climate change. AMP was introduced in 2004 and quickly revolutionized preventing vessel emissions during port visits. The AMP program has been tremendously successful in reducing emissions of in-port vessels. A 2019 study examining over 16 years of data concluded that the use of shore power at the Port of Los Angeles has reduced air pollution. The use of AC shore power during a 24-hour docking can lead to an emission reduction of about 95% for auxiliary engines of a single container ship, according to the research. This equates to a reduction of 1 ton, 0.5 tons, and 0.03 tons per day in NOx, SOx, and particulate matter for each system-equipped vessel (Arunachalam et al.,2019). Air quality improvements before and after AMP implementation offer comparative evidence of what AMP can achieve. According to a 2015 report, between 2005 and 2014 alone, the use of AMP resulted in reductions of 57%, 90%, and 26% in particulate matter emissions, sulfur oxides, and nitrogen oxides, respectively, from ocean-going vessels at the port (Cannon et al., 2015).

The AMP program is part of a broader smart green port concept that can actively help mitigate the climate change challenge, and the success of the program supports that goal. This greatly reduces greenhouse gas emissions, as this allows vessels to shut down their auxiliary engines and plug into the electrical grid while in a docked position. One recent estimate found the emissions reductions associated with a fully implemented shore power capability system at the Port of Los Angeles could amount to approximately 95,000 metric tons of CO2 equivalent emissions reductions per year. Overall, the AMP scheme serves as a sound lesson to other ports globally on how technology-driven development can be harnessed to reduce the environmental impact of port activity. The program expanded to shore power at all of the port's container terminals and its cruise terminal. As awareness of climate change continues to grow and spill over into both policy and technological innovation in the maritime domain, the AMP program can demonstrate the ability of smart green port partnerships to reach global decarbonization goals with meaningful reductions of emissions and associated equity changes in the impacts of port emissions on vulnerable communities in the port of operation (Setyo et al., 2023). The program's success underscores the potential for similar technologies to be deployed at a larger scale, all of which could play a role in a concerted effort to lessen the climate footprint of waterborne trade (Lee et al., 2022).

Hamburg's smartPORT is among the highest levels of intelligent traffic management systems (ITMS) integration with concerns of sustainability, thereby acting as a guideline for intelligent, green port strategies against climate change in all their ramifications. Advanced data analytics, IoT-enabled infrastructure, and real-time communication networks are used to reduce congestion and resultant emissions while operational efficiency improves in stages. This is in line with the focus of overall digital innovations on environmental stewardship, in accordance with global frameworks on climate mitigation, the Paris Agreement, and the IMO decarbonization goals.

ITMS at the Port utilizes sensor networks and machine-learning algorithms that optimize the flow of trucks, ships, and rail traffic. Using the Truck Parking Guidance System as one example, real-time data from GPS and in-road sensors are streamed to drivers to guide them to open truck parking slots. This reduces waste from idling by about 12% a year (Homayouni et al., 2024). Meanwhile, it introduces congestion-responsive traffic light management within the Port Road Management system, which cuts down average delays in major corridors by 30% and NO_x emissions by 18%. Besides, such systems

http://dx.doi.org/10.21622/MACI.2025.02.1.1162

use predictive analytics, usually foreseeing times of peak demand using historical and real-time data for the pre-deployment of resources in anticipation (Pham, 2023).

Through Hamburg's smartPORT initiative, Hamburg showcases the power of intelligent technologies to not only improve port operations but also how they can lessen the burden of climate change. The port has significantly improved congestion reduction and emissions mitigation through advanced traffic management systems. Intelligent traffic management is part of Hamburg's smart port strategy, which uses real-time data analytics to improve the flow of vehicles within the port area. The system has also led to a 15%-decrease in traffic congestion along with a 12% drop in CO2 emissions from port-related transport activities (between 2020 and 2024). The application of smart technologies in port environmental protection is shown by Hamburg in terms of the development of intelligent port greening applications, which are oriented towards greenhouse gas reduction in the port. It is actually the type of convergence power data that can bring about sustainable port development. Reliance on innovative technology is critical concerning environmental issues that the shipping industry grapples with.

As part of this study about smart green ports and greenhouse gas emissions reduction in ports.

They conducted interviews with the design teams from September to November 2024. We undertook 25 semi-structured interviews with key informants involved in port operations and management. The interviewees included:

- 5 port authorities senior management (15+ years' experience)
- 4 middle-tier port operations managers (8-12 years of experience)
- 3 environmental compliance officers of major ports
- 4 reps from shipping companies that are based in ports
- 4 officials from the Maritime Transport & Logistics Sector
- 3 researchers focused on maritime logistics and sustainability
- 3 reps of local environmental NGOs

Interviews were aimed at collecting perspectives on the current state of smart green port initiatives, obstacles to implementation , and views on climate change mitigation strategies. The main items discussed included:

- Technological implementations (all existing and planned to improve port efficiency and reduce environmental impact).
- Barriers to the adoption of smart green port technologies
- Perceptions of the relationship between port operations and climate Change by Stakeholders.
- Strategies in Current Practice and Potential Future Development for Mitigation of Greenhouse Gas Emissions from Port Operations.
- Policy and regulations in facilitating sustainable operations in ports.
- Potential areas of joint action between ports, government agencies, and local communities to address climate change challenges.

The interviews we conducted allowed us to gain additional qualitative insight that complemented our review of the literature and quantitative breakdown of the situation. Lessons learned from these dialogues have given substance to the challenges and opportunities that ports face to become smarter and sustainable while responding to climate change.

The need for collaboration stakeholders will need to work together to create effective climate action plans that integrate other sustainability goals. This will be done in close engagement with local communities, government, and industry partners to help create well-rounded approaches to sustainability that balance economic drivers and environmental impacts. Green smart ports are a global sectoral response to the problem of climate change. These smart green ports integrate technology and sustainable methods to enhance operational efficiency and contribute to global environmental mitigation initiatives. This commitment to sustainability will be vital moving forward as the maritime industry continues to adapt and plentiful challenges remain as society moves further away from the pandemic. Collaboration towards common sustainability goals will become the pillar of this dynamic industry.

5. DISCUSSION

Smart ports are about embracing smart technologies and sustainable practices in the way ports operate and represent a bigger trend toward an overall paradigm shift in the way that the maritime industry is addressing challenges related to climate change. It is noteworthy that these findings from this specific study are of sufficient consistency and importance that they merit providing additional explanation and context. First, according to some publications, the use of artificial intelligence (AI) and the Internet of Things (IoT) technology systems as part of smart green ports has demonstrated substantial gains related to operational and environmental performances. For instance, the Port of Rotterdam has deployed a complete sensor network and digital twin concept that has provided the waiting time for vessels a 20% reduction and thus lower CO2 emissions. This echoes the findings of additional studies highlighting the innovative prospect of digitalizing technology to optimize port management and reduce Greenhouse emissions (Su et al., 2024b).

However, transitioning to renewable energy in port operations becomes crucial to fighting the climatic consequences. By reducing docked vessel emissions by 95%, for example, the Port of Los Angeles is due to its Alternative Maritime Power (AMP) program (Ahmed et al., 2024). The steep decrease underscores how shore-to-ship power systems can address air-quality issues in port cities, a conclusion that bolsters broader research on the environmental dividends of bringing electricity into maritime activities (Wang et al., 2024). Furthermore, the findings uncover a nascent trend of systemic sustainability integration in port operations. Green infrastructure demonstrates how clean technology can not only help solve congestion problems through smart traffic management, as in the Port of Hamburg, but also reduce emissions (Ogbu et al., 2023).

This holistic approach to sustainability complements recent literature that stresses the importance of integrated processes in ports' adaptation to climate change (Izaguirre et al., 2021). These initiatives have positive social and environmental impacts, and their success often depends on engagement with stakeholders and the broader community, the study shows. Such an important finding is in line with another one regarding the key role of collaborative governance in fostering resilience to climate change in port areas (Ihara et al., 2020). The study presents empirical evidence from the case studies analyzed here in support of the theoretical frameworks described in earlier literature on the socio-economic dimensions of sustainable port development.

Nevertheless, the results also confirm major barriers to smart green port technology deployment, especially in developing parts of the world. Financial limitations and technical barriers are the main hindering factors; similar findings were obtained from other studies on adaptation to climate change within ports of developing countries. This highlights the requirement to develop financing mechanisms as well as capacity building to address such gaps between the ports of developed and developing nations on climate change preparedness. Comparing these findings with the extensive literature on climate change mitigation in the maritime sector shows that smart green ports pioneer novel solutions. The combination of innovative technology and increased sustainability in the port environment provides a model for other sectors confronted with the challenge of balancing operational optimization and environmental sustainability (Barona et al., 2023).

In recent years, the discussion of smart green ports has gained greater traction with the maritime industry battling two challenges: enhancing operational efficiency while balancing environmental sustainability. This trend is driven by the urgent necessity to address climate change and optimize the productivity of port operations. The smart green ports are characterized by the application of cutting-edge technologies and sustainable practices working together to foster a more resilient and efficient marine environment (Bougioukou, 2023).

http://dx.doi.org/10.21622/MACI.2025.02.1.1162

This transformation is fundamentally powered by cutting-edge technologies, such as the Internet of Things, artificial intelligence, and geospatial technologies. These developments enable ports to monitor and manage operations in real time, resulting in better decision-making. Tracking vessel movements and cargo logistics through IoT devices also helps for better berth allocation, leading to reduced ship waiting times, etc. Moreover, those capabilities are augmented by artificial intelligence by providing predictive analytics and utilization rate prediction for congestion detection, which optimizes operations that increase productivity (Saraswati & Wirawan, 2024). The smart green port also requires a concrete use of renewables. These days, many ports are considering ways to minimize their carbon footprint through the use of ocean, wind, and solar energies. This would not only decrease dependence on fossil fuels but also fulfill international objectives on sustainability. The Port of Rotterdam is a very good example of impactful renewable energy projects that significantly decrease GHG emissions (Notteboom et al., 2020).

Another important factor in this sense is sustainable infrastructural development. Indeed, contemporary port facilities make use of eco-friendly materials and are fitted with energy-efficient systems that minimize environmental impacts, ensure the ports function operationally and are supportive of longevity and sustainability. For example, the inclusion of green roofs and state-of-the-art waste management systems adds to the ecological footprint of port facilities in a functioning manner (Sadiq et al., 2021). Productivity in smart green ports is normally evaluated by the number of containers they can handle, expressed in Twenty-foot Equivalent Units. Generally speaking, smart green ports tend to be more productive due to better use of resources and automation of processes. With automated cargo handling systems, it is possible to speed up the loading and unloading operations, which significantly reduces vessel turnaround times (Ibrahim et al., 2024). There is a considerable ambition on climate change mitigation strategies in most of the ports. On the other hand, initiatives aimed at improving air quality in cities such as the Port of Los Angeles are committed to reducing its emissions by 30% by 2025. Another trend, this one with a climate-resilient bent, is gaining momentum as ports plan and prepare for the potential impacts of climate-driven events such as rising sea levels or extreme weather. Proactive measures aimed at improving resilience are underway, including investment in infrastructure improvements like flood defenses and sustainable drainage systems (León-Mateos et al., 2021).

Effective stakeholder engagement is key to ensuring the better alignment of climate action plans with broader sustainability objectives. It could involve local communities, government agencies, and industry partnerships in a holistic view of sustainability that focuses on economic viability and environmental stewardship (Bulmer & Yáñez-Araque, 2023).

The mind map below visually illustrates the diverse interconnected elements of smart green ports as a sustainable solution in view of climate change for the maritime industry.

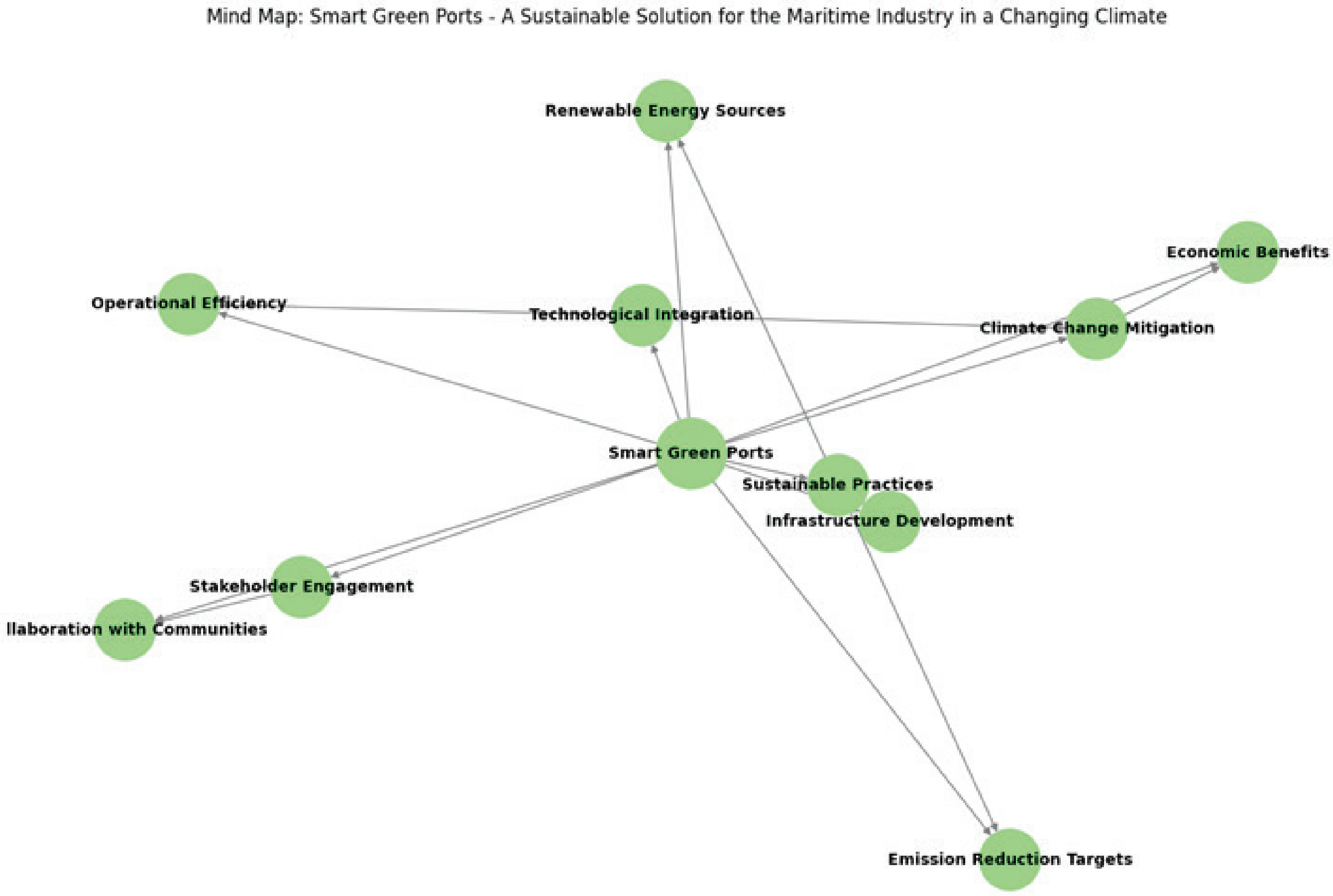

Figure 1. the interconnected components of smart green ports as a sustainable solution for the maritime industry in the context of climate change

Smart green ports have emerged and reinforced a paradigm shift within the maritime sector to balance efficient and competitive operations with environmental sustainability due to a quickening pace of climate change. In this study, we explore the underlying intertwined processes and the synergies this compound approach makes possible, ultimately contributing to a more sustainable future for international trade. At its core, sustainable practices focus not only on what the companies they promote are using in terms of renewable energy and waste minimization but also on overall sustainable practices. The smart green port concept is aspirational in having not only the minimum ecological footprint for port operations but also mandatory compliance with international environmental regulations that will evolve as the world moves forward. Approaches that go hand in hand with eco-construction and energy by design facilitate the realization of a sustainable infrastructure to ensure a low-impact and environmentally commendable development.

The use of technology is a key factor in upgrading traditional ports to smart green hubs. Utilizing IoT devices, AI, and real-time data analytics improves operation effectiveness by streamlining cargo handling, minimizing vessel turnaround periods, and better timing resources. The integration of different data sources offers more than efficiency improvements; it facilitates predictive analytics that can anticipate and respond to hidden environmental consequences, which is in line with larger climate change offsetting and mitigation goals. The switch to green energy, like wind and solar power, is another important component. As this transition takes place, reliance on fossil fuels is cut massively, which in turn leads to lower GHG emissions, aiding sustainable development and climate change mitigation efforts on the ground. By establishing concrete emission reduction targets, it becomes easier to set measurable benchmarks for assessing progress in the future. These targets provoke accountability and provide a basis for assessing the impact of different sustainability efforts.

http://dx.doi.org/10.21622/MACI.2025.02.1.1162

Efforts to mitigate climate change are not limited to reducing emissions but may also include proactive strategies like flood defenses and climate-resilient infrastructure. These kinds of investments mitigate the impacts of climate change on port operations, from sea level rise to extreme weather events. In fact, these sustainable practices can not only positively impact the environment but also contribute to creating a highly profitable business by bringing in sustainability-oriented stakeholders. What promotes this is a symbiosis between environmental awareness and economic competitiveness. The other component is stakeholder engagement, which mobilizes collective action toward common sustainability objectives. Working together with local communities, governments, and industry players enables partnerships that balance operational goals with local environmental challenges and international climate obligations. This collective approach makes sustainability initiatives more effective and sustainable over time.

There are far-reaching economic benefits of intelligent green ports. Some of the primary expected results include improved operational efficiency resulting from energy savings, the establishment of a more sustainable brand identity that enhances marketability, and improved competitiveness in global trade networks. Thus, better marginal costs create a virtuous cycle, providing the incentive to reinvest income into more and better green technology and hastening the shift to a low/zero carbon maritime sector. But smart green ports embody a complete paradigm for modern port operations that reflects both environmental and economic imperatives. The intricacies of the interrelation between sustainable practices and the development of infrastructure, technology integration, renewable energy sources, mitigation of climate change, stakeholder engagement, and economic benefits have been traversed in this paper. Sustainable ports act as a significant step towards solving climate change issues through the adoption of smart technologies and eco-friendly solutions.

6. RESULTS

The results of this analysis highlight that smart green ports have very high potential with respect to addressing environmental challenges coupled with enhanced operational efficiency in the maritime sector. Integration of advanced technologies such as artificial intelligence (AI), Internet of Things (IoT), and smart geographic information systems (GIS) has become a modern transformative approach that can help optimize port operations while reducing greenhouse gas emissions. Some key observations being made in this regard include the remarkable productivity improvements seen in ports undertaking smart technologies. For example, through automated systems, real-time data analytics has helped to conduct cargo handling with speed and logistical management. Indeed, the case studies in the report, such as that on the Port of Rotterdam and Maersk Line, indicated that AI-driven solutions may achieve up to remarkable fuel efficiency with substantial reductions in emissions. These developments add to environmental sustainability, apart from improving the economic viability of port operations. Moreover, research shows that there is a clear relationship between technology adoption and environmental impact. In general, the higher the smart technology integration in ports, the higher the reduction in emissions achieved. On the other hand, those with lower technology uptake can realize significant marginal gains from implementing smart speed management systems for vessels. This inverse relationship underlines the importance of investment in technological advancement to drive productivity and sustainability.

The findings also point to the need for coordination between stakeholders, such as port authorities, shipping companies, and local communities. It further requires coordinated strategies within overall broader sustainability goals for effective climate action plans. The involvement of multiple stakeholders ensures a holistic approach to solving the issue of climate change and, at the same time, maintaining economic resilience in the shipping industry. Evidence shows that smart green ports do indeed address the issues of climate change while permitting efficient operations on the one hand. As a result, innovative technologies and the cooperation of stakeholders might offer ways in which large, far-reaching sustainability programs throughout the world could keep the environmental footprint to a minimum. Only with further development and integration of smart solutions in the future will challenges within the maritime industry be overcome successfully and lead to a more sustainable and efficient industry.

7. RECOMMENDATIONS

Several recommendations to further enhance the effectiveness of smart green ports and their contribution towards sustainability can be formed based on current research and best practices. The key to this is for all port authorities to pursue a holistic approach to energy management, embracing renewable energy sources. That includes investment in solar, wind, and other renewable energy technologies that will contribute to minimizing the consumption of fossil fuels. Partnerships between port authorities and energy providers may be one way in which appropriate infrastructure can be developed, enabling the take-up of renewable energy and making substantial cuts in GHG emissions. The second is the development of technologies that help the port industry achieve more with minimal wastage of resources in its operations. This, if incorporated, allows for improved real-time monitoring and data analysis because of IoT devices and AI use.

It can use predictive analytics to anticipate congestion in the ports and stress-less management of such bottlenecks from cargo handling and clearance systems for efficiency. This involves collaborating with local communities, government agencies, shipping companies, and environmental groups. Collaboration in this way allows these groups to share knowledge and develop best practices that work to balance environmental goals with economic viability. It is very important to set clearly defined GHG emission reduction commitments in line with international climate change agreements. These goals should be ambitious but realistically accessible, showing our commitment to sustainability and providing a measurable framework for advancement. Within the framework of regular assessments, emissions and operational practices will be evaluated, and better performance will be achieved thanks to increased accountability. Additionally, building up hierarchies for training and capacity for port personnel are key investments, enabling these personnel to be prepared for the new operating environment being created.

Training professionals with the skills to handle more complex technology and to adopt more sustainable practices will greatly increase operational efficiency. Implementing regular employee development programs encourages innovation and adaptability across port operations. Further, it is important that ports are involved in research efforts to develop new technologies as well as new approaches to create new ways to promote sustainability. Academia and industrial experts should work together on innovative solutions to the bespoke challenges of each port. Pilot projects will then be rolled out to experiment with these new methods before scaling up. In the end, the adoption of these recommendations can make this port smart and green , be an emblem of sustainability in daily operations, and, at the same time, increase productivity. The use of renewables, new technologies, stakeholder involvement, emission reduction targets, workforce training, and R&D will meaningfully aid the goals of a smart green port in combatting climate change.

The proposed integrated structure for smart green ports represents a significant shift to address the multifaceted challenges posed by sustainability in the maritime industry and mitigation of climate change. Using this theoretical way of interweaving economic technology and human behavior and achieving sustainability through stakeholder engagement, a model for port operations illustrating the path toward environmental stewardship is developed. The framework understands that the effectiveness and success of a technological solution can be used through a proper working relationship with all stakeholders. This emphasizes the co-dependent relationship between operational efficiency and environmental responsibility, stating that these are not mutually exclusive goals but rather mutually reinforcing factors. The proposed framework would enable and enhance port details functions and services available in the port by using the latest technologies in the developed IoT, AI, and big data, as well as tracking and monitoring of the maritime environmental impact and mitigation of potential risks. These technologies provide real-time information on emissions, energy consumption, and other important environmental parameters, enabling port authorities to make informed decisions and implement targeted sustainability programs.

Even more importantly, this construct allows for input from the community and stakeholders. It understands that local needs are different, so sustainability needs to be implemented locally and appropriately for the community. Digital platforms

http://dx.doi.org/10.21622/MACI.2025.02.1.1162

can enable this engagement, serving as conduits for up-to-the-minute environmental data to the general public as well as collecting stakeholder feedback. The framework also embeds climate resilience as a core component, as climate change impacts pose greater risks to port infrastructure and operations. It recommends the deployment of advanced sensor networks and the use of AI-powered predictive analytics to help ports plan for the climate-based threats to come, like rising sea levels. This port-level approach ties into the broader idea of climate change and can allow ports to develop a road map toward the climate crisis.

This comprehensive framework for smart green ports is built on the following key elements:

- Implement an overall energy plan focused on renewable energy integration. Advancing solar, wind, and other renewable energy sources to reduce dependence on fossil fuels
- Collaborate with energy providers to put in place the required infrastructure to enable renewable energy adoption.
- Focus on using new technologies to increase efficiency.
- Implementing IoT (Internet of Things) devices and using artificial intelligence for better real-time monitoring and data analytics.
- Apply predictive analytics to both forecast congestion and improve cargo handling processes.
- Build partnerships among multiple stakeholder groups to create sustainability programs.
- Get buy-in from local communities, government agencies, shipping companies, and environmental organizations to transfer knowledge and start developing best practices that align environmental goals with economic viability.
- Emission reduction targets must be set in line with international climate agreements.
- Train your port staff and build their capacity by providing staff with skills to use advanced technologies and sustainable practices.
- Getting involved in research projects investigating new technologies and methods for sustainability.
- Partner with academic institutions and industry experts to create innovative processes and solutions for port challenges
- Hold pilot projects to test out new methods before scaling up.

These recommendations allow ports to become more intelligent green bodies focused on sustainability and operational efficiency.

When it comes to smart green ports (SGPs) and climate change mitigation, different communities and stakeholders play a role in port sustainability initiatives, making it important to clarify who these communities and stakeholders are. This distinction becomes important in the context of discussions about community engagement and participatory approaches in smart green port development. The industry, which includes shipping companies, ship owners, port operators, and other market stakeholders, often prioritizes operational efficiency vs cost along with compliance with global regulations (Durlik et al., 2024b). Their favorite smart green port initiatives are usually related to digitalization programs that support logistics efficiency, fuel saving, and better port operation overall (Imafidon et al., 2024). A case in point is the deployment of automated guided vehicles (AGVs) and Artificial Intelligence to assist in berth planning at the Port of Singapore, for example, which have displayed substantial gains in operational efficiency benefiting this community (Carvalho et al., 2016). By contrast, the citizen community, consisting of residents in close proximity to ports, has different priorities framed in terms of environmental quality, public health, and local economic opportunities (Buticchi et al., 2022).

The community is particularly concerned about air and noise pollution, traffic congestion, and the impact of port developments on their overall quality of life. The citizen community, in particular, is concerned with smart green port initiatives addressing its needs (e.g., shore-to-ship power systems to alleviate the emission of idling vessels (Wang et al., 2024). Though these communities have their own interests, there are also areas of overlap that need to be recognized, especially regarding environmental sustainability and climate change adaptation. This reduces greenhouse gas emissions and leads to cleaner air and increased community resilience to climate risks (Lechtenböhmer et al., 2018). An alignment of smart port and smart city initiatives will ensure that smart green port initiatives will address the needs and requirements of the port as well as the city, respectively. This is possible by means of participatory stakeholder involvement processes with representatives from the maritime sector, local communities, environmental organizations, and government (Bazaras et al., 2017). Collectively, these represent more holistic and broadly acceptable sustainability initiatives that can address climate change while acknowledging the myriad interests that potentially affect all stakeholders.

8. FUTURE RESEARCH DIRECTIONS

This analysis should, therefore, inform future studies on the topics of smart green ports and climate change mitigation, enhancing infrastructure, and society-based actions for better overall sustainability perspectives. There are multiple areas that require further exploration:

- Longitudinal studies on the long-term effects of smart green port technologies on local ecosystems and communities. These studies should seek to address how new port practices will impact environmental quality, economic development prosperity, and social well-being in the long run. Such research could contribute to understanding the social sustainability and resilience of smart green projects in response to changing climate threats.

- Research and comparative analyses of diverse models of community engagement across multiple geographic and cultural contexts. As the smart green port phenomenon spreads, so does the need to explore the different manners and reasons why societies engage in sustainability efforts. Such research may allow us to find out what best practices are specific and how far they can be adapted to work in different port environments (Us et al., 2022).

- Analysis of pioneering participatory action research techniques to engage local stakeholders in the co-design and co-implementation of smart green port activities. If community members could become stewards of local environmental projects like trees, parks, greenways, urban flooding, etc, this could ensure community ownership of the projects, as well as provide good data on what kinds of engagement work best in their area (Ogut et al., 2024).

- Integrating Smart Green Port Technologies with Indigenous Knowledge Systems in maritime regions This research could lead to discovering unique strategies for sustainable port management by combining new technologies with old-world wisdom (P et al., 2024).

- Among them is the development and validation of socially comprehensive metrics for measuring social capital and community resilience in the context of smart green port initiatives. These tools could help assess how effective different approaches to engaging people have been and the role they play in how communities adapt to climate change (Basile, 2021).

- This way provides the opportunity for a new wave of technology-enabled citizen science programs in the environmental monitoring and management of the island's smart green port. Research may look at how grassroots data collection and analysis efforts by the community can support and play a role in advancing port sustainability (Rasowo et al., 2024).

- Study of the role of education on the involvement of long period of community attachment to smart green ports. May Thus, research the acceptability of inter-generational education programs that connect port sustainability initiatives with local schools and community centers (Unegbu et al., 2024).

- Study of necessary and effective conflict resolution mechanisms between local communities and port authorities in deploying smart green technologies. This work is critical for mediating conflicting interests and establishing trust in controversial contexts (Balbaa et al., 2019).

http://dx.doi.org/10.21622/MACI.2025.02.1.1162

Such selected research areas would greatly enhance our understanding of the capability of smart green ports to achieve the goals of mitigating climate change and providing the feasibility of community engagement and sustainable development in the maritime context.

REFERENCES:

01. Ahmad, D. S. N. A., Fazleen Abdul Fatah, Abdul Rahman Saili, Jamayah Saili, Nur Masriyah Hamzah, Rumaizah Che Md Nor, & Zubaidah Omar. (2024). Exploration of the Challenges in Adopting Smart Farming Among Smallholder Farmers: A Qualitative Study. *Journal of Advanced Research in Applied Sciences and Engineering Technology*, *45*(1), 17–27. https://doi.org/10.37934/araset.45.1.1727

02. Ahmed, H. A., Mandour, M. A., & Helal, D. M. (2024). An Analytical Study of Urban Tissue Design Strategies for Climate Change Mitigation and Adaptation. *Engineering Research Journal*, *183*(3), 252–265. https://doi.org/10.21608/erj.2024.299809.1061

03. Alamoush, A. S., Ölçer, A. I., & Ballini, F. (2022). Port greenhouse gas emission reduction: Port and public authorities' implementation schemes. *Research in Transportation Business & Management*, *43*, 100708. https://doi.org/10.1016/j.rtbm.2021.100708

04. Alzate, P., Isaza, G. A., Toro, E. M., Jaramillo-Garzón, J. A., Hernandez, S., Jurado, I., & Hernandez, D. (2024). Operational efficiency and sustainability in smart ports: a comprehensive review. *Marine Systems & Ocean Technology*, *19*(1–2), 120–131. https://doi.org/10.1007/s40868-024-00142-z

05. Arunachalam, S., Naess, B., Seppanen, C., Valencia, A., Brandmeyer, J. E., Venkatram, A., Weil, J., Isakov, V., & Barzyk, T. (2019). A new bottom-up emissions estimation approach for aircraft sources in support of air quality modelling for community-scale assessments around airports. *International Journal of Environment and Pollution*, *65*(1/2/3), 43. https://doi.org/10.1504/IJEP.2019.101832

06. Ayesu, E. K. (2023). Does shipping cause environmental emissions? Evidence from African countries. *Transportation Research Interdisciplinary Perspectives*, *21*, 100873. https://doi.org/10.1016/j.trip.2023.100873

07. Balbaa, A., Swief, R. A., & El-Amary, N. H. (2019). Smart Integration Based on Hybrid Particle Swarm Optimization Technique for Carbon Dioxide Emission Reduction in Eco-Ports. *Sustainability*, *11*(8), 2218. https://doi.org/10.3390/su11082218

08. Barona, J., Ballini, F., & Canepa, M. (2023). Circular developments of maritime industrial ports in Europe: a semi-systematic review of the current situation. *Journal of Shipping and Trade*, *8*(1), 25. https://doi.org/10.1186/s41072-023-00153-w

09. Basile, V. S. (2021). *THE TRIPLE LAYERED BUSINESS MODEL CANVAS IN SMART AGRICULTURE: THE CASE OF EVJA STARTUP*. *2*, 79–113. https://doi.org/10.14596/pisb.2844

10. Basulo-Ribeiro, J., Pimentel, C., & Teixeira, L. (2024). Digital Transformation in Maritime Ports: Defining Smart Gates through Process Improvement in a Portuguese Container Terminal. *Future Internet*, *16*(10), 350. https://doi.org/10.3390/fi16100350

11. Bazaras, D., Palšaitis, R., Petraška, A., & Zvaigzne, A. (2017). Criteria System of Emergency Situations Risks Assessment in the Baltic Sea Ports. *Transport and Telecommunication Journal*, *18*(4), 275–281. https://doi.org/10.1515/ttj-2017-0024

12. Bougioukou, E. (2023a). Investigating the role of technological advancements in port operations and the development of smart, green and sustainable ports. *TAPPI Journal*, *22*(5).

13. Bougioukou, E. (2023b). Investigating the role of technological advancements in port operations and the development of smart, green and sustainable ports. *TAPPI Journal*, *22*(5).

14. Bulmer, E., & Yáñez-Araque, B. (2023). Tackling Climate Change through Multi-Stakeholder Partnerships: Promoting SDG 17 to Combat Climate Change. *Energies*, *16*(9), 3777. https://doi.org/10.3390/en16093777

15. Buticchi, G., Carne, G. de, Pereira, T. A., Wang, K., Gao, X., Yang, J., Ko, Y., Zou, Z., & Liserre, M. (2022). *A Multi-port Smart Transformer for Green Airport Electrification*. https://api.semanticscholar.org/CorpusID:252998954

16. Cannon, C., Gao, Y., & Wunder, L. (2015). *Port of Los Angeles—Shanghai Municipal Transportation Commission EcoPartnership on shore power*. https://api.semanticscholar.org/CorpusID:106844697

17. Carvalho, L. M., Teixeira, J., & Matos, M. (2016). Modeling wind power uncertainty in the long-term operational reserve adequacy assessment: A comparative analysis between the Naïve and the ARIMA forecasting models. *2016 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*, 1–6. https://doi.org/10.1109/PMAPS.2016.7764083

18. Cavalli, L., Lizzi, G., Guerrieri, L., Querci, A., De Bari, F., Barbieri, G., Ferrini, S., Di Meglio, R., Cardone, R., Tardo, A., Pagano, P., Tesei, A., & Lattuca, D. (2021). Addressing Efficiency and Sustainability in the Port of the Future with 5G: The Experience of the Livorno Port. A Methodological Insight to Measure Innovation Technologies' Benefits on Port Operations. *Sustainability*, *13*(21), 12146. https://doi.org/10.3390/su132112146

19. Chien, F., Ngo, Q.-T., Hsu, C.-C., Chau, K. Y., & Iram, R. (2021). Assessing the mechanism of barriers towards green finance and public spending in small and medium enterprises from developed countries. *Environmental Science and Pollution Research*, *28*(43), 60495–60510. https://doi.org/10.1007/s11356-021-14907-1

20. Clemente, D., Cabral, T., Rosa-Santos, P., & Taveira-Pinto, F. (2023). Blue Seaports: The Smart, Sustainable and Electrified Ports of the Future. *Smart Cities*, *6*(3), 1560–1588. https://doi.org/10.3390/smartcities6030074

21. D'Amico, G., Szopik-Depczyńska, K., Dembińska, I., & Ioppolo, G. (2021). Smart and sustainable logistics of Port cities: A framework for comprehending enabling factors, domains and goals. *Sustainable Cities and Society*, *69*, 102801. https://doi.org/10.1016/j.scs.2021.102801

22. Densberger, N. L., & Bachkar, K. (2022). Towards accelerating the adoption of zero emissions cargo handling technologies in California ports: Lessons learned from the case of the Ports of Los Angeles and Long Beach. *Journal of Cleaner Production*, *347*, 131255. https://doi.org/10.1016/j.jclepro.2022.131255

23. Dev, D. S., & Manalo, J. A. (2023). Gender and adaptive capacity in climate change scholarship of developing countries: a systematic review of literature. *Climate and Development*, *15*(10), 829–840. https://doi.org/10.1080/17565529.2023.2166781

24. Dinh, G. H., Pham, H. T., Nguyen, L. C., Dang, H. Q., & Pham, N. D. K. (2024). Leveraging Artificial Intelligence to Enhance Port Operation Efficiency. *Polish Maritime Research*, *31*(2), 140–155. https://doi.org/10.2478/pomr-2024-0030

25. dos Reis, M. T. L. G. V., Poseiro, P. G. G., Fortes, C. J. E. M., Conde, J. M. P., Didier, E. L., Sabino, A. M. G., & Grueau, M. A. S. R. (2014). *Risk Management in Maritime Structures* (pp. 1179–1190). https://doi.org/10.1007/978-3-642-55122-2_102

26. Durlik, I., Miller, T., Kostecka, E., Łobodzińska, A., & Kostecki, T. (2024a). Harnessing AI for Sustainable Shipping and Green Ports: Challenges and Opportunities. *Applied Sciences*, *14*(14), 5994. https://doi.org/10.3390/app14145994

27. Durlik, I., Miller, T., Kostecka, E., Łobodzińska, A., & Kostecki, T. (2024b). Harnessing AI for Sustainable Shipping and Green Ports: Challenges and Opportunities. *Applied Sciences*, *14*(14), 5994. https://doi.org/10.3390/app14145994

28. Dzemydienė, D., Burinskienė, A., Čižiūnienė, K., & Miliauskas, A. (2023). Development of E-Service Provision System Architecture Based on IoT and WSNs for Monitoring and Management of Freight Intermodal Transportation. *Sensors*, *23*(5), 2831. https://doi.org/10.3390/s23052831

29. el Makhloufi, A. (2023). *AI Application in Transport and Logistics: Opportunities and Challenges*. CoE City Net Zero, Faculty of Technology, Amsterdam Univeristy of Applied Sciences. https://research.hva.nl/en/publications/ai-application-in-transport-and-logistics-opportunities-and-chall

30. Elmahdi, A., & Jeong, J. (2024). From Debt to Sustainability: Advancing Wastewater Projects in Developing Countries through Innovative Financing Mechanisms—The Role of Debt-for-Climate Swaps. *Climate*, *12*(8), 122. https://doi.org/10.3390/cli12080122

31. ESPO. (2021). European Sea Ports Organisation Environmental Report 2021. *Espo*, *4*(4), 32.

32. Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital Twin: Enabling Technologies, Challenges and Open Research. *IEEE Access*, *8*, 108952–108971. https://doi.org/10.1109/ACCESS.2020.2998358

33. Funda, V., & Francke, E. (2024). Benefits and challenges of AIOPS adoption and usage in HEIs in developing countries. *South African Journal of Higher Education*, *38*(6). https://doi.org/10.20853/38-6-6096

34. Glimfjord, J., & Shariza, K. M. (2024). *A qualitative study on MNCs in the shipping industry, and their adaptation to environmental sustainability* [Master Degree Project].

35. Goniewicz, K., Burkle, F. M., & Khorram-Manesh, A. (2025). Transforming global public health: Climate collaboration, political challenges, and systemic change. *Journal of Infection and Public Health*, *18*(1), 102615. https://doi.org/10.1016/j.jiph.2024.102615

36. Gviliya, N. A., & Kochurova, A. A. (2022). Forming smart port system in logistic infrastructure of Northern Sea Route. *Vestnik of Astrakhan State Technical University. Series: Economics*, *2022*(3), 89–95. https://doi.org/10.24143/2073-5537-2022-3-89-95

37. Homayouni, S. M., Pinho de Sousa, J., & Moreira Marques, C. (2024). Unlocking the potential of digital twins to achieve sustainability in seaports: the state of practice and future outlook. *WMU Journal of Maritime Affairs*. https://doi.org/10.1007/s13437-024-00349-2

38. Housni, F., Boumane, A., Rasmussen, B. D., Britel, M. R., Barnes, P., Abdelfettah, S., Iakhmas, K., & Maurady, A. (2022). Environmental sustainability maturity system: An integrated system scale to assist maritime port managers in addressing environmental sustainability goals. *Environmental Challenges*, *7*, 100481. https://doi.org/10.1016/j.envc.2022.100481

39. Ibrahim, I., Jalil, S. A., & Abdul Rasam, A. R. (2024a). Smart GIS Applications for Enhancing Green Port Practices in Malaysian Seaports: A Proposed Conceptual Framework. *Semarak International Journal of Transportation and Logistics*, *1*(1), 1–12. https://doi.org/10.37934/sijtl.1.1.112

40. Ibrahim, I., Jalil, S. A., & Abdul Rasam, A. R. (2024b). Smart GIS Applications for Enhancing Green Port Practices in Malaysian Seaports: A Proposed Conceptual Framework. *Semarak International Journal of Transportation and Logistics*, *1*(1), 1–12. https://doi.org/10.37934/sijtl.1.1.112

41. Ihara, I., Zhao, R., Pandyaswargo, A. H., & Onoda, H. (2020). Evaluating the Effectiveness of Japan's Climate Change Mitigation and Clean Technology Development Policies. *Indonesian Journal of Computing, Engineering and Design (IJoCED)*, *2*(1), 1. https://doi.org/10.35806/ijoced.v2i1.98

42. Imafidon, H., Enwerem, M., & Boye, A. (2024). Adapting Green Building Practices and Smart Technology in Developing Countries. *African Journal of Environmental Sciences and Renewable Energy*, *16*(1), 183–202. https://doi.org/10.62154/ajesre.2024.016.010407

43. İnal, Ö. B. (2024). *An Approach to Green Ports in Terms of Low-Carbon Energy and Sustainability*. *11*(1), 43–49.

44. Issa Zadeh, S. B., Esteban Perez, M. D., López-Gutiérrez, J.-S., & Fernández-Sánchez, G. (2023). Optimizing Smart Energy Infrastructure in Smart Ports: A Systematic Scoping Review of Carbon Footprint Reduction. *Journal of Marine Science and Engineering*, *11*(10), 1921. https://doi.org/10.3390/jmse11101921

45. Issa Zadeh, S. B., López Gutiérrez, J. S., Esteban, M. D., Fernández-Sánchez, G., & Garay-Rondero, C. L. (2023). Scope of the Literature on Efforts to Reduce the Carbon Footprint of Seaports. *Sustainability*, *15*(11), 8558. https://doi.org/10.3390/su15118558

46. Izaguirre, C., Losada, I. J., Camus, P., Vigh, J. L., & Stenek, V. (2021). Climate change risk to global port operations. *Nature Climate Change*, *11*(1), 14–20. https://doi.org/10.1038/s41558-020-00937-z

47. Junaidi, W. (2024). Strategic Use Cases of Digital Transformation Implementation in Cities in Developing Countries. *Business Economic, Communication, and Social Sciences Journal (BECOSS)*, *6*(3), 201–210. https://doi.org/10.21512/becossjournal.v6i3.12084

48. Karagkouni, K., & Boile, M. (2024). Classification of Green Practices Implemented in Ports: The Application of Green Technologies, Tools, and Strategies. *Journal of Marine Science and Engineering*, *12*(4), 571. https://doi.org/10.3390/jmse12040571

49. Katemliadis, I., & Markatos, G. (2021). Stakeholders' involvement in sustainability planning and implementation: the case of Cyprus. *Worldwide Hospitality and Tourism Themes*, *13*(6), 709–718. https://doi.org/10.1108/WHATT-07-2021-0095

50. Kumar, A., Calzavara, M., Velaga, N. R., Choudhary, A., & Shankar, R. (2019). Modelling and analysis of sustainable freight transportation. *International Journal of Production Research*, *57*(19), 6086–6089. https://doi.org/10.1080/00207543.2019.1642689

51. Kurniawan, F., Aziza, M. R., Hasanah, N. A., Junikhah, A., Alam, L. S., Wibawa, A. P., & Hammad, J. (2024). The Innovative Smart Green Campus as Life-Based Learning Characteristics of Future Learning Efforts to Complete the SDG's. *Journal of Lifestyle and SDGs Review*, *5*(2). https://doi.org/10.47172/2965-730X.SDGsReview.v5.n02.pe02908

52. Lechtenböhmer, S., Schostok, D., Kobiela, G., Knoop, K., Pastowski, A., & Heck, S. (2018). *Deep decarbonisation pathways for transport and logistics related to the Port of Rotterdam : PoR transport ; synthesis report*. https://api.semanticscholar.org/CorpusID:169540913

53. Lee, J.-U., Lee, W.-J., Jeong, E.-S., Noh, J.-H., Kim, J.-S., & Lee, J.-W. (2022). Algorithm for Monitoring Emissions Based on Actual Speed of Ships Participating in the Korean Vessel Speed Reduction Program. *Energies*, *15*(24), 9555. https://doi.org/10.3390/en15249555

54. León-Mateos, F., Sartal, A., López-Manuel, L., & Quintás, M. A. (2021). Adapting our sea ports to the challenges of climate change: Development and validation of a Port Resilience Index. *Marine Policy*, *130*, 104573. https://doi.org/10.1016/j.marpol.2021.104573

55. Mahmud, K. K., Chowdhury, M. M. H., & Shaheen, Md. M. A. (2024). Green port management practices for sustainable port operations: a multi method study of Asian ports. *Maritime Policy & Management*, *51*(8), 1902–1937. https://doi.org/10.1080/03088839.2023.2258125

56. Meyer, C., Gerlitz, L., & Prause, G. (2023). Sustainable Electrification and Digitalisation for Greening Small and Medium-Sized Ports along the TEN-T Corridors. *CONECT. International Scientific Conference of Environmental and Climate Technologies*, 47. https://doi.org/10.7250/CONECT.2023.028

57. Min, H. (2022). Developing a smart port architecture and essential elements in the era of Industry 4.0. *Maritime Economics & Logistics*, *24*(2), 189–207. https://doi.org/10.1057/s41278-022-00211-3

58. Notteboom, T., van der Lugt, L., van Saase, N., Sel, S., & Neyens, K. (2020). The Role of Seaports in Green Supply Chain Management: Initiatives, Attitudes, and Perspectives in Rotterdam, Antwerp, North Sea Port, and Zeebrugge. *Sustainability*, *12*(4), 1688. https://doi.org/10.3390/su12041688

59. Ogbu, A. D., Nsisong Louis Eyo-Udo, Mojisola Abimbola Adeyinka, Williams Ozowe, & Augusta Heavens Ikevuje. (2023). A conceptual procurement model for sustainability and climate change mitigation in the oil, gas, and energy sectors. *World Journal of Advanced Research and Reviews*, *20*(3), 1935–1952. https://doi.org/10.30574/wjarr.2023.20.3.2304

60. Ogut, O., Tzortzi, J. N., & Bertolin, C. (2024). Creating a Roadmap to Forecast Future Directions in Vertical Green Structures as a Climate Change Mitigation Strategy: A Critical Review of Technology-Driven Applications. *Sustainability*, *16*(11), 4543. https://doi.org/10.3390/su16114543

61. Oloruntobi, O., Mokhtar, K., Gohari, A., Asif, S., & Chuah, L. F. (2023). Sustainable transition towards greener and cleaner seaborne shipping industry: Challenges and opportunities. *Cleaner Engineering and Technology*, *13*, 100628. https://doi.org/10.1016/j.clet.2023.100628

62. Othman, A., El Gazzar, S., & Knez, M. (2022). Investigating the Influences of Smart Port Practices and Technology Employment on Port Sustainable Performance: The Egypt Case. *Sustainability*, *14*(21), 14014. https://doi.org/10.3390/su142114014

63. P, S., S, P., P, R., Panotra, N., D, T., Upadhyay, L., Meghana, B. S., & Sakhamo, K. (2024). A Critical Review on Fostering Community Involvement in Sustainable Horticulture Initiatives. *Journal of Scientific Research and Reports*, *30*(8), 394–404. https://doi.org/10.9734/jsrr/2024/v30i82262

64. Pham, T. Y. (2023). A smart port development: Systematic literature and bibliometric analysis. *The Asian Journal of Shipping and Logistics*, *39*(3), 57–62. https://doi.org/10.1016/j.ajsl.2023.06.005

65. Philipp, R. (2020). Digital readiness index assessment towards smart port development. *Sustainability Management Forum | NachhaltigkeitsManagementForum*, *28*(1–2), 49–60. https://doi.org/10.1007/s00550-020-00501-5

66. Rasowo, J. O., Nyonje, B., Olendi, R., Orina, P., & Odongo, S. (2024). Towards environmental sustainability: further evidences from decarbonization projects in Kenya's Blue Economy. *Frontiers in Marine Science*, *11*. https://doi.org/10.3389/fmars.2024.1239862

67. Sadiq, M., Ali, S. W., Terriche, Y., Mutarraf, M. U., Hassan, M. A., Hamid, K., Ali, Z., Sze, J. Y., Su, C.-L., & Guerrero, J. M. (2021). Future Greener Seaports: A Review of New Infrastructure, Challenges, and Energy Efficiency Measures. *IEEE Access*, *9*, 75568–75587. https://doi.org/10.1109/ACCESS.2021.3081430

68. Sankla, W., & Muangpan, T. (2022). Smart and Sustainable Port Performance in Thailand: A Conceptual Model. *Journal of Sustainable Development*, *15*(4), 1. https://doi.org/10.5539/jsd.v15n4p1

69. Saraswati, R., & Wirawan, A. (2024a). IoT and the Maritime Frontier: Innovations in Vessel Safety and Tracking. *Asian American Research Letters Journal*, *1*(4).

70. Saraswati, R., & Wirawan, A. (2024b). IoT and the Maritime Frontier: Innovations in Vessel Safety and Tracking. *Asian American Research Letters Journal*, *1*(4).

71. Satta, G., Vitellaro, F., Njikatoufon, A. G., & Risitano, M. (2024). Green strategies in ports: a stakeholder management perspective. *Maritime Economics & Logistics*. https://doi.org/10.1057/s41278-024-00294-0

72. Schneider, C., Lechtenböhmer, S., & Samadi, S. (2020). Risks and opportunities associated with decarbonising Rotterdam's industrial cluster. *Environmental Innovation and Societal Transitions*, *35*, 414–428. https://doi.org/10.1016/j.eist.2019.05.004

73. Setyo, A. A. A., Kurniadi, D., & Hozairi, H. (2023). Bibliometric Analysis of Research Development on Green Port Implementation in 2015-2023. *Dinamika Bahari*, *4*(2), 11–19. https://doi.org/10.46484/db.v4i2.382

74. Sotirov, M. K., Petrova, V. M., & Dimitrov, D. P. (2024). *Theoretical Framework for Future Developments: AI-Based Predictions and Risk Assessment for Coastal Ports in the Bulgarian Sector of the Black Sea*. https://doi.org/10.20944/preprints202407.1541.v1

75. Su, Z., Liu, Y., Gao, Y., Park, K.-S., & Su, M. (2024a). Critical Success Factors for Green Port Transformation Using Digital Technology. *Journal of Marine Science and Engineering*, *12*(12). https://doi.org/10.3390/jmse12122128

76. Su, Z., Liu, Y., Gao, Y., Park, K.-S., & Su, M. (2024b). Critical Success Factors for Green Port Transformation Using Digital Technology. *Journal of Marine Science and Engineering*, *12*(12). https://doi.org/10.3390/jmse12122128

77. Sunghyun, S., Kim, D., Park, K., & Bae, H. (2024). *Artificial Intelligence-based Smart Port Logistics Metaverse for Enhancing Productivity, Environment, and Safety in Port Logistics: A Case Study of Busan Port*.

78. Unegbu, H. C. O., Yawas, D. S., Dan-asabe, B., & Alabi, A. A. (2024). Investigation of Community Engagement in Sustainable Construction Projects: Case Studies from Nigeria. *Journal of Sustainable Construction*, *4*(1), 10–36. https://doi.org/10.26593/josc.v4i1.8109

79. Us, Y., Pimonenko, T., Lyulyov, O., Chen, Y., & Tambovceva, T. (2022). Promoting Green Brand of University in Social Media: Text Mining and Sentiment Analysis. *Virtual Economics*, *5*(1), 24–42. https://doi.org/10.34021/ve.2022.05.01(2)

80. Wang, J., Li, H., Yang, Z., & Ge, Y.-E. (2024). Shore power for reduction of shipping emission in port: A bibliometric analysis. *Transportation Research Part E: Logistics and Transportation Review*, *188*, 103639. https://doi.org/10.1016/j.tre.2024.103639

81. Xiao, G., Wang, Y., Wu, R., Li, J., & Cai, Z. (2024). Sustainable Maritime Transport: A Review of Intelligent Shipping Technology and Green Port Construction Applications. *Journal of Marine Science and Engineering*, *12*(10), 1728. https://doi.org/10.3390/jmse12101728

82. Yu, H., Deng, Y., Zhang, L., Xiao, X., & Tan, C. (2022). Yard Operations and Management in Automated Container Terminals: A Review. *Sustainability*, *14*(6), 3419. https://doi.org/10.3390/su14063419

83. Yu, P., Zhaoyu, W., Yifen, G., Nengling, T., & Jun, W. (2023). Application prospect and key technologies of digital twin technology in the integrated port energy system. *Frontiers in Energy Research*, *10*. https://doi.org/10.3389/fenrg.2022.1044978

84. Zhang, Z., Song, C., Zhang, J., Chen, Z., Liu, M., Aziz, F., Kurniawan, T. A., & Yap, P.-S. (2024). 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*, *912*, 169075. https://doi.org/10.1016/j.scitotenv.2023.169075

85. Zhao, R., Song, Y., Zhao, Z., Fu, Q., & Zhao, R. (2024). Bi-Objective Combinatorial Optimization Model for Emission Reduction Projects at Container Terminals Considering Investment Amount and Reduction Efficiency. *Transportation Research Record: Journal of the Transportation Research Board*. https://doi.org/10.1177/03611981241255364

View publication stats