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MACI JOURNAL OF MULTIDISCIPLINARY ADAPTIVE CLIMATE INSIGHTS

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TABLE OF CONTENTS:

page no.

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

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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 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

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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.

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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 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).

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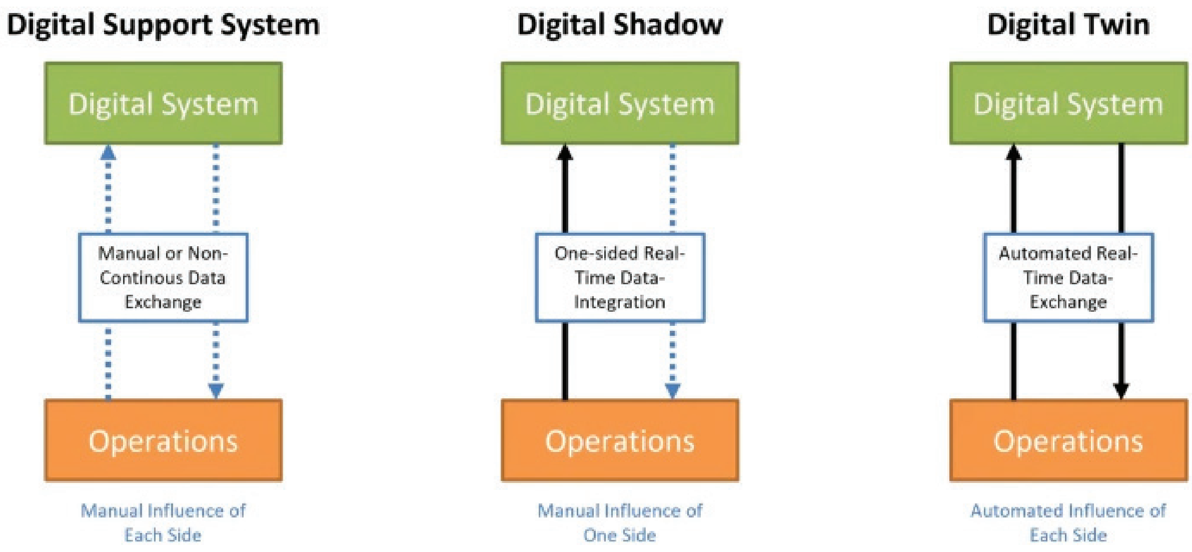

Figure 1. Differentiating the digital twin levels

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 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).

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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.

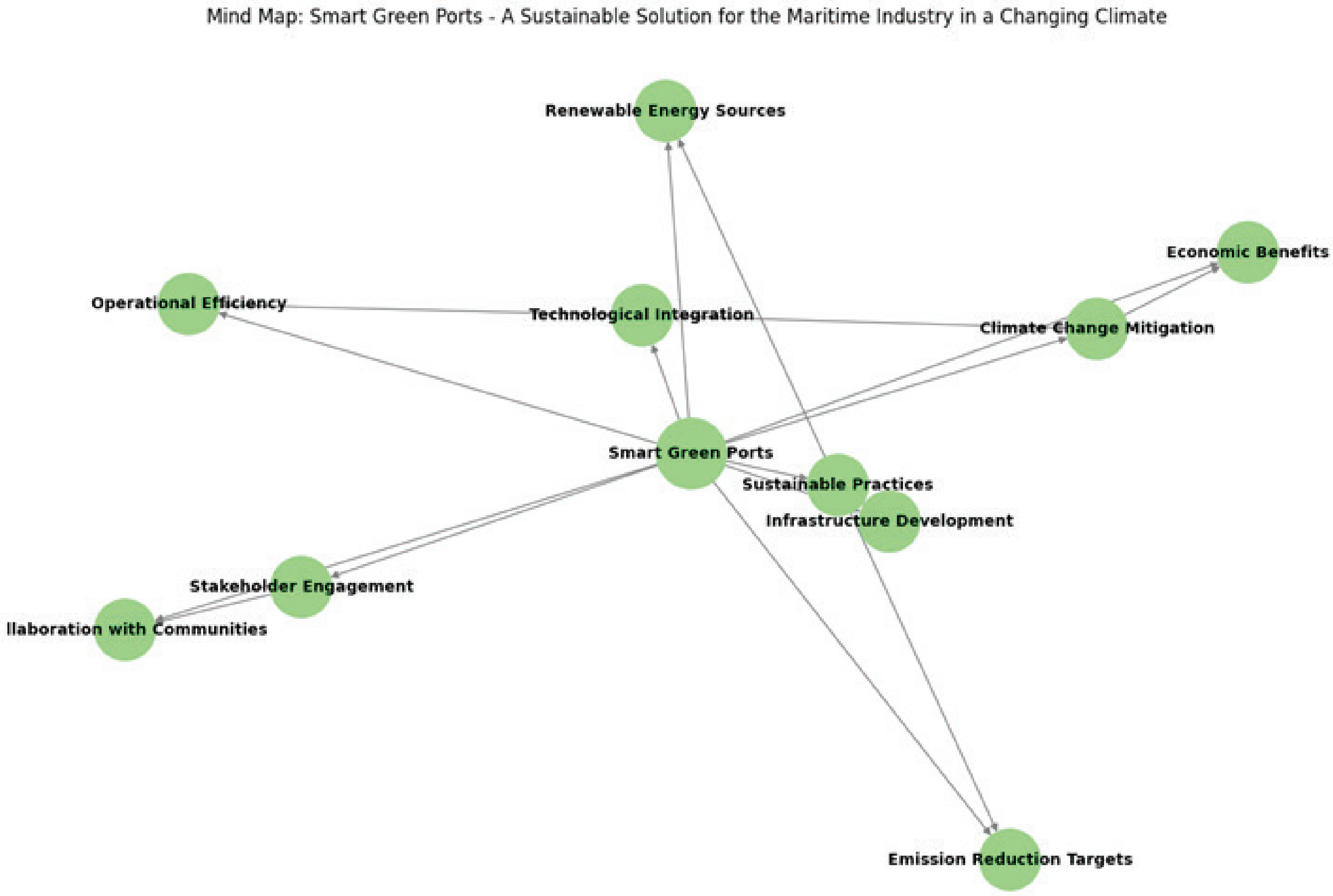

Figure 1. the interconnected components of smart green ports as a sustainable solution for the maritime industry in the context of climate change

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.

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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

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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).

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.

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AN EMPIRICAL ANALYSIS OF NET-ZERO EMISSION TARGETS OF CANADA AND THE EUROPEAN UNION

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ABSTRACT:

The 2015 Paris Agreement stipulates that participating countries should aim to achieve a balance of emissions and sinks of greenhouse gases by 2050. This is an essential pre-condition for a subsequent reduction in atmospheric levels of carbon dioxide. Several countries have formulated and presented their proposed pathways to this condition of net- zero emissions. Employing a methodology based on a revised Kaya Identity and the concept of emission intensity, the paper examines the feasibility of the pathways to net zero published by the Canadian government and the European Commission. By analysing the link between emissions and gross domestic product, it is shown that the path to net- zero emissions proposed by Canada is technically feasible but dependent on the deployment of a suite of negative emission technologies none of which has yet to be demonstrated at scale. In the case of the EU27, it is argued that the proposed pathway to a condition of net-zero emissions in 2050 is not a plausible scenario, and that the emissions of greenhouse gases in mid-century are likely to be more than three times higher than the level projected by the European Commission.

KEY-WORDS: Net zero emissions, Residual emissions, Energy intensity, Negative emission technologies, Kaya Identity, Canada emissions, EU emissions.

1. OBJECTIVES AND MOTIVATION

The objective of the analysis that follows is to present a coherent empirical framework for the analysis of national strategies to reduce emissions of greenhouse gases (GHG) to a point of net-zero emissions (NZE). This condition is defined in Article 4 of the Paris 2015 Agreement and stipulates that countries that are parties to the accord shall take measures to arrive at a NZE condition "in the second half of the century" (UNFCCC, 2016). Many countries, including Canada and the 27-member European Union (EU27), have published plans that purport to show how their GHG emissions will decrease to the NZE condition by 2050.

The net-zero condition assumes that a country's GHG emissions in 2050 will be balanced by measures that absorb an equal quantity of carbon from the atmosphere thus producing the net-zero condition. These measures are generally referred to as 'negative emission technologies' (NETs). They operate as carbon sinks and can be distinguished as either *natural* or *engineered*. Living biomass (primarily trees) is the most effective natural carbon sink, while engineered sinks include bioenergy with carbon capture and storage (BECCS), and direct air capture (DAC). Other less advanced and more conceptual engineered sinks include ocean fertilisation and enhanced weathering.

The net-zero condition therefore consists of a balance between a country's *actual* emissions in 2050 (its *residual* emissions), and the combined absorptive effect of the measures that compensate for those emissions. One of the objectives of the research described here, it to show that residual emissions of a country *cannot* decline to zero. It follows that the condition of net zero emissions *always* involves a point of equilibrium between residual emissions and the absorptive effects of a suite of negative emission technologies—because invariably there is more than one.

Governments that design and implement policies to reduce GHG emissions to the point of net zero are therefore faced with a interesting trade off. Driving down emissions to the lowest possible level is more costly, but these costs will be offset by savings in the deployment of negative emission technologies (either natural or engineered or both). Alternatively, residual emissions may only be reduced to the point where the incremental cost of further reductions is considered to be excessive; the deployment of negative emission technologies would then need to be of greater scale and capacity.

The question of technical feasibility also arises. Serious doubts have been raised about the efficacy of BECCS and Direct Air Capture. The natural sinks are more reliable but are at risk of degradation from wildfires and the destructive infestations of insects. A consideration of the precautionary principle may therefore lead governments to propose that residual emissions should be brought down to an absolute minimum, thus reducing the risk of the net-zero condition being unattainable due to the limited efficacy of the proposed carbon sinks.

This paper seeks to address the issues and answer the questions outlined above, and to examine the pathways to net zero emissions published by the government of Canada and the European Commission. In each case, the emission of greenhouse gases in 2050 is balanced by the deployment of a set of negative emission technologies that are intended to fully offset the residual emissions. The degree to which this objective is likely to be achieved is examined.

The methodology presented below is applicable to all countries that have formulated a pathway to a condition of net-zero emissions by 2050. It outlines an empirical approach that examines the feasibility of a country's proposed program to reduce its emissions of greenhouse gases to a level where they may be realistically balanced by the combined effect of a set of negative emission technologies.

2. INTRODUCTION

The concept of net-zero emissions of greenhouse gases is a foundational element of the 2015 Paris Agreement. In Article 4 it is stipulated that Parties shall aim '*to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of the century…*' (UNFCCC, 2016). But the articulation of this requirement does not indicate if anthropogenic emissions should decline to a particular level, only that they should be balanced; although Article 4 also advises that '*developed country Parties should continue taking the lead by undertaking economy-wide absolute emission reduction targets*' (UNFCCC, 2016).

Several countries have published reports which set out how they envisage reducing their GHG emissions to a condition of net zero by 2050. For example, the EU27 pathway to NZE shows emissions declining from 3740 million tonnes of carbon dioxide equivalent (MtCO2e)[1] in 2015 (Per capita greenhouse gas emissions including land use, 2024a) to residual emissions of about 500 MtCO2e at the point of net zero in 2050 (European Commission, 2024). The pathway published by Canada shows emissions falling from about 700 MtCO2e in 2000 to 165 MtCO2e at the net zero point in 2050 (Canada Energy Regulator, 2023).

Residual emissions must be balanced by negative emission technologies (NETs). In Europe, the principal NET is land use, land use change and forestry (LULUCF), while a sink labelled as 'Industrial removals' (presumably BECCS and direct air capture) makes a small contribution. In Canada, four negative emission technologies are proposed: LULUCF, direct air capture; hydrogen production; and bioenergy with carbon capture and storage (Canada Energy Regulator, 2023).

A country's residual carbon emissions cannot decline to zero. A comprehensive review of over 180 countries over the last 25 years shows that a country's emissions are proportional to its Gross Domestic Product (GDP). The proportionality changes as economies electrifiy and become more energy efficient but it can be shown that the ratio of GHG emissions to a dollar of GDP has a lower bound of approximately 50 gCO2e/$GDP.[2] This limit is confirmed by a consideration of the global carbon cycle. Emissions of carbon from land use change continue even if all economic sectors are 100 per cent electrified and emission-free—which is itself unrealistic in any modern economy.

What this means is that a country that strives to move down a pathway to net zero emissions must necessarily compensate for its residual emissions by deploying one or more negative emission technologies. The question is which?

Four technologies are generally proposed as the means of removing carbon from the atmosphere and thus balancing the residual emissions of a country and achieving the net zero condition: Afforestation and reforestation; land management to increase soil carbon; bioenergy with carbon capture and storage; and direct air capture. Other more imaginative interventions have been proposed, including ocean fertilisation and enhanced weathering. However, ocean fertilisation is judged to have very high levels of uncertainty and ecological risk, while enhanced weathering requires the mining, transport and utilisation of very large quantities of minerals: between 1 and 3 tonnes of rock for every tonne of carbon removed. Moreover, neither technology is judged to be capable of operating at the minimum level of carbon capture and removal required (European Academies Science Advisory Council, 2018).

2.1. Afforestation and Reforestation

The global carbon cycle includes the absorption of carbon dioxide by the world's forests and natural landscapes as trees and other biomass photosynthesize carbohydrates. However, counting on the world's forests, wetlands, mangroves and other biomes to continue to absorb several billion tonnes or more of carbon dioxide from the atmosphere is not without risk. The world's forests continue to be cut down as agriculture encroaches onto forest lands, while wildfires and infestations by insects are increasing in scope and intensity as global temperatures continue to climb. In many places, wetlands and mangroves are also being slowly incapacitated (FAO, 2024). In 2023, wildfires emitted 6.7 billion tonnes of carbon dioxide—more than double EU emissions from the burning of fossil fuels (FAO 2024). Rates of deforestation, although declining, have averaged 4.7 million hectares a year over the last decade (FAO, 2024). This pessimistic analysis does not lead to the conclusion that the land sink is likely to collapse. On the contrary, the European Academies Science Advisory Council concluded that "regarding the role of **afforestation, reforestation and other natural climate solutions**, this remains the least costly and most easily deployable existing CDR (carbon dioxide removal) technology" (emphasis in original) (European Academies Science Advisory Council, 2019).

2.2. Land Management

Industrial agricultural practices are generally detrimental to the quality of the soil: which is why there is so often a heavy reliance on chemical fertilizers. But agriculture can be regenerative and

[1] 'Carbon dioxide equivalent', CO2e, is a way of accounting for the environmental impact of the other greenhouse gases as equivalent units of carbon dioxide

[2] All GDP data in this report are expressed in international dollars at 2021 prices.

sustainable in which case agricultural land will absorb carbon from the atmosphere. In fact, soils hold twice as much carbon as the atmosphere—about 1.7 *trillion* tonnes (Global Carbon Project, 2024).

Soil organic carbon can be increased by growing cover crops; leaving crop residues to decay and decompose naturally; applying manure or compost; using low- or no-till soil preparation; and employing other land management techniques to improve soil quality and structure (European Academies Science Advisory Council, 2018).

This approach is the basis of the '4 per mille' initiative that was started in France following COP21 in 2015. The objective is to increase soil organic carbon by 0.4 per cent a year, an increase which could potentially absorb 2 to 3 billion tonnes of carbon a year (International '4 for 1000' Initiative, Soils for Food Security and Climate, n.d.). Basic principles include no-till agriculture; intercropping; agroforestry; adaptive grazing periods and rotations; land restoration; and improved water and fertilizer management including the use of organic fertilizers and compost (International '4 for 1000' Initiative. Soils for Food Security and Climate, n.d.).

2.3. Bioenergy and Carbon Capture and Storage

Known as BECCS, bioenergy and carbon capture and storage is often the technology that policymakers call into play when their preliminary forecasts of future emissions fail to chart a pathway to a net zero condition by 2050. A BECCS module is plugged into the mathematical model and the required net-zero emission target is rapidly attained. This analytical rescue operation has been increasingly exposed as invalid and unacceptable (European Academies Science Advisory Council, 2022).

First described as a 'backstop' technology by the European Academies Science Advisory Council (EASAC) (European Academies Science Advisory Council, 2018), the Council has become increasing critical of the technology, stating in 2018: "*The role of bioenergy with carbon capture storage (BECCS) remains associated with substantial risks and uncertainties, both over its environmental impact and ability to achieve net removal of CO2 from the atmosphere. The large negative emissions capability given to BECCS in climate scenarios limiting warming to 1.5°C or 2°C is not supported by recent analyses and policy-makers should avoid early decisions favouring a single technology such as BECCS* (European Academies Science Advisory Council, 2019).

A more recent report issued by EASAC in 2022 saw no reason to change its earlier conclusion that "policy should avoid favouring BECCS and proceed first on the cost-effective nature-based solutions", which they footnote as referring to "Reforestation, afforestation, recovery of peatlands, mangroves, etc." The report goes on to state that "lowering the expectation of CDR (carbon dioxide removal) technologies adds even more pressure to accelerate conventional abatement action as rapidly as possible" (European Academies Science Advisory Council, 2019).

2.4. Direct Air Capture

Direct air capture (DAC) involves the absorption of carbon dioxide directly from the air using a chemical absorbent. Since the concentration of CO2 in the air is very low: only about 0.043 per cent, the process requires extensive structures of powerful fans to suck in and expel huge volumes of air. This work requires very large amounts of electricity. The captured carbon dioxide is then compressed and pumped underground into permanent storage: a step that also requires electrical power. We know that the technology works: carbon dioxide can be absorbed from the atmosphere. The question is whether the technology can be deployed at a scale where it consistently captures at least a billion tons of CO2 a year —which is the scale required if DAC is going to be make a serious contribution to reduce atmospheric levels of carbon dioxide.

The electricity required to absorb a tonne of carbon dioxide using either liquid or solid absorbents is estimated to be between 1800 and 2600 kWh/tCO2 respectively (International Energy Agency, 2024). A network of DAC installations capturing and sequestering 1 GtCO2 a year would therefore require 360 – 630 TWh of electricity a year; roughly the output of 140 - 240 small nuclear reactors. The amount of thermal energy is also substantial: 5.3 – 7.2 GJ/tCO2 (International Energy Agency, 2023), which converts to 168 GW of high-temperature heat for DAC systems capturing 1 GtCO2 per year. This is approximately 100 times the power of The Geysers geothermal plant in the USA (Geothermal power, 2025).

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The substantial energy consumption of Direct Air Capture technology is driven by the physical process of trying to absorb carbon dioxide at a concentration of 0.043% from a stream of air at ambient temperatures. The provision of substantial amounts of carbon-free electricity is also costly—an economic burden which direct air capture cannot avoid.

Not mentioned above is the challenge of permanently sequestering the captured carbon dioxide in underground repositories, an essential component of direct air capture, which adds another level of difficulty to the technology.

The uncertainty surrounding the viability of the two main engineered carbon sinks, BECCS and DAC, and the risks associated with a reliance on nature-based approaches based on land use and forestry argues for a policy where the need for negative emission technologies is kept to a minimum. This in turn implies that *residual* emissions should be reduced as much as possible. This conclusion has been reiterated by the EASAC, for example in 2019, when the council stated that mitigation (i.e. actual emission reductions) should be "made the first priority ahead of any reliance on future NETs." (European Academies Science Advisory Council, 2019).

3. METHODOLOGY

Residual emissions cannot be reduced to zero, but they can be reduced to a minimum level which appears to be approximately the same for all countries at the same level of economic development. To examine this hypothesis in more detail it will be necessary to employ a form of the Kaya Identity (Kaya identity, 2015): a mathematical identity which states that emissions of carbon dioxide can be expressed in terms of four factors: population, per capita GDP, energy use per unit of GDP, and CO2 emissions per unit of energy (Bush, M.J., 2024). As an identity, the factors cancel out, but the disaggregation into groups of easily available data has proved extremely useful. In this analysis we use a variation of the identity which disaggregates per capita emissions of greenhouse gases (not just CO2) into four factors which include the generation of electricity as well as total energy consumption. It is written as:

$$\frac{CO2e}{pop} = \frac{CO2e}{elec} x \frac{elec}{E} x \frac{E}{GDP} x \frac{GDP}{pop} \qquad (1)$$

Where:

- CO2e/pop is per capita GHG emissions, tCO2e
- CO2e/elec is *total* emissions of CO2e per unit of electricity generated, tCO2e/GWh
- elec/E is the ratio of electricity generated and total energy consumption, E, (both in GWh)
- E/GDP is the energy intensity of GDP, GWh/$GDP
- GDP/pop is per capita gross domestic product, $GDP

The first three terms on the right-hand side of the modified Kaya identity shown in Equation 1 is called the Emission Intensity (EI) where:

$$EI = \frac{CO2e}{elec} x \frac{elec}{E} x \frac{E}{GDP} \quad \text{tCO2e/\$GDP} \qquad (2)$$

The identity can therefore be reduced to a simple relationship between per capita GHG emissions and per capita GDP.

$$\frac{CO2e}{pop} = EI \; x \frac{GDP}{pop} \quad \text{tCO2e per capita} \qquad (3)$$

A country's emissions can be calculated from its per capita GDP if its emission intensity is known. It follows that policies aimed at reducing emissions should focus either on reducing the EI or per capita GDP or both. Since it is almost axiomatic that a country's per capita GDP should increase over time, GHG emissions can only be reduced if emission intensity is reduced faster than increases in per capita GDP.

3.1. Emission Intensity

The values of the EI for all countries in the OurWorldInData database (Per capita greenhouse gas emissions including land use, 2024b) can be calculated from the tables of GHG emissions per capita and per capita GDP. Across 185 countries, the 2023 values range from a high of 4758 gCO2e/$GDP in the Central African Republic, to a low of 55 gCO2e/$GDP in Switzerland. Twenty-one countries, mainly African and all very low income, have EIs above 1000 gCO2e/$GDP. Low-income countries as a group have an average EI value of 1118 gCO2e/$GDP.

Of particular interest for this study are the countries that have low EI values. Table 1 shows seven countries (out of 185) that had EI values below 100 gCO2e/$GDP in 2023.

Table 1: Low EI countries in 2023

Low EIF country	EI gCO2e/$GDP
Hong Kong	84
Ireland	97
Luxembourg	90
Malta	61
Montenegro	86
Singapore	77
Switzerland	55

Source: Our World in Data database: GDP per capita and Per capita GHG emissions (Per capita greenhouse gas emissions including land use, 2024b)

4. RESULTS AND DISCUSSION

It is instructive to examine how EI values have varied over time in these low emission- intensity countries. Can the EI decline to zero and if so, over what time frame does this transition occur in a best-case scenario? Figure 1 shows the EI values for these seven countries from 2000 to 2023. The five countries grouped in the centre are labelled in declining order.

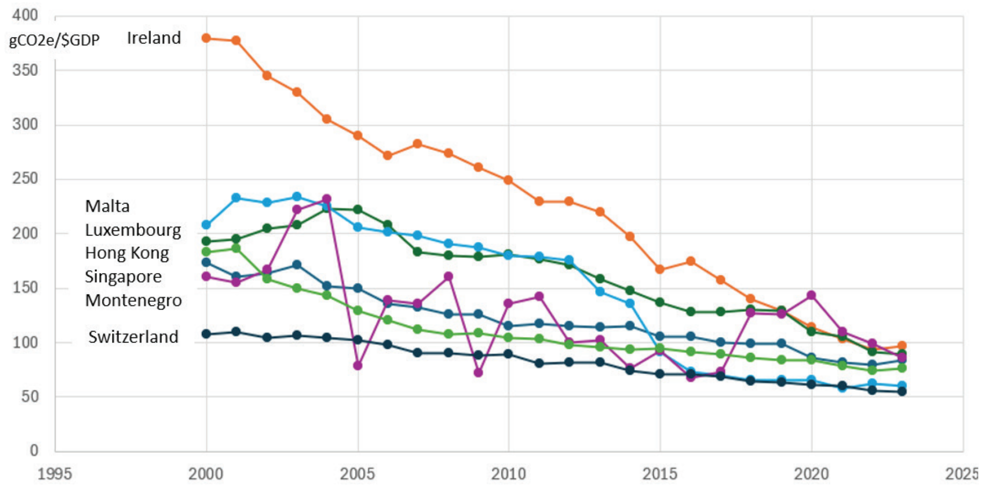

Figure 1. Emission Intensity trends in low EI countries, 2000-2023

Source : Our World in Data (per capita greenhouse gas emissions including land use, 2024c). Emission intensity is calculated from the ratio of per capita GHG to per capita GDP. All GDP values in this paper are expressed in International dollars (USD) at 2021 prices.

Immediately obvious is the indication that in all cases Emission Intensities appear to decline asymptotically to a limiting value of approximately 50 gCO2e/$GDP. This characteristic can be explained by considering the three constituent factors of shown in Equation 2. The first is the ratio of *all* GHG emissions to the amount of electricity generated. GHG emissions can never fall to zero. A country's carbon emissions are driven by the carbon cycle and they are always non-zero. The second factor is the ratio of electricity generation to total energy consumption. As an economy electrifies this element will tend towards unity. The third factor, E/GDP, is the energy intensity of GDP. This can certainly be reduced but once again it cannot fall to zero. Consider a thermodynamic explanation. GDP is a proximate indicator of the work being done by an economy. It takes a huge amount of work and energy to power up and drive forward all the physical, chemical, and mechanical processes of a modern productive economy. The greater the GDP the greater the amount of work and energy required to maintain its operations. The energy intensity of an economy can certainly be reduced: as many countries have demonstrated. But it cannot be brought down to zero—a physical impossibility.

A lower bound on the value of emission intensity has important implications for a country's proposed pathway to a condition of net zero emissions in 2050. The lower bound is not a physically defined constant. The lowest value calculated among a group of 185 countries is 55 gCO2e/$GDP: the value for Switzerland (Table 1). The lower bound could be considered as the edge of a zone of increasing

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improbability. Values below 50gCO2e?$GDP should be viewed with increasing scepticism and their validity strongly questioned.

4.1. Net Zero Emissions

Canada has published its proposed pathway to arrive at the point of net zero emissions by 2050. Figure 2 shows the projected pathway to reduce emissions from about 700 MtCO2e in 2024 to 165 MtCO2e in 2050, at which time a portfolio of negative emission technologies is proposed to offset the residual emissions. These NETs include land use, land use change and forestry; hydrogen production; direct air capture; and bioenergy with carbon capture and storage (BECCS) (Canada Energy Regulator, 2023).

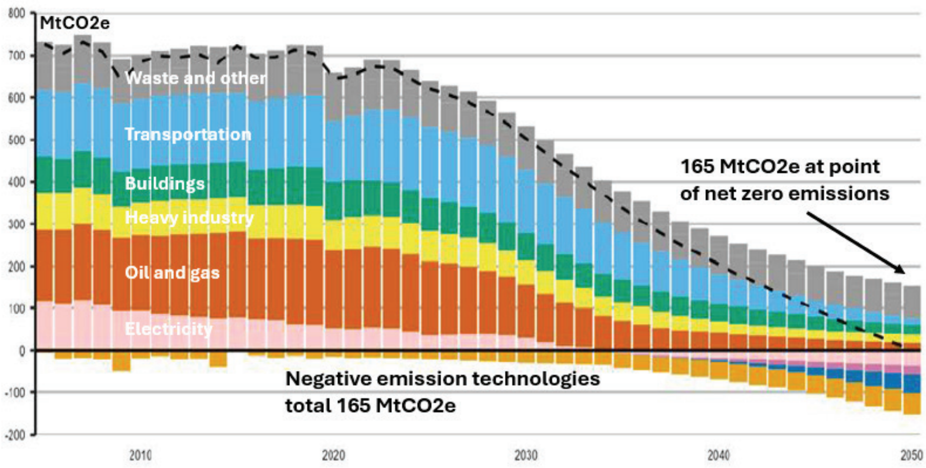

Figure 2. Canada's pathway to net zero emissions in 2050

Source: Canada's Energy Future 2023: Energy supply and demand projections to 2050 (Canada Energy Regulator, 2023). The negative emission technologies (in descending order) are BECCS; hydrogen production; direct air capture; and land use, land use change and forestry. Hydrogen produced from biomass gasification is not a negative technology (U.S. Department of Energy, n.d.).

Is this trajectory feasible? To answer this question we need to estimate Canada's per capita GDP in 2050, which is used to calculate the EI at the point of net zero emissions. Canada's per capita GDP growth rate was 0.7 % per annum (p.a.) from 2000 to 2023 (GDP per capita, 2021). Over the next 25 years, we assume the long-term trend will remain approximately at this level. Projecting forward from 2023 at growth rates between 0.7% and 1.0% p.a. gives per capita GDP in 2050 between $67,500 and $73,150.

The population that year using the M1 scenario (Statistics Canada, 2025) is 49.3737 million so emissions per capita at the net zero point are 165/49.3737 = 3.342 tCO2e. The emission intensity at the NZE point can now be calculated from these data as this value divided by per capita GDP, which gives an EI ranging from 46 to 50 gCO2e/$GDP.

These values are right at the estimated lower bound of emission intensity. Driving down Canada's EI from its present value of over 300 to 46 gCO2e/$GDP in 2050 is challenging but certainly possible (and we note that Ireland has already demonstrated a similar trajectory). We will discuss how this reduction can be achieved; but first we will examine the European plan. Europe's path to net zero emissions by 2050 is shown in Figure 3

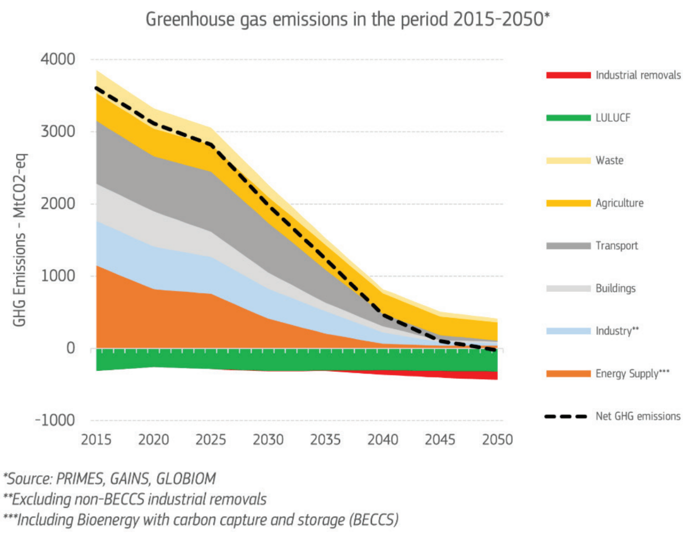

Figure 3. Europe's pathway to net zero in 2050

Source : European Commission. 2040 climate target (European Commission, 2024). https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en

The graph shows that GHG emissions on this pathway decline to approximately 500 MtCO2e in 2050. These emissions are then balanced by an equal amount of negative emission technologies: land use, land use change and forestry (LULUCF); and a technology referred to as 'industrial removals' which we assume to be either BECCS, DAC or both. The EU27 population in 2050 is projected to be 447.9 million (Eurostat, 2023), which gives per capita emissions in 2050 as 500/447.9 = 1.12 tCO2e. This is implausible. It is a value lower than the carbon footprint of the middle 40 percent demographic cohort in sub-Saharan Africa (Chancel L., Bothe P., Voituriez T., 2023).

EU27 per capita GDP in 2050 can be estimated as being in the range of $75,000-$85,000 which gives EI values of 13 – 15 gCO2e/$GDP. These figures are impossibly low and point to the troubling conclusion that the EU27 proposed pathway to achieving net zero emissions by 2050 is unrealistic: the EU is unlikely to be able to reduce its GHG emissions to 500 MtCO2e per annum by 2050. A more credible figure based on per capita GDP of $75,000; a population of 447.9 million; and with EI at its minimum value, suggests GHG emissions in 2050 will be at least 1600 MtCO2e per year.[3]

The measures proposed by the EU to "deliver the European Green Deal" are important and valid. However, there is compelling empirical evidence that the 2050 sectoral emission targets are unrealistic (European Commission, 2023). Innovative engineering solutions are unlikely to change this assessment since the lower bound on emission intensity is predominantly defined by the physical reality of an economy.

5. INTERNATIONAL CONTEXT AND RELEVANCE

Over 190 countries have signed up to the 2015 Paris Agreement and thereby committed to achieving a condition of net zero emissions by 2050, which is defined in Article 4 as "*a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty.*"(UNFCCC, 2016)

A country's Nationally Determined Contribution (NDC) is intended to "communicate ambitious efforts" to achieving this objective. An NDC should therefore explain what measures a country intends to take in order to arrive at a condition of net zero emissions in 2050. This report should also include estimates of the residual emissions in 2050 and the negative emission technologies that will be employed to compensate for them. The methodology described in this paper provides a simple analytical procedure for conducting a first test of the validity of a country's proposal. It is applicable to all countries that publish annual socio-economic data and information on the level of their emissions of greenhouse gases. However, other indicators that assess the effectiveness of measures to achieve a condition of net zero emissions are also relevant (Angekumbura, M., 2024).

Emissions of greenhouse gases cannot be substantially reduced unless a country's emission intensity is brought down close to its minimum possible level. There are three ways to accomplish this task. As shown in Equation 2, emission intensity is the product of three factors:

1. **The factor CO2e/elec,** is the ratio of *all* GHG emissions to the level of electricity generation. This element can only be reduced to a minimum value if the generation of electricity is reliant on emission-free technologies. These would be predominantly renewable sources of energy, or a combination of renewables and nuclear energy. Although nuclear is a mature technology and capable of generating gigawatt-scale power, it is well established that solar and wind even with energy storage are substantially less costly (Lazard, 2024). The current enthusiasm for small modular reactors is unlikely to change this assessment (Ramana, M.V., 2024). In countries where all power generation is 100 percent emission-free, this factor declines to a low level—but it cannot decline to zero because every country has areas of trees and other biomass which emit carbon dioxide as part of the carbon cycle. Other greenhouse gases including methane from organic waste and nitrous oxide from fertiliser runoff may also be present. Fossil-fuel power generation with carbon capture and storage (CCS) is also technically feasible. However, a thorough

[3] The calculation is $75,000 (2050 per capita GDP) x 50 gCO2e/$GDP x 447.9 million (2050 population) = 1680 MtCO2e or 3.75 tCO2e per capita

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investigation by the Institute for Energy Economics and Financial Analysis conducted in 2022 concluded unequivocally that "CCS is not cost competitive with renewables and storage as a climate change mitigation option for the power sector." (Robertson, B., Moussavian, M., 2022).

But the policy implications are clear: electrical power generation must transition to emission-free sources of energy.

2. **The second factor, elec/E,** is the ratio of electricity generation to *total* energy consumption. This element measures the degree of electrification of all economic sectors. It makes little sense to generate emission-free electricity if economic sectors rely on fossil fuels. Every economic sector, starting with transportation, buildings, and manufacturing, should eventually become 100 per cent electric. Electrification of heavy industry is more challenging but certainly possible. Over time, and under a continuing policy of electrification, this factor will trend to a value close to unity.

3. **The third factor, E/GDP,** is the energy intensity of GDP. It is a metric often showcased because it has declined significantly in many countries as they have become more efficient in their use of energy (often due to higher levels of electrification). However, it cannot fall to zero. The idea of 'absolute decoupling' is valid up to a point: the consumption of energy can indeed fall while GDP continues to grow. But the ratio cannot fall to zero. Low-income African countries have values as low as 0.24 kWh/$GDP (Rwanda), while among modern economies Switzerland is the lowest with 0.52 kWh; Ireland is at 0.60 kWh; and Hong Kong at 0.61 kWh per dollar of GDP (all three are among the low EI countries shown in Figure 1) (Energy Intensity, 2022). Policies to reduce this metric should focus on the efficiency with which electricity is used. For example, heating a home with electric baseboard heaters works perfectly well, but it is much more efficient to install a heat pump. Similarly with lighting: not all electric light bulbs are the same. LED lights use only a small fraction of the electricity consumed by an incandescent bulb. Smaller electric vehicles consume less energy than electric SUVs. Other measures that reduce the value of this metric include retrofitting buildings to improve their thermal efficiency and the widespread installation of rooftop solar.

These three programmatic elements: emission-free electricity generation; the electrification of economic sectors, and greater energy efficiency, are the keys to achieving a condition of net-zero emissions by the middle of the century. Each one is essential.

The economic policies that will induce a decline in emission intensity are well established although infrequently applied in a coherent manner. There are three tools in the toolbox: regulation, incentives, and disincentives. For example, inducing utilities to phase out fossil-fueled power generation may require a combination of carbon pricing, caps on emissions, and incentives that provide attractive financing options for alternative sources of carbon-free energy. The electrification of the transport sector requires all three measures: limits on tailpipe emissions coupled with incentives for the purchase of electric vehicles and an increased excise tax on gasoline and diesel fuel. The thermal efficiency of new construction should be tightened through straightforward revisions to code which also ban connections to fossil gas for all new buildings. The electrification of industry should be promoted by carbon pricing and by the availability of preferential financing options. In all cases, the active involvement and leadership of governments at all levels is essential. Apart from enabling and facilitating the carbon pricing initiatives, and managing the programs of incentives and disincentives, governments must facilitate the permitting procedures and expedite the megawatt-scale installations of solar farms and onshore and offshore wind power. Finally, governments have an essential role to play extending the high-voltage direct-current electrical transmission systems that are essential for the distribution of the greater amounts of power that electrification will require.

The inevitability of residual carbon emissions at significant levels in high-income countries in 2050 once again raises the question of how to compensate for these emissions so as to achieve a condition of net zero. To answer this question, we should examine the carbon cycle.

5.1. The Global Carbon Cycle

The Global Carbon Project shows a detailed graphical representation of the 'anthropogenic perturbation of the global carbon cycle'. The salient points are shown in Table 2 for the period 2014-2023.

Table 2: Anthropogenic perturbation of the global carbon cycle

Anthropogenic flux	Emissions GtC/yr	Sink GtC/yr
Fossil carbon dioxide	9.7 ±0.5	
Land use change	1.1 ±0.7	
Land uptake		3.2 ±0.9
Ocean uptake		2.9 ±0.4
Total flux	10.8 ±1.2	6.1 ±1.3

Source: Global Carbon Project. https://globalcarbonbudget.org/gcb-2024/

The difference between the total of these fluxes is the absorption by the atmosphere, where its carbon content of roughly 800 Gt is increasing by about 5.2 Gt a year (Global Carbon Project, 2024).

The almost complete transition to emission-free electrical power generation by 2050 will remove the largest source of emissions of carbon dioxide: fossil fuels. If emissions from land use change remain unchanged, the global land sink is approximately 2.1 ±0.9 GtC per year,[4] which converts to a sink of between 4 and 11 billion tonnes of carbon dioxide a year.

Even at the lower value, this scenario presents the possibility of a significant capture of carbon dioxide from the atmosphere--a flux that *at a minimum* is almost four times as large as those generally attributed to the potential global capacity of BECCS or DAC—technologies which are assumed to be realistically capable of capturing only about 1 GtCO2e a year.

6. CONCLUSION

A condition of net-zero emissions is unlikely to be achieved unless a country's emission intensity is reduced to a low level. The reduction of emission intensity depends on three fundamental policies that must be carried out concurrently. The first is the phasing out of all electricity generation fueled by fossil fuels. All electricity generation must be based on renewable sources of energy: solar energy, wind power, hydropower, and geothermal energy. Nuclear energy is also an option. The second is focused on the electrification of all economic sectors starting with transportation (already underway), followed by buildings, industry, and agriculture. The third policy is aimed at improving the efficiency of electricity consumption by incentivising the adoption of the most efficient technologies for electric heating, cooling, and lighting.

Residual emissions at the point of net zero are unavoidable. Greenhouse gas emissions can never be completely eliminated. This means that the deployment of negative emission technologies under a condition of net zero emissions is a requirement. The natural carbon sinks include forest lands, wilderness and wetlands areas, and coastal zones where mangroves are abundant. These areas must be protected, managed, and if possible expanded. Regenerative agriculture that stores soil organic carbon also plays a role. Engineered carbon sinks such as bioenergy with carbon capture and direct air capture may eventually prove to be effective but the evidence so far is not persuasive.

The Canadian government has presented a scenario where GHG emissions decline from about 700 GtCO2e in 2023 to 165 GtCO2e in 2050. A realistic estimate of per capita gross domestic product in that year suggest that Canada's emission intensity will need to fall to about 50 gCO2e/$GDP. Although ambitious, this is a feasible scenario.

For the European Union, the analysis leads to a troubling conclusion. Under plausible assumptions of GDP per capita in 2050, the proposed emission intensity for EU27 is less than 15 gCO2e/$GDP: well below the minimum level demonstrated by the empirical data and confirmed by the physical basis of the metric. The European Commission should urgently re-evaluate its forecast of the group's residual emissions in 2050 and re-assess its proposals for a program of negative emission technologies intended to compensate.

[4] Assuming the larger range is applicable.

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LIVING LABS IN SHIPPING: ADVANCING THE UN SUSTAINABLE DEVELOPMENT GOALS

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ABSTRACT:

This study investigates the role of Living Labs (LLs) in creating innovative solutions for sustainable shipping, explores stakeholder involvement, issues addressed, methodologies employed, and the alignment with UN Sustainable Development Goals (SDGs).

Design/Methodology/Approach: *This study utilizes a qualitative approach to examine various typologies of living labs in the shipping sector. A literature search in April 2025 identified 56 documents from the SCOPUS database, with nine selected for in-depth analysis. Additional information was gathered from professional literature and industry sources, resulting in eight indicative living labs. The study aims to tabulate these cases and discuss the involved stakeholders, specific issues addressed, and the Sustainable Development Goals (SDGs) they support.*

Findings: *LLs are emerging as co-creation methods for innovative solutions in the shipping industry, primarily in the Global North. These LLs, mostly established after 2018, focus on digitalization, supply chain optimization, energy efficiency, decarbonization, and waste management. Key stakeholders align with the Triple Helix model (government, industry, academia), with a potential benefit from incorporating civil society (Quadruple Helix). The LLs contribute to multiple SDGs, notably SDG 9 (Industry, Innovation, and Infrastructure) and SDG 17 (Partnerships for the Goals).*

Research Implications/Limitations: *A gap exists in the literature regarding the actual impact assessment of shipping LLs. The study is limited by its desk research approach, relying solely on literature. Future research should incorporate in-depth case studies with interviews for a more realistic understanding.*

Practical Implications/Limitations: *The UN SDGs can serve as a framework for evaluating shipping innovations across environmental, social, and economic dimensions. Efficient LL processes, once validated, can be embraced by the shipping industry, contributing to its sustainability.*

Originality: *The study provides insights into the emerging role of LLs in the shipping industry and their alignment with the UN SDGs, offering a foundation for future research and practical implementation in pursuit of a more sustainable maritime sector.*

KEY-WORDS: Innovation in Shipping, Living Laboratories, Shipping Decarbonisation, Shipping Digitalization, UN SDGs.

1. INTRODUCTION

Shipping provides substantial benefits to society by facilitating widespread freight transportation that is not only cost-effective but also energy-efficient. It accounts for the transport of more than 80% of global goods by volume (UNCTAD, 2024). Shipping effectively connects producers and consumers in a globalized world, facilitating trade at relatively low costs. It is especially significant for countries in the Global South, which have pressing needs for food and resources. Consequently, shipping plays a crucial role in advancing several Sustainable Development Goals (SDGs) (UN, 2017; IMO, n.d.), particularly the most critical ones for human welfare, such as SDG 1 – No Poverty and SDG 2 – Zero Hunger (Figure 1).

Figure 1. The 17 Sustainable Development Goals of the United Nations

The marine industry is anticipated to face numerous challenges, including evolving regulations, climate change, energy shortages, and rapid technological advancements (Zaman et al., 2017). Fuelled by advancements in sensor technology, IT, automation, and robotics, technological development is evident across all marine sectors. To effectively adapt to forthcoming regulations and market pressures, the industry must maintain its rapid pace of development over the next decade.

One of the most pressing global environmental challenges of today, with potentially harmful impacts on the economy, social welfare, and the environment, is climate change. Today's shipping is almost entirely dependent on fossil fuels, and therefore, it is associated with externalities such as greenhouse gas emissions and air and marine pollution. The sector is estimated to contribute to approximately 2.5% of total global greenhouse gas emissions, compared to 16% from road transport (Jaramillo et al., 2022). Since 2011, the International Maritime Organization (IMO) has adopted measures to improve the energy efficiency of ships, such as the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). In accordance with the Paris Agreement, the IMO launched its 2023 revised strategy with the strategic goal of achieving net-zero emissions from shipping by 2050. To reach this ambitious target, alternative fuels like biofuels, hydrogen, ammonia, and methanol must increase their market share from 0% in 2023 to 80% by 2050 (IMO, 2023). This necessitates a radical transformation of the energy landscape in shipping within the next 25 years. The timeline is further compressed by the fact that a ship built today has an operational lifespan of around 20 years, meaning that current fuel choices will significantly impact future performance, adding another layer of complexity to the issue.

The necessary transformations should prioritize not only technological innovation but also stakeholder involvement. This ensures that changes are relevant and responsive to real-world problems and that envisioned solutions are seamlessly created, vetted, and implemented by the shipping industry. The International Maritime Organization's (IMO) success in shipping exemplifies the effective implementation of stakeholder engagement. While the IMO serves as a global forum where member states make final formal decisions, the lengthy and meticulous process of drafting regulatory instruments is guided and shaped by the participation of numerous shipping sector stakeholders, including non-governmental and intergovernmental organizations (Tan, 2005).

An emerging methodology for effective citizen and stakeholder participation in the co-creation of innovation is the concept of the living labs (LLs). According to Hossain et al. (2019), a living lab is a physical or virtual space to solve societal challenges, especially in urban areas, by bringing together various stakeholders for collaboration and collective ideation. For Mastelic (2019), "a living lab is an innovation intermediary, which orchestrates an ecosystem of actors in a specific region. Its goal is to co-design products and services in an iterative way with key stakeholders in public-private people partnerships and in a real-life setting. One of the outcomes of this co-design process is the co-creation of social value (benefit). To achieve its objectives, the living lab mobilizes existing innovation tools and methods or develops new ones". Finally, according to ENoLL (European Network of Living Labs), living labs are open innovation ecosystems in real-life environments using iterative feedback processes throughout a lifecycle approach of innovation to create sustainable impact (ENoLL, n.d). The LLs are experimentation environments that foster co-creation and open innovation among the main actors of the Quadruple Helix Model, namely citizens, government, industry, and academia (ENoLL, n.d). Living labs, therefore, are inspired by traditional scientific laboratories, serving as environments for experimentation and innovation. However, unlike the controlled and artificial settings of the traditional labs, LLs operate in real-world contexts. The human element is a critical component of their processes, encompassing both the participants (which are stakeholders or end users) and the overseeing organization. Furthermore, LLs are more than mere spaces for discussion, education, or awareness raising, such as workshops or focus groups. Their primary goal is to iteratively develop innovative solutions to real-world problems.

In this landscape, it is also important to recognize that regulations or innovative solutions intended to solve one problem can sometimes worsen another. An example is the introduction of hydrogen as a maritime fuel, which, despite its zero operational GHG emissions, relates to substantial upstream emissions from its production, transportation, and storage. Moreover, unresolved safety concerns and the significantly higher costs compared to traditional fuels pose further challenges (Kostidi et al., 2025). Consequently, any effort to address a specific problem should account for its related environmental, economic, and social impacts (Kotrikla, 2017) to promote balanced and sustainable progress. A comprehensive framework that could guide, shape, and evaluate shipping innovations is their alignment with the UN's 17 Sustainable Development Goals (UN, 2017), which strive to eliminate poverty, ensure prosperity, and safeguard the planet by 2030.

In this framework, the aim of the study is to investigate the role of living labs in the creation of innovative solutions for sustainable shipping. The stakeholders involved, the specific issues addressed, the methodologies employed, and the results achieved are searched with reference to specific cases. Finally, the connection between the living labs' work in the realm of shipping and the UN's sustainable development goals is explored.

The reminder of this paper is structured in the following way: At first the methodology is described. Then, eight cases of living labs in the shipping realm are presented. Next, based on the cases presented and the scientific literature reviewed, discussion is made on the characteristics, main actors and stakeholders, scale and complexity, and evaluation of the LLs in shipping, and their alignment with the UN SDGs. Finally, the conclusions of the paper are presented.

2. METHODS

This study uses a qualitative approach to investigate different typologies of living labs in the realm of shipping. At first, the scientific literature was searched in April 2025. SCOPUS database was searched (article title, abstract, and keywords) using the terms ("Living Lab*" OR LLs) AND (port OR shipping OR maritime). The search identified 56 documents. After reviewing the abstracts, 9 of them were chosen for further analysis, while the remaining documents were excluded because they were either irrelevant to the study's focus or provided only brief references to the topic.

This information was completed by searching the internet for data from the professional literature including documents from governmental, intergovernmental and non-governmental organizations, the shipping industry and the press.

Specific cases of living labs in shipping were retrieved. The cases that included information in most of the following fields were considered for further analysis: Segment of the shipping industry and subject area, stakeholders/participants, approximate date of launching, facilitating organization, and geographical area. These selection criteria resulted in an indicative but not exhaustive collection of eight LLs in shipping. The next step was to tabulate the information on the LL cases in shipping and discuss the stakeholders involved, the specific issues addressed, and the SDGs served by the LLs. A diagrammatic flow of the main steps of the methodology is presented in Figure 2.

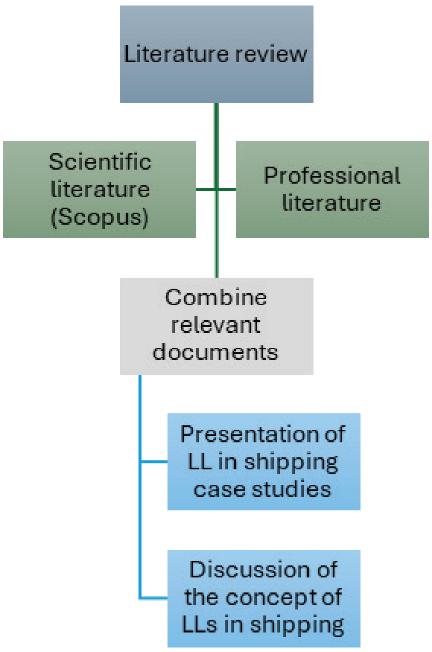

Figure 2. Diagram of the methodology of the study

3. RESULTS AND DISCUSSION

3.1. Cases of LLs in Shipping

Information on living labs in the shipping industry is presented below, based on publicly accessible data in the following areas: Shipping Segment, Subject Area, Stakeholders/Participants, Date of Commencing the Activities, Organization, and Geographical Area. The LL are presented in chronological order of their launching date.

Living Lab Maritime - LABSKAUS

Living Lab Maritime – LABSKAUS was facilitated by Carl von Ossietzky University of Oldenburg in Northwestern Germany, and it appeared in the literature in 2014 (Bolles and Hanh, 2014). The idea is that the development of safety-critical systems such as highly automated and autonomous vessels brings the need to establish a test environment (or 'testbed') close to the real world (in addition to simulative test environments) to support in situ their development, testing, demonstration, validation and certification process. Consequently, the Living Lab Maritime – LABSKAUS is basically a highly sophisticated testbed that provides services such as a reference waterway, a research boat, sensor infrastructure to correlate with the environment, a mobile bridge system, and a Vessel Traffic Services (VTS) System. This complex system supports the solution of technical problems but does not have educational features and is aligned mainly with SDG 9, which has the core aim to foster innovation, and SDG 8, which focuses on decent work and economic growth (Figure 1, Table 1).

MPA Singapore LL

The LL, run by the Marine Port Authorities of Singapore, was launched around 2018 and aims to provide a real operating environment and maritime data for the testing and validation of new solutions/technologies in the port of Singapore, one of the world's busiest hub port and waterways (MPA of Singapore, n.d.). MPA Living Lab aims to bring together the process owners, technology providers, and/or researchers to co-innovate, test-bed new systems, and bring technological and engineering solutions closer to market. It has spaces for the housing of maritime data hubs, remote pilotage, and next generation vessel traffic management experimentation. Physical testbeds at sea, such as designated anchorages, facilitate the trials of marine drones, autonomous vessels, and wireless communication technologies in the port environment. In addition, it includes the co-location of maritime companies, such as Wartsila's Global Acceleration Centre, in the same vicinity. The

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MPA Singapore LL focuses overall on data analytics and intelligent systems, autonomous systems and robotics, smart and innovative infrastructure, and safety and security, directly serving SDG 9, which has the core aim to foster innovation, and indirectly SDG 8, which focuses on decent work and economic growth. In addition, MPA LL experiments on environmental protection, thus supporting SDG 7 on affordable and clean energy, SDG 12 on responsible consumption and production, SDG 13 on climate action, and SDG 14 on protecting life below water. Finally, the co-location of maritime companies in the same vicinity enhances SDG 17 by fostering cooperation.

5G-LOGINNOV Projects' LL

In the framework of the 5G-LOGINNOV Project, part of the European Commission's 5G-Public Private Partnership, three LLs were implemented in Athens (port of Piraeus), Greece, Hamburg, Germany, and Luka Koper, Slovenia (5G-LOGINNOV, 2020; Catana et al., 2023; Kountche et al., 2023). The aims of the partnership (SDG 17) that will be implemented and tested in real operating conditions in the three living lab environments are to minimize the environmental impact of ports (SDGs 7, 13 and 14), to reduce congestion around the port area and disturbance to the cities (SDG 3, SDG 11), to represent a pillar of economic development and business innovation for the region (SDGs 8) and to facilitate the integration of the autonomous truck platoons of the future (SDG 9). The tools, innovative concepts, applications, and devices implemented include the Internet of Things (IoT), data analytics, next-generation traffic management, Cooperative, Connected, and Automated Mobility (CCAM), and the EU 5G logistics corridor.

The Living Lab of the Port of Valencia

The LL of the port of Valencia was announced in 2021 with the objective of improving the logistics sector and promoting new technologies and business opportunities in its immediate environment while improving the sustainability and quality of Valencia and the Valencian Community (Valencia Port, 2021). The LL platform facilitates the exchange of information in real time between port authorities, terminals, tugboats, pilots, and moorers so that all the information associated with the operation is available to all interested parties, enabling better planning, coordination, and decision-making. Valencia Port LL is a space to promote sustainability and decarbonization projects (SDG 13) such as renewable energies, efficient management of energy networks (SDG 7) or circular economy (SDG 12); new business opportunities in the logistics chain (SDG 8); the digitization of port processes (SDG 9); and integration with the immediate surroundings, both the city of Valencia and the Valencian Community (SDG 11). Participants in the LL are local authorities, representatives of the port logistics cluster, and start-ups fostering cooperation to achieve the goals (SDG 17).

The Pier Living Lab

The PIER (Port Innovation, Engagement, & Research) is an LL launched by the Halifax Port Authority in Canada in 2021 (PIER, n.d.) PIER LL engages tech companies, local and global supply chain partners, researchers, SMEs, and startups to solve problems and explore new technologies in a live environment (SDG 17). It focuses on three key areas: supply chain and logistics, supporting an interconnected Port City, and maritime policy development with sustainability as a core function and outcome in each. The vision is a future port with lower emissions. Through workforce development initiatives, a capable, diverse, engaged workforce, including racialized groups, is built. The PIER LL is a tool to advance UN SDG 4 (Quality Education), SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work), SDG 9 (Innovation), SDG 10 (Reduced Inequalities) SDG 11 (Sustainable Cities), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), SDG 14 (Life Below Water) and SDG 10 (Reduced Inequalities).

Techlog's Project Living Labs

Under EU's TECHLOG project that aims to offer technological and educational tools through which international trade, logistics, and transport students or professionals can simulate real-life operations, two permanent cross-border living labs were established, the Western (Cagliari, Italy, and Sfax, Tunisia) and Eastern (Beirut, Lebanon, and Alexandria, Egypt) in 2022 (TECHLOG, 2022), all of them transfer technologies for logistics innovation in Mediterranean area (SDG 10). These cross-border open labs were created to facilitate technology transfer between research centers specializing in driving simulators and transport communities, thus supporting SDG 9 and SDG 17. The project pursued a dual objective: Firstly, to craft inventive training protocols for practitioners (SDG 4), accompanied by proposals for related public policies (SDG 16), and secondly, to offer recommendations for optimizing business processes (SDG 8). The emphasis was on fine-tuning and optimizing Virtual Reality (VR) and Augmented Reality (AR), utilizing the synergy of Artificial Intelligence AI and the Internet of Things (IoT) to seamlessly integrate them for specific tasks and varying levels of control. The living labs played a crucial role in the development and testing of new training protocols (TECHLOG, 2023).

Newlab-Michigan Central

The Port of Monroe is Michigan's (USA) only port on Lake Erie and serves as the gateway to the State of Michigan's far-reaching multimodal transportation network. Located on the deep-draft frontage of the River Raisin, with direct rail access and immediate proximity to major freeways, the Port of Monroe represents the closest convergence of major freight assets anywhere in the region. In 2023, the Port of Monroe was announced as the first partner in the Newlab-Michigan Central testing network, a portfolio of multimodal pilot sites in Southeast Michigan that will serve as platforms to enable rapid testing of new technologies in real-world conditions (Port of Monroe, n.d.). As the on-the-ground project facilitator, Newlab is assembling a network of organizations and startups to drive the recently launched Multimodal Logistics Challenge, an initiative designed to accelerate cross-sector collaboration (SDG 17) around low-carbon (SDG 7 and SDG 13) and multimodal logistics (SDG 8, SDG 9, and SDG 11).

FOREMAST LLs

Under the FOREMAST project, funded by Horizon Europe, three LLs were realized in 2024 to support solutions for European coastal and inland or congested urban regions, implementing vessel prototypes and a Digital twin platform (FOREMAST, 2025). The LL of Ghent develops and tests a sustainable vessel solution in the Ghent region to shift the transport of goods from roads to water, contributing to a greener urban distribution. The LL of Caen develops and tests a new innovative catamaran vessel design and prototype tailored for urban goods transport. Finally, the LL in Galati, Romania, demonstrates replicability and develops an optimized vessel concept addressing the specific inland and Black Sea coastal navigation areas located in South-Eastern Romania. The LLs contribute to SDG 7, SDG 13, and SDG 11 by shifting the traffic to a more energy-efficient mode (shipping compared to road transport) whereas at the same time, promote health and well-being by reducing road congestion and air pollution (SDG 3) and foster innovation (SDG 9) through partnerships (SDG 17).

3.2. Discussion of the Living Lab Concept in Shipping

Table 1: Living Labs for the co-creation of innovation in shipping (list in chronological order of announcement)

Name	Shipping Segment	Subject	Stakeholders/ Participants	Activity since (approx.)	Organized/ facilitated/ led by	Area/City/ Country	UN SDGs
Living Lab Maritime - LABSKAUS	Canals and harbors	Navigation safety	n.a.*	2014	Carl von Ossietzky University of Oldenburg	Oldenburg, Northwestern Germany	8, 9
MPA Living Lab	Ports	Smart, intelligent, and autonomous systems (marine drones, autonomous vessels, and wireless communication technologies)	Industry partners (process owners and technology providers), researchers, and local universities	2018	MPA Singapore	Singapore	7, 8, 9, 12, 13, 14, 17
5G-LOGINNOV Projects' LL	Ports, freights, and the logistic supply chain	Environmental impact minimisation supported by tools such as IoT, data analytics, next generation traffic management, Cooperative, Connected, and Automated Mobility (CCAM), and the EU 5G logistics corridor	ICT manufacturers, telecommunications operators, service providers, SMEs, and Research Institutions	2020	5G-LOGINNOV project	Piraeus, Greece Hamburg, Germany Koper, Slovenia	3, 7, 8, 9, 11, 13, 14, 17

Name	Shipping Segment	Subject	Stakeholders/ Participants	Activity since (approx.)	Organized/ facilitated/ led by	Area/City/ Country	UN SDGs
Valencia port LL	Ports and Logistics	Digital transformation, sustainability, climate adaptation	Local authorities, representatives of the port logistics cluster, and start-ups	2021	Port of Valencia	Valencia, Spain	7, 8, 9, 11, 12, 13, 17
The Pier Living Lab	Ports, shipping, land	Maritime transportation and logistics, ports, policies	Tech companies, local and global supply chain partners, researchers, SMEs, and startups	2021	Halifax Port Authority	Halifax, Canada	4, 7, 8, 9, 10 11, 12, 13, 14, 17
Techlog's Living Labs	Logistics	Advanced technologies like Artificial Intelligence (AI), Virtual Reality (VR), and Augmented Reality (AR).	Maritime and transport companies and institutions, chambers of commerce, port authorities, terminal operators, training agents, universities	2022	University of Cagliari and Arab Academy for Science, Technology and Maritime Transport	Western LL (Cagliari, Italy, and Sfax, Tunisia) Eastern LL (Beirut, Lebanon, and Alexandria, Egypt)	4, 8, 9, 10, 16, 17
Newlab-Michigan Central	Logistics, Inland ports	Acceleration of cross-sector collaboration around low-carbon, multimodal logistics	A network of organizations and startups	2023	Michigan Central	Port of Monroe, Lake Erie, Michigan, USA	7, 8, 9, 11, 13, 17
FOREMAST LLs	Inland/ Coastal/ Urban	Integrating practical advancements in vessel automation alongside innovative green propulsion and ship design.	-	2024	-	Ghent, Belgium Caen, France Galati, Romania	3, 7, 9, 11, 13, 17

**Nonavailable*

3.2.1. Characteristics:

The living labs listed in Table 1 suggest they are currently emerging intervention methods for co-creating innovative solutions to real-world problems, primarily in the Global North. As Table 1 shows, the oldest shipping-related LL began in 2014, with the remaining seven initiatives starting after 2018. Geographically, most shipping LLs are in Europe (Belgium, France, Germany, Greece, Italy, Romania, Slovenia, and Spain), with others in Africa (Egypt and Tunisia), America (USA and Canada), and Asia (Singapore and Lebanon). This European concentration may be due to EU initiatives promoting citizen and stakeholder participation in policy, research, and innovation, including funding programs like HORIZON (EC, n.d.).

3.2.2. Main actors:

Based on the shipping LL examples discussed (Table 1) and the scientific literature, the main actors involved appear to align in most of the cases with the Triple Helix model of innovation, encompassing representatives from government, industry, and academia (Ranga and Etzkowitz, 2015). This reflects the real-world problems that these LLs aim to address, primarily digitalization, vessel automation, supply chain optimization, energy efficiency and decarbonization, waste management, and the circular economy. The drivers behind selecting these specific problems are complex (Rodrigue, 2010), but key factors include regulations at the national, regional (EU), and international (IMO) levels, as well as the need to enhance the operations and competitiveness of shipping and ports within the dynamic global environment. Consequently, shipping LLs focus on inventing innovative solutions and systems led by academia and industry, tested within ports and shipping companies, and supervised by policymakers for regulatory compliance. More specifically, the roles of the different actors within the Triple Helix model in the shipping arena (maritime shipping and ports) are (Rodrigue, 2010; Šekularac-Ivošević and Milošević, 2019; Polydoropoulou et al., 2025):

- **Port authorities:** Port authorities are key actors. Beyond managing daily operations and setting strategic goals, they provide a unique real-world environment for experimentation – a fundamental requirement for LLs. Their involvement ensures solutions are not only innovative but also practical, feasible, and seamlessly integrated into existing port workflows.

- **Shipping companies:** Their experience in managing cargo, ships, and the logistics chain, combined with their understanding of port operations, makes them invaluable for optimizing real-world operational and technological aspects. Specifically, they contribute to improvements in cargo handling, reduced waiting and hoteling times, optimized ship speed and weather routing, and the testing of new fuels and technologies aimed at decarbonization and digital solutions.

- **Technology providers:** These actors develop digital solutions (including IoT and automation tools) and low-carbon energy solutions. Their key role is to collaborate closely with port authorities and shipping companies, adapting these solutions to meet the specific challenges and needs within the shipping industry.

- **Policy makers and government representatives:** Policymakers and government representatives can improve regulations by gathering input from the shipping industry on compliance challenges. They play a critical role by providing policy goals and economic support to the LL, and their involvement is essential for aligning the LL's innovations with relevant regulations.

- **Researchers and academia members:** Researchers and academia members offer essential knowledge, innovative solutions, and data analysis expertise. They actively seek opportunities to pilot their ideas in real-world settings to test their effectiveness and identify areas for improvement. Additionally, they can provide support for the economic and organizational aspects of the LL, particularly when they are responsible for convening it.

An exploration of sustainability problems in ports requires a holistic understanding and involvement of actors from the quadruple helix—academia, business, policymakers, and society at large (Gerlitz et al., 2024). Citizen and civil society involvement in the co-creation of innovation improves solution inclusivity and quality (Polydoropoulou et al., 2025). This participation is especially important for ports near cities, where externalities like traffic congestion, noise, and air pollution impact citizens directly. Likewise, citizen input is crucial when testing interventions that affect the quality and cost of shipping services (e.g., product and passenger transportation). Therefore, shipping LLs can significantly benefit from the inclusion of civil society organizations or individual citizens in their endeavors. Figure 3 provides a synopsis of the key elements in shipping LLs: the actors involved, the real-life environments used for testing, and the main areas of innovative solutions that are co-created.

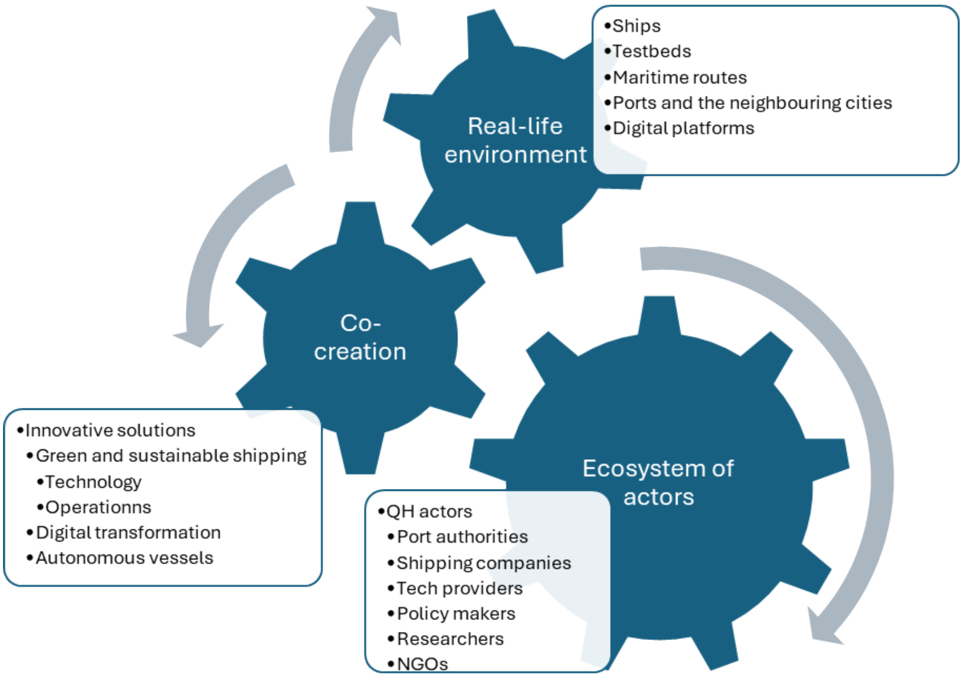

Figure 3. Key characteristics of the living labs in shipping

3.2.3. Scale and complexity:

Living Labs in the shipping industry vary significantly in scale and complexity. Some prioritize developing solutions directly for ships, such as vessel prototypes (FOREMAST, 2025) and onboard automation systems (Bolles and Hanh, 2014) or big data, IoT, and AI to form digital replicas (Kaklis et al., 2023). These LLs often emphasize technical optimization and resemble testbeds, typically involving a limited range of stakeholders. However, many shipping LLs focus on the interactions between vessels and ports, often featuring just-in-time arrival (e.g., MPA of Singapore, n.d.; Valencia Port, 2021) or between ports and their surrounding urban environments (e.g., PIER, n.d.; Kishchenko et al., 2019; 5G-LOGINNOV, 2020; Valencia Port, 2021). Flikkema et al. (2023) employed a Living Lab approach with diverse stakeholders to investigate both digital and non-technological solutions for road, rail, inland waterway, and maritime transport at the Port city of Rotterdam. Their project aimed to have its demonstrators and developments inform the Master Plan for the future European green port.

In addition to ships, ports, and their neighboring cities, small islands (Groppi et al., 2022) and enclosed marine areas like the Baltic Sea (Meškauskienė et al., 2019; Gerlitz et al., 2024) are considered ideal environments for experimentation and innovation, facilitating the replication and scaling-up of successful outcomes. This is particularly valuable in policymaking (Gerlitz et al., 2024), as small-scale trials (e.g., pilot projects) allow for refinements, adaptations, and the exploration of alternative approaches before larger investments in port infrastructure are made. Groppi et al. (2022) characterized small islands as living labs well-suited for testing innovative solutions, such as high Renewable Energy Source (RES) penetration, to generate validated data for mainland replication. Their research revealed that ferries connecting Favignana island (Italy) account for 56% of the island's total energy consumption, leading them to propose ferry electrification using photovoltaic energy. A study by Polydoropoulou et al. (2025) of three Living Labs in Greek Island ports highlights benefits such as accelerated research and innovation, process mapping and validation through stakeholder engagement, risk mitigation via controlled testing, and facilitated knowledge transfer within the port industry ecosystem. Meškauskienė et al. (2019) highlighted the Baltic Sea as a living laboratory for rapidly prototyping and testing solutions ranging from cleaner and safer shipping to remote and autonomous navigation. Furthermore, within the Baltic Sea region, Gerlitz et al. (2024) developed a trans-local LL model to support sustainability transitions in ports through shared governance structures at a macro-regional level. This model enables the enactment of specific sustainability pathways at ports on a micro-scale (local level), with the potential for scaling them up through trans-local exchange. In summary, Living Labs (LLs) for sustainability transitions offer a platform for experimentation and contribute to achieving sustainability across various sizes, scopes, and scales. This requires careful examination at multiple levels: micro (ship or firm level), meso (port ecosystems), and macro (interventions within regional, national, or global socio-technical systems) (Gerlitz et al., 2024). To function effectively, the larger Living Labs require a diverse ecosystem of participants. Recognizing that these actors may have competing objectives (Polydoropoulou et al., 2025), effective moderation and facilitation become crucial.

3.2.4. Evaluation:

Living Labs (LLs) are a relatively recent development, particularly within the shipping industry. As practical experience accumulates, the scientific literature gradually develops, exploring both the theoretical underpinnings and practical implications. To optimize the allocation of future resources, insights into the evaluation of LL processes and their impact are crucial. As the OECD (2022) notes, process evaluations can enhance public authorities' understanding and management of citizen participation, while impact evaluations determine whether these processes reach their intended audience and achieve their desired effects. However, Paskaleva et al. (2021) suggest that the design, implementation, and reporting of Living Lab evaluations, in general, have received limited attention despite the field's development over the past two decades. This study confirms a similar trend regarding LLs in shipping, which is not unexpected given their relatively recent introduction only a decade ago. To address this gap, funding bodies should consider mandating the evaluation of LL performance and the assessment of their outcomes and impacts (Paskaleva et al., 2021). Meškauskienė et al. (2019) propose three domains (with their respective KPIs) for the evaluation of innovative solutions developed within port LLs: Communication and Documentation of Solution Development, Target Group Outreach and Result Presentation, and Innovation and Sustainability.

4. THE ALIGNMENT OF THE SHIPPING LLS WITH THE SDGS

While the UN's SDGs are often framed at a societal or national level and thus perceived as the responsibility of governments (Delgado-Ceballos et al., 2023), this assumption is flawed. Achieving the SDGs requires a collective effort, and businesses possess the potential, expertise, resources, and a fundamental responsibility to advance global sustainability. Corporate Social Responsibility (CSR) and ESG indicators are key initiatives driving this transformation, shifting the corporate focus from profit alone to a more sustainable approach that prioritizes societal well-being (Delgado-Ceballos et al., 2023). Specifically, living labs in the shipping sector, including those examined in this study, contribute to multiple SDGs and strengthen all dimensions of sustainability: social, economic, and environmental. Table 2 highlights the key SDGs supported by shipping-sector living labs, indicating the number of case studies from this paper that contribute to each goal.

Table 2: The SDGs served by the LLs in shipping

SDG Goal	Shipping LL contribution	Number*
3 GOOD HEALTH AND WELL-BEING	**SDG 3.** Good health and well-being. LLs in shipping cocreate solutions that reduce port-related pollution in ports and coastal regions, which contributes to the health and well-being of coastal residents.	2
4 QUALITY EDUCATION	**SDG 4.** Quality education. Living labs in shipping co-create and test inventive training protocols for practitioners to address the numerous challenges of the industry. Those include the rising technological complexity (autonomous vessels, digital navigation systems, AI and smart port infrastructure), shipping decarbonization solutions, updates in the regulatory regime and the crew diversity and cultural differences.	2
7 AFFORDABLE AND CLEAN ENERGY	**SDG 7.** Affordable and Clean Energy. Living labs in shipping promote the development and testing of clean energy solutions for the maritime industry, such as renewable fuels, wind power, and energy-efficient technologies. By reducing reliance on fossil fuels and promoting energy-efficient shipping operations, these labs help drive a transition to cleaner energy sources.	6

http://dx.doi.org/10.21622/MACI.2025.02.1.1265

8 DECENT WORK AND ECONOMIC GROWTH	**SDG 8.** Decent work and economic growth. Living labs in shipping can promote higher levels of economic productivity through diversification, technological upgrading, and innovation, including through a focus on high-value-added and labor-intensive sectors.	7
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	**SDG 9.** Industry, Innovation, and Infrastructure. Living labs foster innovation in shipping by experimenting with new technologies such as autonomous vessels, digitalization, and smart shipping systems. These labs can also enhance infrastructure by testing new logistics systems or digital platforms that streamline global shipping operations, improving efficiency and connectivity.	8
10 REDUCED INEQUALITIES	**SDG 10.** Reduced inequalities. The LLs in shipping can adopt approaches to empower racialized groups and reinforce the cooperation between entities from the global north and the global south.	2
11 SUSTAINABLE CITIES AND COMMUNITIES	**SDG 11.** Sustainable cities and communities. Shipping is a key part of global supply chains and urban infrastructure. By improving port logistics, reducing shipping emissions, and testing smart city innovations for better integration between shipping hubs and urban areas, shipping living labs can help make cities more sustainable.	5
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	**SDG 12.** Responsible Consumption and Production. Shipping is a source of pollution and waste. Living labs can test and implement circular economy practices, such as using sustainable materials, improving waste management, and developing technologies to reduce emissions and fuel consumption.	3
13 CLIMATE ACTION	**SDG 13.** Climate Action. Shipping contributes to global GHG emissions. Living labs can experiment with carbon-neutral technologies, green fuels, and energy-efficient vessels to reduce emissions in the maritime sector. By exploring ways to mitigate climate change through innovative shipping technologies, these labs directly contribute to climate action.	6
14 LIFE BELOW WATER	**SDG 14.** Life Below Water. The shipping industry impacts marine ecosystems through pollution and overfishing. Living labs can help develop environmentally friendly shipping technologies that minimize the ecological footprint of the maritime sector. Innovations that reduce pollution and enhance marine biodiversity protection are aligned with this goal.	3
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	**SDG 16.** Peace, Justice and Strong Institutions. LLs can support the shipping industry to promote effective institutions to ensure the safe, secure and environmentally protective flow of maritime commerce.	1
17 PARTNERSHIPS FOR THE GOALS	**SDG 17.** Partnerships for the Goals. Living labs, by their definition, bring together a wide range of stakeholders, including governments, industries, research institutions, and civil society organizations. By fostering collaboration and partnerships, living labs contribute to building the partnerships needed to implement and scale sustainable solutions in the shipping industry.	7

**The number of LLs in shipping of this study (out of the 8) that serve the specific SDG*

Living labs in the shipping industry, by definition, are central to advancing SDG 9 (Industry, Innovation, and Infrastructure) through the development of innovative solutions to real-world challenges, thereby fostering economic growth and decent work (SDG 8). Their inherent design allows them to significantly contribute to SDG 17 (Partnerships for the Goals) by creating collaborative ecosystems working towards shared objectives. Furthermore, LLs substantially support SDG 7 (Clean Energy) and SDG 13 (Climate Action) by addressing the urgent need for innovative technologies, fuels, and operational practices to combat climate change, an effort reinforced by the IMO's new regulations on ship energy efficiency. These decarbonization and clean energy initiatives positively impact the sustainability of coastal cities (SDG 11), while the focus on environmental challenges promotes SDG 12 (Responsible Consumption and Production) and SDG 14 (Life below Water). As a side effect, the good health and well-being of the coastal communities is improved (SDG 3).

The success of these sustainability initiatives depends on continuous workforce education and training in digital skills, alternative fuels, and new technologies (SDG 4). Because shipping is an industry that connects people from diverse backgrounds, interventions promoting the reduction of inequalities (SDG 10) are particularly valuable, including facilitating women's access to jobs within the sector. Recognizing the complex structure of shipping as a global economic activity, reinforcing effective institutions is paramount to ensuring the safe, secure, and environmentally responsible flow of maritime commerce (SDG 16). Additionally, broadening and strengthening the participation of developing countries in the institutions governing shipping is crucial, given their significant representation among ship-building, flag, and ship-recycling states and within the shipping workforce (SDG 16).

Collectively, these efforts cultivate a more sustainable, innovative, and responsible maritime industry, contributing to overall global sustainability.

5. CONCLUSIONS

Living Labs (LLs) are designed to foster innovation through collaborative co-creation. This study explored the scientific and professional literature to identify LLs operating within the shipping industry. Eight cases were selected based on predefined criteria. The aims, structure, and alignment with the UN Sustainable Development Goals (SDGs) of these shipping-related LLs were then analyzed and discussed, drawing on both their observed characteristics and existing scientific literature.

Living labs have emerged in the shipping industry over the last decade, with most initiatives launching within the past six years. These LLs primarily operate in countries of the Global North, particularly in Europe, reflecting the EU's efforts to promote citizen and stakeholder engagement in policy, research, and innovation. Similar interventions could potentially benefit countries in the Global South, which currently hold a significant share of shipbuilding, flagging, ship dismantling, and maritime workforce.

Shipping living labs concentrate on developing innovative solutions and systems. These initiatives are typically led by academia and industry, with testing conducted within ports and shipping companies and regulatory compliance overseen by policymakers. The stakeholders involved in the eight LLs under study include port authorities, shipping companies, technology providers, policymakers, researchers, and academics. Consequently, these LLs largely adhere to the Triple Helix model of innovation. Incorporating civil society representatives, thereby applying a Quadruple Helix (QH) model, could be particularly beneficial, especially in interventions that directly impact people's lives. Examples include the adoption of alternative fuels (which may affect transport costs), actions at ports and coastal areas (influencing congestion, air/water quality, and noise levels), the development of digital apps for seamless transport, and adaptation measures. In general, citizen input in port and coastal shipping interventions would be valuable. Furthermore, public participation would raise awareness and increase acceptance of potentially radical measures, particularly those needed for shipping decarbonization.

Although the application of living labs in shipping is relatively recent, and they often emphasize technological innovations in shipping digitalization and decarbonization, these entities contribute to several UN Sustainable Development Goals (SDGs). Fundamentally, LLs inherently support SDG 9 (Industry, Innovation, and Infrastructure) by generating innovative solutions to real-world challenges. By their very nature, they also foster collaboration among diverse stakeholders, creating a cooperative ecosystem that aligns with SDG 17 (Partnerships for the Goals).

The environmental SDGs primarily addressed are SDG 13 (Climate Action) and SDG 14 (Life Below Water), reflecting the IMO's regulatory framework focused on energy efficiency and various types of onboard waste (e.g., oil, scrubber water). A range of socioeconomic goals, including SDG 7 (Affordable and Clean Energy), SDG 8 (Decent Work and Economic Growth), and SDG 11 (Sustainable

Cities and Communities), further complement the multifaceted activities of shipping LLs.

The UN SDGs can serve as a comprehensive framework for evaluating new measures in shipping across different dimensions (environmental, social, economic) and balancing outcomes to ensure sustainability. For instance, decarbonization measures (SDG 13) should be subsidized to avoid hindering maritime trade, an economically vital mode of transport that particularly supports developing economies (SDGs 1, 2, and 8).

Given the nascent nature of living labs in shipping, a gap exists in the literature regarding the assessment of their actual impact. As experience accumulates, it is expected that this gap will be filled with valuable insights into how effectively LLs deliver tailored and innovative solutions to real-world challenges. Such studies will be crucial for optimizing resource allocation, streamlining processes, and identifying areas for improvement. To this end, specific Key Performance Indicators (KPIs) that are aligned with the UN Sustainable Development Goals (SDGs) should be established. It is recommended that impact evaluation be an integral component of all shipping LL processes required by their funding agencies. Efficient LL processes, once validated, will be multiplied in the shipping industry, thereby contributing to its overall sustainability.

The examination of Living Labs within the shipping industry highlights their potential to drive collaborative innovation and address sustainability challenges through multi-stakeholder engagement. This enriches the broader discourse on living labs by illustrating how these initiatives facilitate the implementation of UN Sustainable Development Goals in maritime contexts while also underscoring the importance of ongoing evaluation and inclusive participation to enhance the effectiveness and relevance of innovative solutions.

This study is limited by its reliance on desk research, drawing information solely from professional and scientific literature. Future research should incorporate in-depth examinations of real-world living labs in shipping, including interviews with organizers, facilitators, participants, and beneficiaries. This further research could illuminate whether measurable impacts have occurred since the establishment of the labs and whether they have continued or expanded beyond the initial project funding. This would provide a more realistic and comprehensive understanding of the subject. Given the nascent state of the field, further assessment will offer crucial insights into LL design, implementation, and early outcomes, benefiting the entire shipping community.

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HOUSEHOLD AND AGRO-WASTE UPCYCLING INTO SUSTAINABLE UNBREAKABLE ARTWORKS AND FURNITURE PIECES BY ECO-FRIENDLY ORGANIC CHEMICAL REACTIONS

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ABSTRACT:

Millions of tons of agro waste and household waste have been generated that end up in landfills, which in turn affect human health. Waste has serious impacts on the environment through greenhouse gas emissions. Waste is a huge economic burden on governments and distorts the civil and aesthetic appearance. The invention primarily converts waste into crystallized capsules by eco-friendly organic chemical reactions. Secondly, the capsule undergoes a covering by a second chemical reaction to form the final product, which is artwork or furniture pieces that are sustainable and unbreakable. The final product can be manufactured on a large scale since the raw materials are affordable and available, as explained in the feasibility study. Circular Economy is the core concept of the project, which involves upcycling elements that are supposed to be wasted and valorizing them, such as household and agro-waste in potato peels. Moreover, the invention provides practical solutions for the previous technical issues in previously designed inventions. Both stages of the project are safe and non-hazardous. The core components of the first capsule are stone salt and natural stabilizers, and the second stage's reagents are unbreakable resin-making components. The project conducted has not only environmental benefits but also social and economic values; it can be applied in large-scale production, in specialized contemporary museums, and/or exported as artworks and furniture in other countries.

KEY-WORDS: Sustainable-Designs, Eco-Friendly-Polymers, Waste-Upcycling, Circular Economy, Waste Encapsulation .

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1. INTRODUCTION

1.1. Invention Highlights

Millions of tons of Household waste and Agro-waste are sent annually to landfills, they not only have exaggerated amounts of air footprints (Carbon Dioxide, Methane and Nitrogen), but also drastically threaten the public health and civil aesthetics.

The aim of the project is to optimize resources (human, economic, and environmental) by Circular Economy 4 Rs of Reuse, Recycle, Recover, and Reduce, without sending waste to landfills or incinerators. Waste products are fully crystallized into a compact capsule made from rock salt with potato peel starch, then the capsule undergoes a second capsulation by an eco-friendly reaction of:

ECH (Epichloro hydration) + Bisphenol A Diglycidyl ether+ waste
= final product, which is a sustainable, unbreakable body that can be converted into Artwork or Furniture pieces.

1.2. Technical Information

Treatment and upcycling of household waste and agro-waste into Artworks, Sculptures, and Furniture pieces. The project was conducted by eco-friendly chemical reactions with a primary target of resources optimization, additionally circular economy methods are adopted to prevent waste from being discarded in landfills or incinerators.

1.3. Previous Projects in the Same Domain

- **CN109912270A**
  This invention was carried out in China in 2019 when waste materials were recycled by burning methods, then they turned into dust and ashes after careful grinding and chemical additives, and the final products were mixed with concrete [5].

- **JP4004252B2**
  This invention was carried out in China in 2019, when waste materials were recycled by burning methods, then they are turned out into dust and ashes after careful grinding and chemical additives, then final products are to be mixed with concrete [6].

- **CN102060456A**
  In this project, China recycled waste incineration final products and turned them into construction materials by solidifying the dust by chemical reagents and turning them into solid concrete [7].

1.4. Technical Issues in Previous Attempts

The first aforementioned trial relies on solid waste only that can be ground finely. Moreover, it uses cement, which harms the environment. Generally, cement results from burning fossil fuels; this industry is considered as the Third-Largest air pollutant and air footprint emitter. In the second trial waste products are exposed to extremely elevated temperatures which in turn wastes environmental resources and deplete energy supply. In the third previous project, waste is not upcycled or recycled, only the waste byproducts which accumulate in the incinerator.

1.5. The Solution Introduced in the Project

The invention adopts a concept of circular economy approaches in designing the final product; No product, by-product, or waste of any kind is sent to landfills or incinerators. Agro waste from potato peel extracts is used as thickner and stabilizer.

Rock salt is used for capsulizing waste and absorbing remaining moisture which is eco-friendly and has net-zero climate emissions. Hazardous substances are totally avoided such as cement, excessive heat is also avoided throughout the whole process.

Final products are used as Artwork and Furniture pieces of different shapes and sizes, which can be sold, massively produced, and exported, which in turn can be of a huge economic benefit. The chemical reaction involved in the waste final product is: ECH (Epichloro hydrin) + Bisphenol A Diglycidyl ether+ waste = final product

2. STATISTICS

2.1. Statistics-Plastics

- **Statistics-Plastics | PVC (polyvinyl chloride)**
  This polymer has many applications, from pipes to toys and window frames, but is not widely recycled in household waste. It includes acrylic, nylon, and other mixed plastics.

  These are almost not recyclable in household collections [9].

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- **LDPE-low-density polyethylene**
  In terms of plastic carrier bags. These can be recycled but not commonly in household recycling [1].

2.2. Statistics-Aluminum

Although aluminum can be infinitely recycled, 7 million tons of aluminum are still not recycled each year [2].

2.3. Statistics-E-waste

Globally, electronics waste (e-waste) volumes grew to 53.6 million metric tons in 2019, an increase of 21% in only 5 years since 2014 [3].

Only 17.4% of e-waste discarded in 2019 was recycled.

In the U.S, only 15% of the 6.92 million tons of e-waste discarded in 2019 was recycled.

2.4. Toy Industry Waste

The UK's toy industry has been a massive year; consumers spent £370m on them [4].

However, environmentalists say this is contributing largely to the amount of plastic ending up in landfills and oceans.

2.5. Statistics on Household Waste Recycling

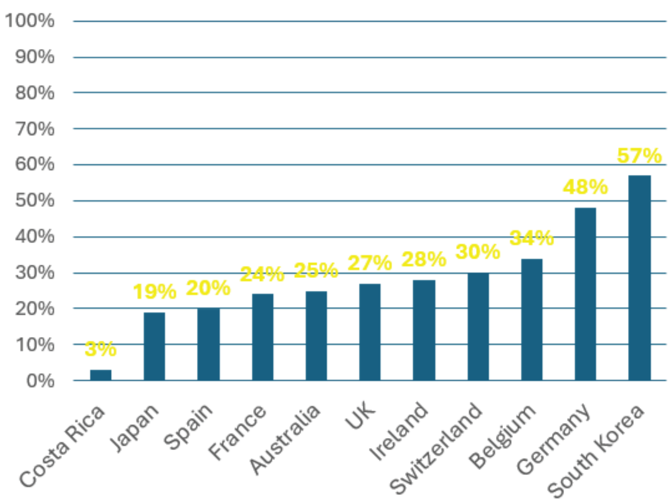


Figure 1. Statistics on how much household waste is recycled globally; South Korea comes as the largest recycling country, contributing 47% of total household waste, while Costa Rica recycles only 3% [8]

3. METHODOLOGY

- **First Stage:** conversion of waste products into crystallized capsules using rock salt and potato peel extracts as stabilizer agents. Primarily, peels are sun-dried and finely ground without resorting to any kind of fossil fuel energy.

  Peel extract: rock salt ratio is 2:1.

  Real case scenario: 500 grams of rock salt and 1000 grams of potato peels are used to capsulate 50 plastic waste bags.

- **Second stage:** the waste capsule is covered by a chemical reaction to make a solid, unbreakable polymer net product.

Table 1: Approximate weight of Waste Encapsulated

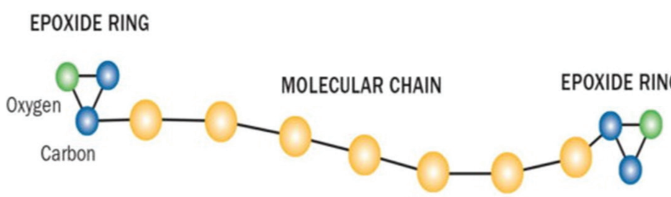
Items no:	Weight of waste (gm)	Weight-encapsulation (gm)
1	90	290
2	100	300
3	120	320
4	150	350
5	110	310
Mean/SD	114/23.02	314/23.02

3.1. Chemical Reaction

ECH (Epichloro hydrin) + Bisphenol A Diglycidyl ether+ waste
= final product

The first chemical reagent is a liquid substance that is added to the second chemical reagent, which is a solidifying agent with a ratio of 4:1 with 10 minutes of stirring. For instance, 1000 ml of sub. 1 is added to 250 of sub. 2 with 10 minutes of stirring; low heat is generated from this reaction, and the final polymer is formulated and solidified after 24 hours. The net product is transparent. However, it can be colored or stained to cover the waste capsule and make the final Artwork and Furniture pieces of a variety of sizes and shapes to suit people's preferences.

Reaction 1: *Enclosed Carbon Oxygen epoxide rings with long chains inside.*



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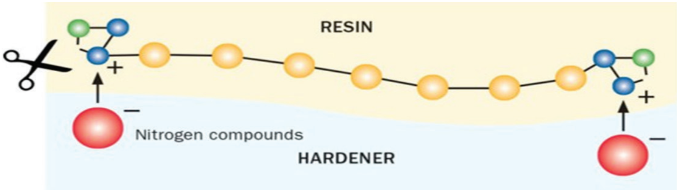
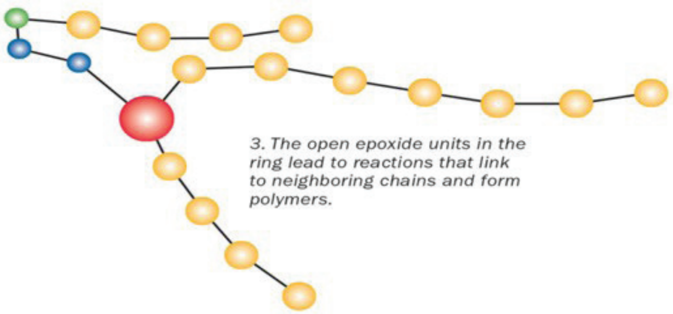
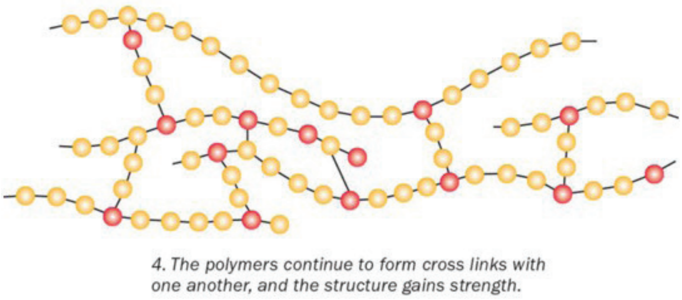
Reaction 2: *Cutting carbon rings and adding Nitrogen for elongation and hardening.*



Reaction 3: *Formation of long hard polymers.*



Reaction 4: *Polymers continue cross-linking with neighbor chains.*



3.2. Project Feasibility

Most of items are free of charge since the project is based on circular economy method of taking, reusing and upcycling waste from Households.

Household waste is FREE of charge.

Starch from potato **peels** is a FREE by-product from food enterprises.

Solid salt costs:

White: **0.05 USD** per kg for 28,000kg **Himalayan 0.05 USD** per kg for 500kg.

Artwork outer **reagents'** materials cost **6 USD** per kg for 100 kg. Estimated cost of an artwork holding waste of 30 plastic bags: **7 USD** for 50 cubic cm final artwork.

Table2: Project feasibility and cost analysis

Item:	Cost:	Large-scale production:
Waste	Free	Consistent supply from waste management facilities
Potato peels	Free	Reliable supply from food processing enterprises
White rock salt	0.05 USD per kg for 28000kg	Bulk discounts
Himalayan rock salt	0.05 USD per kg for 500kg	The previous option is more feasible
Outer reagent	6 USD per kg for 100kg	Negotiating prices
Estimated cost	7 USD	Automation
Energy cost	Minimal heating	Energy-efficient equipment
Equipment cost	3D printers	Maintenance

4. RESULTS

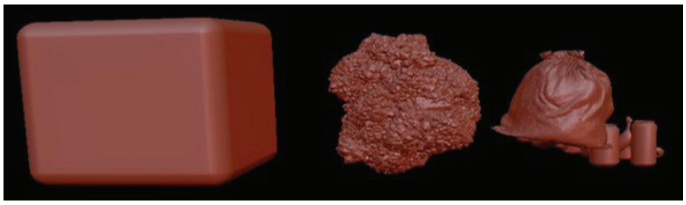


Figure 2. Steps of waste upcycling into a crystallized capsule primarily and then a secondary covering as a finish product

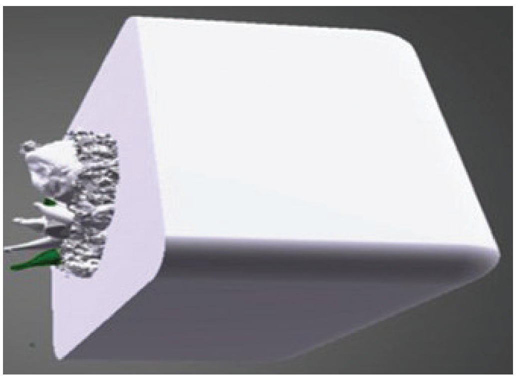


Figure 3. 3D Shape for the stages of upcycling waste into art products

Artwork products (which carry different household waste inside) can be furniture pieces, home décor, and geometrical sculptures that are unbreakable, eco-friendly, and sustainable.

The final executed prototype has successfully upcycled 50 plastic bags in a pyramid shaped artwork of 35cm height and the same width and weighed about 1kg. It took approximately 24 hours for the polymers to fully harden, finally the cube is extremely strong and durable which can withstand extreme pressure without breaking, which was confirmed by pressure testing.

4.1. Processing Efficiency

The whole process can be automated and computerized for faster and larger-scale waste management solutions.

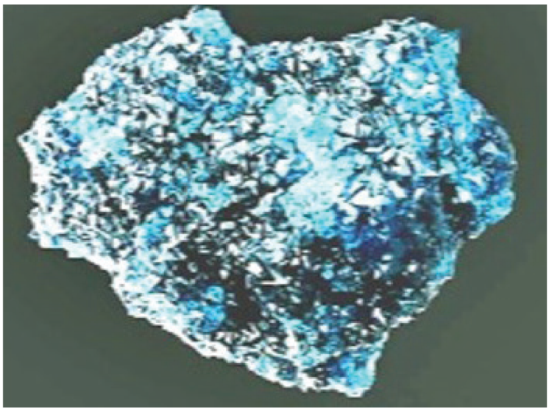


Figure 4. Prototype of the capsule which contains the waste products

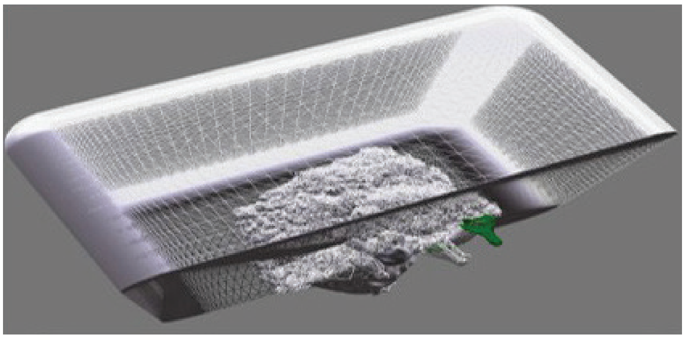


Figure 5. Internal view of the artwork with the subsequent layers

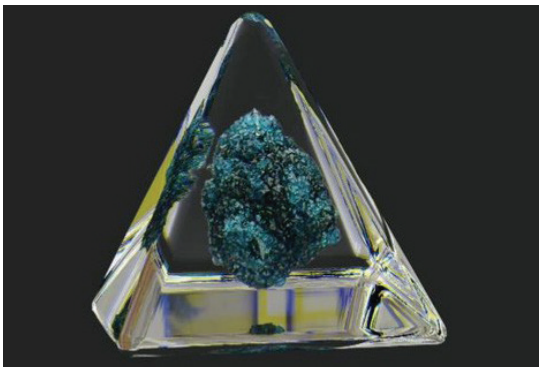


Figure 6. 3D Shape as an example for the artwork final product

4.2. Product Durability

The polymer materials gives the net product durability and hardness with some elasticity to make it unbreakable and long-lasting artworks that can be placed both indoor or outdoor.

Table3: Durability assessment of upcycled artwork and control material

Items	Upcycled waste (n=5)	Control (n=5)	P Value
Mean breaking height (m)	20 ± 2	18±1.5	0.11
Mean compression force (N)	1500 ± 50	800 ± 40	<0.001

4.3. Environmental Impacts

When waste is converted into net products, emissions will be reduced by preventing waste from being sent to landfills or incinerators, especially methane gas generated from household waste, which is 25 times more potent than CO_2.

5. DISCUSSION

Millions of tons of waste (non-recyclable and non-recycled) are generated each year, which end up in landfills and incinerators. Waste impacts the environment through greenhouse emissions, which in turn affects human health and aquatic life and is a huge economic burden for governments. The idea of the project is to encapsulate household waste, toys, stored junk, and plastics into an eco-friendly crystallized form, which will undergo a second covering by a chemical reaction to form non-breakable artworks, decoration or furniture pieces. The product goes through two major pathways: based on circular economy method of reducing, reusing, recovering and recycling, so that nothing ends up in landfills.

1st Phase

Household waste is capsulated by the following reaction: Waste+ Solid Stone Salt+ Starch from potato peels (sun dried and milled) + water= solid crystallized capsules.

2nd Phase

Waste capsule undergoes covering step to form the final piece of artwork which is unbreakable and sustainable. As following: Waste capsule+

ECH+ Bisphenol A diglycidyl ether = final product of Artwork.

5.1. Environmental Benefits of the Invention

1. Significant reduction of GHG emissions from household waste.

2. Cutting down water pollution.

3. Preservation of Aquatic life.

5.2. Social Benefits

1. Better health of populations due to lower emissions.

2. More vivid artistic houses and cities by the final artwork product.

5.3. Economic Benefits

Significant reduction in waste control budgets from the governments.

More importantly this new contemporary "Waste into Art" will definitely be of a huge economic benefit, artworks can be sold, exported and exhibited in museums and tourist attractions.

5.4. Technology Role

By using 3D printers to form a wide variety of molds for artwork formation. This will provide various options of artwork designs that match people needs and taste.

6. CONCLUSION AND RECOMMENDATIONS

The art world is always expanding, with approximately 125 to 250 million artworks created annually. The new art revolution should start to save the planet from waste, where waste is integrated into artworks. Not only will a new contemporary method of art be generated, but huge economic opportunities will also be created. The invention has a pivotal role in shaping the next generation of contemporary Art and furniture industry. Furthermore, Pieces can be sold and exported and can become part of legislation for decorating cities and districts as well as being launched in specialized Museums of Contemporary art.

Disclaimer
There are no hazardous biological substances involved in the whole project.

Ethical Considerations
No consent or official agreements were needed for this research project, and no human participants were involved in the trial.

Competing interests
The study was conducted and funded at the National Research Centre in Cairo, and no external funding bodies were involved in the whole project.

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