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UNIVERSIDADE Đ COIMBRA

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DECARBONISING MARITIME PORTS: A SYSTEMATIC REVIEW OF THE LITERATURE AND INSIGHTS FOR NEW RESEARCH OPPORTUNITIES

Dissertação no âmbito do mestrado em Engenharia e Gestão Industrial, orientada pelo Professor Doutor Luís Miguel Domingues Fernandes Ferreira e pelo Professor Doutor João Miguel Fonseca Bigotte e apresentada no Departamento de Engenharia Mecânica da Universidade de Coimbra

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Decarbonising Maritime Ports: A Systematic Review of the Literature and Insights for New Research Opportunities

Dissertação apresentada para a obtenção do grau de Mestre em Engenharia e Gestão Industrial

Descarbonização dos Portos Marítimos: Uma Revisão Sistemática da Literatura e Perspetivas sobre Novas Oportunidades de Investigação

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Já educada a imaginação, basta querer, e ela se encarregará de construir os sonhos por si.

Fernando Pessoa.

Aos meus pais, à minha irmã, ao meu irmão e às minhas sobrinhas. À minha restante família e aos meus amigos.

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Começo por agradecer do fundo do meu coração à minha família, com especial ênfase para a minha mãe Filomena, o meu pai Agostinho, a minha irmã Lúcia e o meu irmão Pedro. O vosso apoio incondicional foi o alicerce que me permitiu alcançar este marco na minha jornada académica.

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Sem vocês, nada disto se tinha tornado realidade,

O meu mais sincero obrigado.

Resumo

Com o crescente aumento da preocupação global em torno das alterações climáticas e da sustentabilidade ambiental, os portos marítimos tornaram-se atores cruciais na redução das emissões de gases de efeito de estufa. Este estudo esclarece a natureza multifacetada de conceitos como *net-zero*, estratégias de descarbonização, descarbonização das cadeias de abastecimento e descarbonização dos portos marítimos. A investigação sublinha a urgência da transição para operações com baixas emissões de carbono e neutras em carbono para mitigar os impactos ambientais.

Foi conduzida uma revisão sistemática da literatura para identificar os tópicos de pesquisa relacionados com a descarbonização dos portos, tendo sido analisados um total de 124 artigos. Realizou-se uma análise bibliométrica para obter informações valiosas sobre as tendências predominantes e os trabalhos influentes dentro da literatura selecionada. Posteriormente, efetuou-se uma análise de conteúdo para identificar as geografias mais estudadas, as metodologias utilizadas e as medidas consideradas. Por fim, uma análise de *clusters*, realizada com recurso ao *VOSviewer Software*, permitiu discernir os principais tópicos de pesquisa e a sua estrutura organizacional na literatura. Esta análise revelou informações críticas sobre a relação entre vários temas de pesquisa, enriquecendo ainda mais a nossa compreensão do panorama de investigação.

A revisão sistemática da literatura sublinhou a necessidade de esforços de pesquisa direcionados e iniciativas colaborativas na descarbonização dos portos marítimos. Ficou evidente a complexidade dos esforços de descarbonização, enfatizando a necessidade de soluções específicas, adaptadas às circunstâncias locais. Em conclusão, esta dissertação ilumina o caminho em direção a portos marítimos sustentáveis, ao abordar de forma abrangente os desafios e oportunidades associados à descarbonização. Além disso, destaca o papel crucial de avanços tecnológicos, enquadramentos regulatórios e colaboração entre as partes interessadas na consecução das metas de neutralidade.

Palavras-chave: *Net-Zero*, Descarbonização, Portos Marítimos, Revisão Sistemática da Literatura, *VOSviewer Software*.

Abstract

With the escalating global concern surrounding climate change and environmental sustainability, maritime ports have become pivotal players in reducing greenhouse gas emissions. This study elucidates the multifaceted nature of concepts like net-zero, decarbonisation strategies, supply chain decarbonisation, and seaport decarbonisation. The research underlines the urgency of transitioning towards low-carbon and carbon-neutral operations to mitigate environmental impacts.

A systematic literature review was conducted to identify the research topics about the decarbonisation of ports, and a total of 124 articles were analysed. A bibliometric analysis was conducted to gain valuable insights into the prevailing trends and influential works within the selected literature. Subsequently, a content analysis was performed to identify the most studied geographies, the methodologies used, and the measures considered. A cluster analysis, executed through the *VOSviewer Software*, was employed to discern the primary research topics and their organisational structure within the literature. This analysis unearthed critical insights into the relationship among various research themes, further enhancing our understanding of the research landscape.

The systematic literature review underscored the pressing need for focused research efforts and collaborative initiatives in maritime port decarbonisation. It laid bare the complexity of decarbonisation endeavours, emphasising the necessity for context-specific, tailored solutions. In conclusion, this dissertation illuminates the path towards sustainable maritime ports by comprehensively addressing the challenges and opportunities associated with decarbonisation. Moreover, it underscores the pivotal role of technological advancements, regulatory frameworks, and stakeholder collaboration in achieving neutrality targets.

Keywords Net-Zero, Decarbonisation, Maritime Ports, Systematic Literature Review, *VOSviewer Software*.

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ACRONYMS AND ABBREVIATIONS

3PL – Third Party Logistics

AESs – All-Electric Ships

AFIR – Alternative Fuel Infrastructure Regulation

AGVs – Automated Guided Vehicles

AI – Artificial Intelligence

CCU/CCS/CCUS – Carbon Capture and Utilization and Sequestration Programs

CFA – Carbon Footprint Analysis

CO2 – Carbon Dioxide

CMF – Clean Marine Fuels

DEM – Departamento de Engenharia Mecânica/ Department of Mechanical Engineering

EDI – Electronic Data Interchange

EGD – European Green Deal

EMP – Energy Management Plan

ESS – Energy Storage Systems

EU – European Union

FCTUC – Faculdade de Ciências e Tecnologia da Universidade de Coimbra/ Faculty of Sciences and Technology of the University of Coimbra

GRI – Global Reporting Initiative

GHG – Greenhouse Gas

LCA – Life Cycle Analysis

LCOM – Low-Carbon Operations Management

LCSCM – Low-Carbon Supply Chain Management

LNG – Liquefied Natural Gas

IAPH – International Association of Ports and Harbors

ICT – Information and Communication Technologies

IMO – International Maritime Organization

JIT – Just-in-Time

KPIs – Key Performance Indicators

MEGI – Master's in Industrial and Management Engineering

MG – Microgrids

NGOs – Non-Governmental Organisations

NZE – Net-Zero, Zero-Carbon Economy, or Net-Zero Economy

PCS – Port Community System

PM – Particulate Matter

PRISMA – Preferred Reporting Items for Systematic Reviews and Meta-Analyses

PV – Photovoltaic

R&D – Research and Development

RE – Renewable Energies

RFID – Radio Frequency Identification

ROI – Return on Investments

RQs – Research Questions

SCM – Supply Chain Management

SDG – Sustainable Development Goals

SG – Smart grids

SLM – Smart Load Management

SLR – Systematic Literature Review

SWH – Solar Water Heating

TAS – Truck Appointment System

TAT – Turnaround Time

TBL – Triple Bottom Line

TMF – Traffic Mitigation Fee

UAV – Unmanned Aerial Vehicle

UC – Universidade de Coimbra/ University of Coimbra

UN – United Nations

VSR – Vessel Speed Reduction

VTM – Vessel Traffic Management

WPSP – World Ports Sustainability Program

1. INTRODUCTION

The current document emerges within the scope of the dissertation aimed at attaining the Master's Degree in Industrial and Management Engineering (MEGI) by the Department of Mechanical Engineering (DEM) from the Faculty of Science and Technology at the University of Coimbra (FCTUC). This chapter introduces the conducted work and the objectives to be achieved. Moreover, the employed methodology and the structure of the dissertation are also presented.

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1.1. Background

The challenges resulting from climate change are multidimensional and include various elements, whether from social, economic, or environmental components (de Sousa Jabbour et al., 2019; Mishra et al., 2022). Being climate change an overall change of weather or environmental conditions in a region or location, a response to climate change needs to be an international movement toward decarbonisation away from fossil fuels and ultimately an environmental sustainability achievement (Alzahrani et al., 2021; Howell et al., 2017).

A great example can be found in the European Union regulations and legislations, the Alternative Fuel Infrastructure Regulation (AFIR), one of the most recent ones on the topic of recharging or refuelling alternative solutions in the transport sector (road vehicles, ships, among others) (Council of the European Union, 2023). The United States Administration is also trying to be an example through the Federal Sustainability Plan, which includes the Federal Supplier Climate Risks and Resilience Rule, requiring more disclosure on emissions, identifying climate-related risks, and strengthening the federal supply chain resilience (White House, 2022).

Supply chain management (SCM) is a complex process, and the challenges of climate change increase this complexity, forcing changes in the traditional functions of supply chains because of pressure from political and legal bodies, other industries, or the final consumer (Das and Jharkharia, 2018; Mishra et al., 2022). The consequences of climate change are becoming increasingly frequent and could result in a global catastrophe (Kemp et al., 2022; Rosen and Guenther, 2015). They are making the existing stakeholders more aware of organisations' individual behaviours and supply chains (Das and Jharkharia, 2018).

At the rate of climate change, actions to achieve Sustainable Development Goals (SDG) are increasingly needed and urgently at the most varied possible levels - individual, organisational, or political (Buettner, 2022). Global carbon neutrality by 2050 is considered by the United Nations (UN) one of the most urgent missions to achieve peace, protection, and partnerships across the planet and among all people (Guterres, 2020; Mishra et al., 2022). The European Union (EU) intends to achieve net-zero by 2050, aiming at reducing 80% to 95% of the GHG emissions (Alzahrani et al., 2021; European Commission, 2023).

Unforeseen situations, such as armed conflicts, political and financial crises, or increasingly extreme weather events, call attention to the urgency of desirable supply chain abilities of organisations and to the need for agile and flexible strategies to deal with the increasingly complex and uncertain external environment (Durugbo and Al-Balushi, 2022; Schoemaker et al., 2018). Disruptive events urge traditional human activities to transition to higher technological and automated levels (Zhou et al., 2022).

Sustainable development can be defined as the practice of business activities and strategies that satisfy the needs of an organisation while enhancing and protecting resources needed in the future (Brundtland and Khalid, 1987). Society acknowledges the impacts climate change has had on the planet, and the global industry plays a significant role in reducing emissions and changing the economic landscape (Kumar et al., 2023). Considering that business leaders expect to increase firms' investments in sustainability (Gartner, 2022) and the influential pressure from stakeholders in carbon neutrality commitment, the main objective of a firm's strategic management focused on sustainability should be to achieve net-zero (Mishra et al., 2022; Zhang et al., 2022).

The role to be played by organisations when defining decarbonisation strategies is to induce changes in consumption and production and consequently contribute to the management of supply chains in a "greener" way (Das and Jharkharia, 2018; de Sousa Jabbour et al., 2019). Many leading organisations have started to define neutrality operations and SCM strategies, which include sharing these strategies, community energy management, mitigation of greenhouse gas (GHG) emissions, and pollution control (Das and Jharkharia, 2018; Jaccard et al., 1997; Nakićenović, 1996; Zhang et al., 2022).

The initiatives described above include a set of activities - increasing energy efficiency, recycling, and promoting efficient materials and products - which could be implemented by Low Carbon Supply Chain Management (LCSCM) as a first step for a decarbonisation strategy that fully reduces emissions to a net-zero level (Das and Jharkharia, 2018; de Sousa Jabbour et al., 2019).

1.2. Motivation

The result of inefficiency in supply chain management is more GHG emissions (Mishra et al., 2022) and, consequently, a more negative environmental impact. Freight transport is the main contributor to increased emissions in supply chains (Singh et al., 2022). Despite the well-established reputation of maritime transport as one of the most efficient modes of transport, there is a pressing need to recognise the pivotal role of seaports in achieving net-zero objectives (Alzahrani et al., 2021; Styhre et al., 2017).

Moreover, the escalating concerns surrounding the unprecedented temperatures recorded across the Earth's oceanic expanse, culminating in marine heatwaves, serve as a stark reminder of the urgency that must resonate with both ports and their stakeholders (Hoegh-Guldberg and Bruno, 2010). As we potentially face an impending El Niño period, the looming prospect of intensified extreme weather events and global heat milestones further underscores the critical importance of these considerations (Readfearn, 2023).

The increasing significance of environmental awareness within the academic, business, and political communities, as well as the general public, provided significant support for the motivation behind undertaking this study (Sarkis et al., 2011). Within the Portuguese context, PETROGAL, a fossil fuel refinery located near Portugal's largest maritime port, the Port of Sines, is the nation's most prominent polluter. It emits nearly one million tons more emissions than the second-ranking entity on the pollution scale (Soares, 2023). Consequently, comprehending the measures and practices that seaports can swiftly implement becomes urgent and vital. These efforts are crucial for the ports' sustainability, the well-being of their neighbouring stakeholders and the broader global environment.

Through the literature analysis, which will be referenced later in this document, the crucial role of maritime ports in attaining global neutrality goals becomes unequivocal. However, based on the conducted analysis, the absence of identification of key research clusters focused on decarbonising maritime ports has been observed. This distinctive aspect underscores the unique contribution of this study.

Henceforth, the primary objective of this dissertation is to discern the principal research topics within maritime port decarbonisation and to pinpoint the existing research gaps.

1.3. Research Methodology

The research methodology aims to address how the project was conceived and what its foundation is. It is a plan to transform research questions into a research project. The framework proposed by Saunders et al. (2019), known as the "research onion", was employed to achieve this. The research philosophy and approach will influence how the objectives and research questions are addressed. Consequently, the research questions influence the selection of the research strategy, the techniques for data collection and analysis, and the timeline for conducting the research project. In *Figure 1.1.* it is possible to see the adaptation of the "research onion" to the present work.

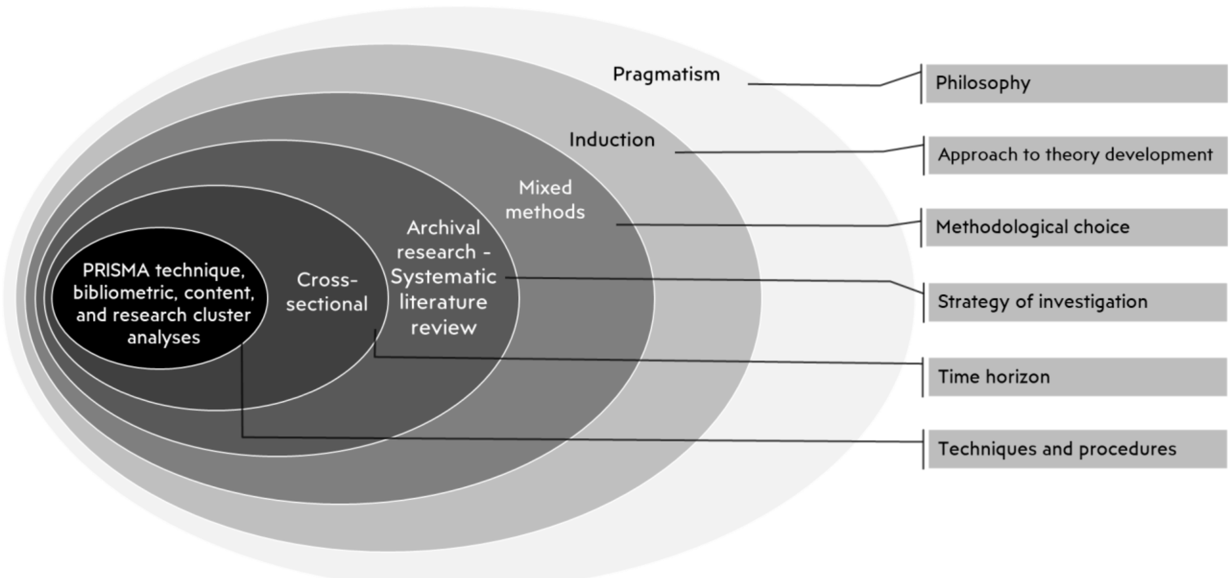

Figure 1.1. Research Onion (Adapted from Saunders et al. (2019)).

The research philosophy reflects the investigator's perspective on reality. As the foundational layer, it influences the entire research approach adopted throughout the project. In this context, the chosen philosophy was pragmatism once it implies an interpretative vision about the topic that is the focus of the writing. Given that this research aims to aggregate other work in the literature to infer future directions for investigation in maritime port decarbonisation, the research approach is inductive.

This exploratory study aimed to comprehend maritime port decarbonisation research's status and emerging perspectives. By adopting an archival research strategy, more specifically, a systematic literature review strategy, qualitative methods were used predominantly to analyse the content of the gathered documents. However, a quantitative method was also employed to analyse the collected papers and articles when conducting the bibliometric analysis.

A cross-sectional time horizon is well-suited to the nature of the study, as it facilitates the presentation of a comprehensive, contemporary, and systematic analysis of the existing research landscape concerning maritime port decarbonisation. This approach enables the capture of both the breadth and evolution of research findings, thereby enhancing the overall comprehension of the field. A systematic literature review was initiated to execute the research project, followed by subsequent bibliometric, content, and principal research cluster analyses. These techniques were employed to attain a more profound understanding of how ports can decarbonise.

1.4. Document Outline

The document was divided into 4 main chapters. The first and current chapter contextualises the focal theme and its motivation, outlines the primary objectives, and outlines the document's structure. The second chapter provides a theoretical foundation covering net-zero aspirations, decarbonisation strategies, and supply chain decarbonisation. This groundwork is essential for a comprehensive grasp of the dissertation's aims.

In the third chapter, a systematic literature review takes precedence. Serving as the core segment of the dissertation, it is also the most extensive, encompassing the presentation of pivotal concepts concerning seaport decarbonisation. Within this chapter, the research questions addressed in this study are elucidated, crucial decarbonisation measures for maritime ports are identified, and the methodology employed is designed and executed. Furthermore, the systematic literature review outcomes are scrutinised, leading to an in-depth discussion of the results. This discussion illuminates prospective avenues for each identified research cluster.

Chapter 4 culminates by presenting the derived conclusions from this study, offering a brief overview of the achieved results, discussing primary findings, outlining limitations, and suggesting potential future research directions.

2. THEORETICAL BACKGROUND

2.1. Net-Zero

One of the main concepts when talking about decarbonisation strategies is net-zero. The net-zero, zero-carbon economy, or net-zero economy (NZE) means there should be a balance between the GHG emissions produced and the amount withdrawn from the atmosphere (Mishra et al., 2022). After implementing practices and techniques for direct emissions reduction, if there are remaining emissions, these must be resolved by another type of well-regulated program (Fankhauser et al., 2022). A net zero economy will benefit the world in achieving sustainable development if there is always a balance between economic, environmental, and social aspects. (Mishra et al., 2022; Singh et al., 2022).

Net-zero means that not only the resolution of large emitters should be promoted, but techniques to solve the total emissions need to be found and all other factors that influence human health and the conservation of the various natural resources (Buettner, 2022; Mishra et al., 2022). Throughout the decision-making process, to help strategic management monitor the sustainability and decarbonisation objectives and effectiveness in the pursuit of net-zero, Sustainability Key Performance Indicators (KPI) must be defined (Hristov and Chirico, 2019). Commitment to sustainability initiatives requires all functions and hierarchical levels of a company to be held accountable, especially executive leadership positions (Gong et al., 2018).

Since climate change is a global problem, the main challenges to achieve net-zero are the need for cohesive actions, regulations and policies shared by multiple nations in favour of the environment, if possible, the very restructuring of the traditional business models of companies and the development of specific technical knowledge (Mishra et al., 2022). Decarbonisation strategies with a net-zero objective are highly transformative and demanding - they require an 80% reduction in fossil fuels consumption - and it is, therefore, possible that some strategies start with less demanding targets - low-carbon implies a 20% reduction in fossil fuel consumption - offsetting excess emissions (Mishra et al., 2022; Seto et al., 2021). Offset strategies, like carbon capture and sequestration programs and their utilisation, balance remaining emissions and reduce companies' carbon footprint (Xu et al., 2023).

In opposition to net-zero, some organisations seek to implement natural zero or actual zero (Buettner, 2022; Seto et al., 2021). Natural zero is a much more demanding target, consisting of offset strategies' non-consideration and exclusion. This way, organisational processes are developed to balance emissions without resorting to compensation programs, such as reforestation, donations to non-governmental organisations (NGOs), or offset strategies (Mishra et al., 2022; Seto et al., 2021).

Additional measures, like offset strategies, can hide the emergency of reducing direct emissions, and the long-term net-zero target can be compromised (Buettner, 2022). Immediate emissions reduction can be achieved by consuming energy from renewable sources or implementing a waste management framework, like 3Rs or 7Rs (Mishra et al., 2022; Singh et al., 2022). Although the actual zero may be impossible in some industries, it should be sought, particularly in transport, energy production and accommodation (Seto et al., 2021).

The increased reliance on non-fossil fuels and digital technologies can help to combat climate change, reduce GHG emissions, respond to pollution problems and, consequently, leverage net-zero strategies (Parkinson et al., 2019). Digitalisation is critical to support energy transition, and a digital culture to address the challenges of decarbonisation is needed (MIT Technology Review, 2023). Information and communication technologies (ICT) positively and significantly affect environmental sustainability and digitalisation through virtualisation, data monitoring collection, and enhanced connectivity can promote carbon emission reductions in energy, transportation, and smart manufacturing sectors (Bolton et al., 2022; Gouvea et al., 2018).

The carbon, climate, and environmental neutrality targets often need clarification regarding net-zero and emissions reductions. To clarify, according to Stefan and Buettner (2020), carbon neutrality only includes CO2 emissions. "Carbon neutrality +" is used when considering CO2 emissions and methane (CH4) emissions (Buettner, 2022). Climate neutrality includes "carbon neutrality +" and all other GHG - N2O, HFC, and PFC, among others - (Stefan and Buettner, 2020), being 65% of the total GHG emissions CO2 emissions (Lee et al., 2017). Environmental neutrality considers the gases included in the climate neutrality target and all other gases and substances (e.g., particulates or particulate matter (PM)) that impact the environment and the health of living beings (Stefan and Buettner, 2020). In *Figure 2.1.* it is possible to see a scheme with different levels of neutrality.

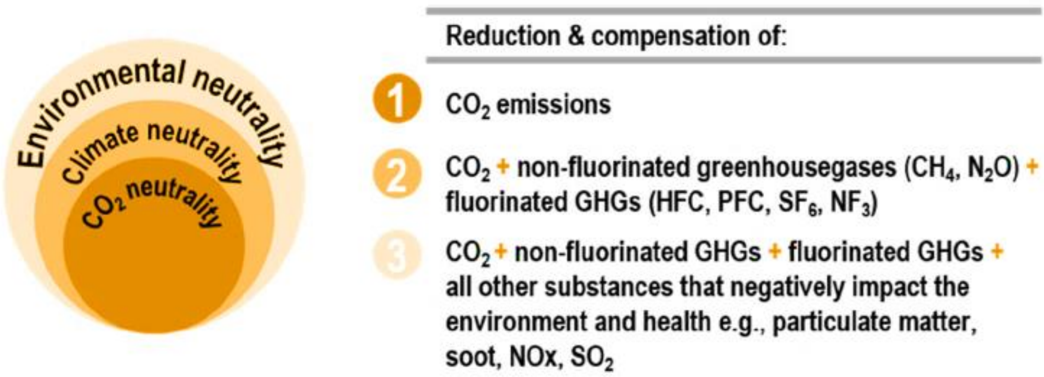

Figure 2.1. Definition of the different types of neutrality (Source: (Buettner, 2022)).

Although fundamental practices that lead to NZE lack global recognition and how to achieve these targets is somewhat abstract, many countries, including the European Union countries, have already committed to climate neutrality by 2050 or earlier (Buettner, 2022; Singh et al., 2022).

Institutional instruments focused on low-carbon technologies and strategies, such as the European Green Deal (EGD) (Sharma et al., 2022), the Sustainable Product Initiative (Buettner, 2022), or the Inflation Reduction Act (McKinsey & Company., 2022) can be efficient initiatives for mitigating emissions, meeting national and international targets and laws, achieving green and sustainable economies, and protecting life on Earth (Alzahrani et al., 2021; Mishra et al., 2022; Watari et al., 2021). In essence, the practical implications of NZE are known on a global scale, but sustainable growth related to NZE needs to be clearly defined by organisations.

2.2. Decarbonisation Strategy

Economic, social, and environmental, the Triple Bottom Line (TBL) sustainability dimensions have gained growing importance for researchers, especially firms trying to define differentiated strategies and innovative competitive advantage (Rosati and Faria, 2019; Sharma et al., 2022). In a sustainability context, knowledge-creating resources, technological equipment, tools, and techniques are considered an opportunity for growth, compliance with regulations, maintenance of a green supply chain, and capability building (Singh et al., 2022).

In their study, Singh et al. (2022) identified that most industries, such as fast fashion, electronics, construction, automotive, and freight services, must adopt a decarbonisation strategy for their future. Despite being extremely relevant, decarbonisation appears underdeveloped in the literature as an enabler of sustainable growth (Mishra et al., 2022; Zhang et al., 2022).

Decarbonisation can be acknowledged as the process to achieve a low-carbon economy (Barros et al., 2014). Kılkış and Kılkış (2018) stated that a framework to develop sustainable industrial practices to create a balance between the amount of GHG emissions and a targeted reduction is needed. According to de Sousa Jabbour et al. (2019), businesses are pivotal to decarbonisation. Decarbonisation is considered an enabling measure to achieve the net-zero goal, or the carbon neutrality target, being much more clear-cut and tangible than a simple low-carbon commitment (Seto et al., 2021; Zhang et al., 2022).

Since CO2 has the most warming ability when trapped within the atmosphere, the most abundance, and a long atmospheric lifetime, this gas should be the focus of decarbonisation strategies (Styhre et al., 2017; UNCTAD, 2021; Williamsson et al., 2022). A decarbonisation strategy can also focus on reducing the burden on the power sector with a set of mitigation methods, like integration of energy efficiency use, energy savings, and investments in renewable energy (Alamoush et al., 2020; Styhre et al., 2017). Regarding fuels, a GHG emission potential reduction is only possible by primarily developing a complete life cycle analysis (Gilbert et al., 2018). Decarbonisation can be related to an electrification strategy using renewable sources and a commitment to emission reduction targets (Zhou et al., 2022).

A decarbonisation strategy can be interpreted and achieved in many ways. However, Buettner (2022) elaborated a set of steps for defining an “ideal” decarbonisation strategy for the industrial sector. According to this author, the preliminary steps for the strategic considerations should be to design the guidelines that a company’s executive leadership must follow.

The approach to developing decarbonisation strategies should initially focus on supply chain issues such as supplier selection, emission scopes, GHG emissions, low carbon emissions and operations, logistical challenges, and eco-innovation (Mishra et al., 2022). In other words, supply chain decarbonisation includes the various decisions and trade-offs of Low Carbon Supply Chain Management (Das and Jharkharia, 2018). After answering the design issues, Buettner (2022) defines that it is possible to proceed to the following steps, which include: “general measures”, “specific measures”, “economic viability”, and “dynamic adjustment to changing environments”.

In those following steps, it is included to make a technological leap in achieving net-zero (Buettner, 2022). Industry 4.0 opens new opportunities for implementing decarbonisation strategies through tools that increase productivity with almost zero waste (Bag and Pretorius, 2022). Automation, digitalisation, and electrification must play a role in sustainable supply chains (Mishra et al., 2022; Zhou et al., 2022). For example, electric equipment thrives in digitised and automated environments (Zhou et al., 2022).

Many countries have started to move towards neutrality targets because of the increased global warming awareness and the importance of emissions reduction plans (Alzahrani et al., 2021). With the increasing demand for the adoption of sustainable practices by multinational companies and their supply partners, the need for net-zero carbon supply chain practices, like the decarbonisation of supply chains, has become critical (Vimal et al., 2022; Zhang et al., 2022). A decarbonisation strategy in the global supply chain context is necessary to manage complexity while adopting a sustainable SCM framework (Singh et al., 2022).

Considering that over 90% of an organisation's GHG emissions are a consequence of supply chain activities, according to the United States Environmental Protection Agency, organisations should consider network resulting emissions using shared information (Plambeck, 2012; Vimal et al., 2022). To engage multi-tier suppliers and customers, firms need a supply chain learning approach for their decarbonisation targets (Gong et al., 2018).

2.3. Decarbonisation of Supply Chains

The supply chain is the network of all participants in producing and delivering a product or service to consumers (Sanders, 2020). The attainment of sustainability has been recognised in supply chain management (SCM) as a highly significant subject (Singh et al., 2022). SCM manages product, information, or cash flows in the supply chain (Sanders, 2020). A supply chain might merge conflicting nodes, making it challenging to meet multiple targets and flows simultaneously, like sustainability goals and practices (Vimal et al., 2022). Considering that supply chain activities have, on average, 5.5 times higher emissions compared to direct operations emissions, according to the CDP Global Supply Chain Report from 2019/2020, pushbacks in strategic partnerships, like the lack of coordination, seems a much more serious problem, considering the urgency of transformative actions in a collaborative way (Zhang et al., 2022).

In times of crisis, supply chain managers should develop crisis-induced strategies instead of conventional ones focusing on competitive advantages (Durugbo and Al-Balushi, 2022). Nevertheless, no matter what type of strategy, the social, environmental and profitability objectives must be attended to develop a sustainable supply chain (Gurzawska, 2020). Integrating environmentally sustainable practices is the core principle of green SCM, focused on positively impacting the climate, such as reducing GHG emissions (Singh et al., 2022; Zaid et al., 2018).

Global trading has dramatically changed recently (Zhou et al., 2022). Even with low carbon emissions during direct operations, the total emissions can be multiplied by 10 times by suppliers, which increases the upstream supply chain carbon footprint, making the decarbonisation process for all supply chain members a necessity (Bataille, 2020; Singh et al., 2022). Being decarbonisation in supply chains referred to as a critical practice for the development of a circular economy and the development of supply chains, adoption strategies are required (Allen et al., 2021; Korhonen et al., 2018; Labanca et al., 2020).

Xu et al. (2023) define SCM decarbonisation as a process of pursuing low- or zero-carbon supply chain management (LCSCM) and implementing LCSCM solutions on an organisation's agenda has already been receiving some attention. Zhang et al. (2022) identified the six building blocks in a multi-tier supply chain required for carbon neutrality achievement: investments in decarbonisation, supply chain leadership, supply chain collaboration, supply chain learning, supply chain digitisation, and supply chain visibility.

Achieving NZE depends on adopting technologies (Sundarakani et al., 2021). Technology-based SCM decarbonisation presents as a practice for the integration of digital and physical technologies that characterise Industry 4.0 technologies and decarbonisation technologies (Alamoush et al., 2020; Sundarakani et al., 2021; Xu et al., 2023).

2.3.1. Low Carbon Supply Chain Management

Cleaner and low-carbon economies are increasingly widespread thanks to action by the United Nations and the SDG (Mishra et al., 2022). LCSCM is an essential part of these economies as it is the mechanism to integrate CO2, or GHG emissions, as both constraints and objectives of supply chain design and planning. LCSCM has two perspectives: the first focuses on the functional and operational aspects of supply chain management, like low-carbon production; the second is concerned with conceptualising and calculating the carbon footprint (CF) of the supply chain for carbon efficiency improvement

(Das and Jharkharia, 2018; Xu et al., 2023). *Figure 2.2.* schematises the various categories of LCSCM.

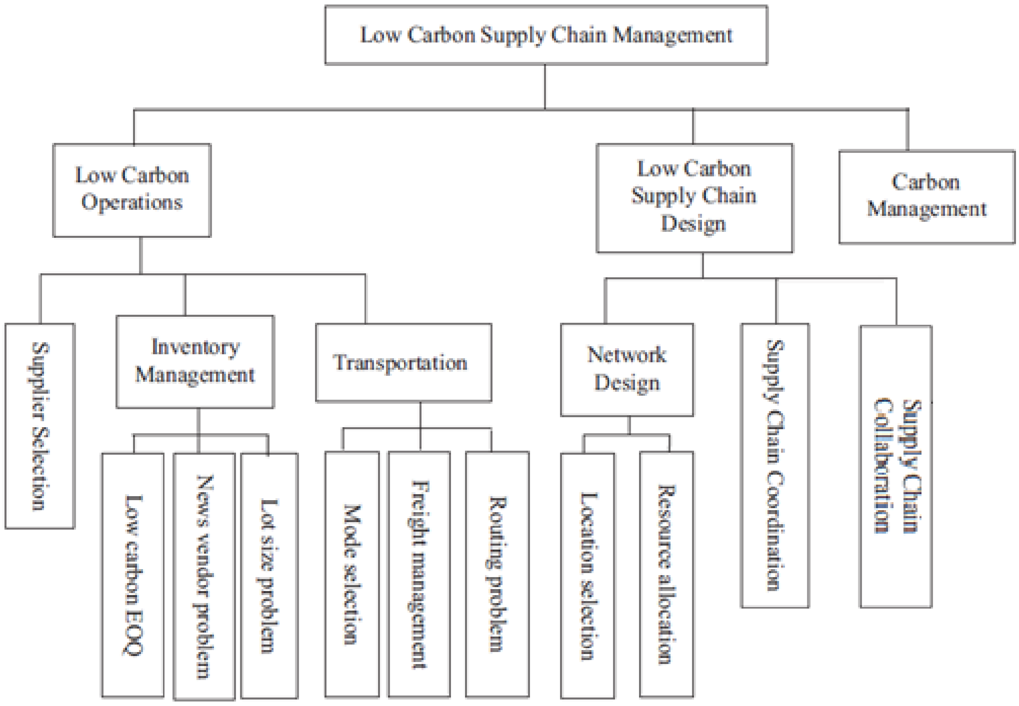

Figure 2.2. LCSCM categories (Adapted from Das and Jharkharia (2018)).

The main objective of LCSCM is to reduce all supply chain emissions without compromising the organisation's economic interests, which requires stakeholders' involvement in all value chains (Kumar et al., 2023). Generally, investors are pessimistic about the financial outcomes of emissions reduction initiatives despite the positive relationship between return on sales and emission reduction (Lewandowski, 2017; Zhang et al., 2022). Therefore, there should be a set of trade-offs between the economic and environmental objectives of supply chains, which increases the complexity of the decision-making process in the supply chain (Das and Jharkharia, 2018).

Lack of development in the logistics industry, insufficient efficient infrastructure, uncertainty in resource availability, and fluctuations in costs and public opinion create variability and cause disruption in implementing net-zero in supply chains (Gupta and Garg, 2020). However, according to de Sousa Jabbour et al. (2019), and corroborated by Zhang et al. (2022), pressures from different supply chain stakeholders are essential for low-carbon operations adoption as well as support from top management, and a well-defined focal firm's supply chain leadership. Proper supply chain leadership creates a cascading effect on a multi-tier commitment network to a neutrality target (Lee et al., 2014).

2.3.1.1. Low Carbon Operations Management

Low Carbon Operations Management (LCOM) is one of the components of LCSCM. It is defined as integrating carbon efficiency into the planning, execution and control of all processes and activities of an organisation to minimise carbon emissions and energy consumption (Böttcher and Müller, 2015; Du et al., 2015). LCOM is the ideal practice for all industrial operations in all regions from an environmental point of view, and it is seen as a possible framework to achieve the industry goals of lower GHG emissions and higher business sustainability (Akadiri et al., 2020; Kedia, 2016).

Managing carbon emissions has become one of the main challenges in organisational decision-making (Gasbarro and Pinkse, 2016). For example, the excessive logistical operations or the necessity for green policies in SCM scope requires strengthening carbon emission management (Singh et al., 2022). LCOM can make managing carbon emissions a reality (de Sousa Jabbour et al., 2019). According to de Sousa Jabbour et al. (2019), within low-carbon operations, one can consider 3 main areas:

- **Low Carbon Products:** This depends on the product design, which will consequently influence the selected suppliers. According to Das and Jharkharia (2018), supplier selection is a problem dependent on environmental and commercial variables, which affect the profitability of companies, the quality of products and services, and consumer satisfaction.
- **Low Carbon Production and Processes:** Reflects on developing energy efficiency projects, renewable energy sources, high-tech waste management and carrying out a carbon inventory (Das and Jharkharia, 2018; Melander and Pazirandeh, 2019).
- **Low Carbon Logistics:** Includes all transport-related activities and decisions – transportation mode, fleet sizing, and routing issues. Successful LCOM measures are associated with robust supply chain logistic arrangements (Kumar et al., 2023). According to Das and Jharkharia (2018), there is a trade-off to be made between carbon emissions and operational performance. For example, decreasing total GHG emissions can be achieved

by consolidating demand and load, using heterogeneous and varied transport modes, or participating in collaborative distribution networks and ecosystems, with the risk of increasing lead time variability and total transportation cost (Boschian et al., 2013).

One of Kumar et al. (2023) conclusions is the need for specific laws and regulations to motivate the industry to implement LCOM and develop cohesive NZE policy mechanisms.

2.3.1.2. Low Carbon Supply Chain Design

The need to focus on solutions collectively results from the sustainability issues affecting every firm in a supply chain and the increased attention to ecological consciousness in the supply chain (Kumar et al., 2023; Singh et al., 2022). According to Das and Jharkharia (2018), low-carbon supply chain design includes supply network design decisions and decisions for supply chain collaboration and coordination strategies:

- **Supply Chain Design:** It aims to make decisions - location of facilities and allocated resources - for the optimal supply chain configuration that minimises total cost and carbon emissions. An eco-efficient design can be developed where GHG impact is felt in conjunction with demand, supply, responsiveness, and supply chain capacity.
- **Supply Chain Coordination:** Mechanism in which different companies define strategies - revenue sharing, quantity discounts, resetting the retail price and the final selling price, making order quantity agreements - to maximise total profits. In LCSCM, supply chain coordination differs from the usual if one considers the restriction of carbon emissions (Ji et al., 2017).
- **Supply Chain Collaboration:** This strategy is currently considered for inventory allocation, last-mile delivery, product development, and mainly for minimising GHG emissions. Therefore, organisational performance factors and environmental metrics must be considered in the decision-making for eventual partnerships and supplier selection - characteristics, profile, and technological and CO2 management competencies (Theißen and Spinler, 2014). Technology is essential to systematically managing effective decarbonising collaborations (Xu et al., 2023).

The complexity of these practices, the difficulty of managing them, the cultural and linguistic differences, the obstacles in taking advantage of opportunities in a quick and agile way, the risks of rupture, or the financial risks are just some examples of the impediments to the success of the decisions presented (Ashby, 2016). Still, Third Party Logistics (3PL) is revealed to have an essential role in integrating Low Carbon Supply Chains (Liu et al., 2020; Mishra et al., 2022). The literature highlights the need for cooperation among all SCM parties (working together as equal partners) to reduce costs and GHG emissions (Kotzab et al., 2019; Xu et al., 2023).

2.3.1.3. Carbon Management

Carbon emission management is the most accepted measure to tackle carbon emissions, both at macro and micro levels, being a significant subject in decision-making (Kumar et al., 2023). However, despite all the supply chain management standards, strategies, and systems, a clear set of carbon management practices for carbon efficiency improvement is still needed (Xu et al., 2023).

The leading practices are life cycle analysis (LCA) (Gilbert et al., 2018; Parkinson et al., 2019) and carbon footprint analysis (CFA) (Alderson et al., 2012; Clarke et al., 2017) at the product level, company level, and global supply chain level (Das and Jharkharia, 2018). Briefly, for the calculation of carbon footprint, there are already some standards (ISO 14067, PAS 2050) and some literature available, but it is possible to go even further in the CFA at the product level (Benjaafar et al., 2013; Sundarakani et al., 2010).

Scopes analysis of carbon emissions is essential when calculating a carbon footprint (Buettner, 2022; Das and Jharkharia, 2018). A pre-condition for proper GHG emissions estimation is supply chain visibility, which means supply chain leaders need to account for all scopes of emissions (Zhang et al., 2022). According to Ranganathan and Bhatia (2004), carbon and GHG emissions can be classified according to 3 scopes (*Figure 2.3.*):

- **Scope 1:** Includes all carbon and other GHG emissions directly associated with a company and its activities, such as emissions from company vehicles or facilities, which are essential to reduce (Kumar et al., 2023).
- **Scope 2:** Includes all indirect emissions from a company's activities, such as purchasing electricity.

- **Scope 3:** Includes all other indirect emissions not included in the previous categories. Some examples include purchasing materials and services, business and employee travel, upstream transportation and distribution, and end-of-life treatment.

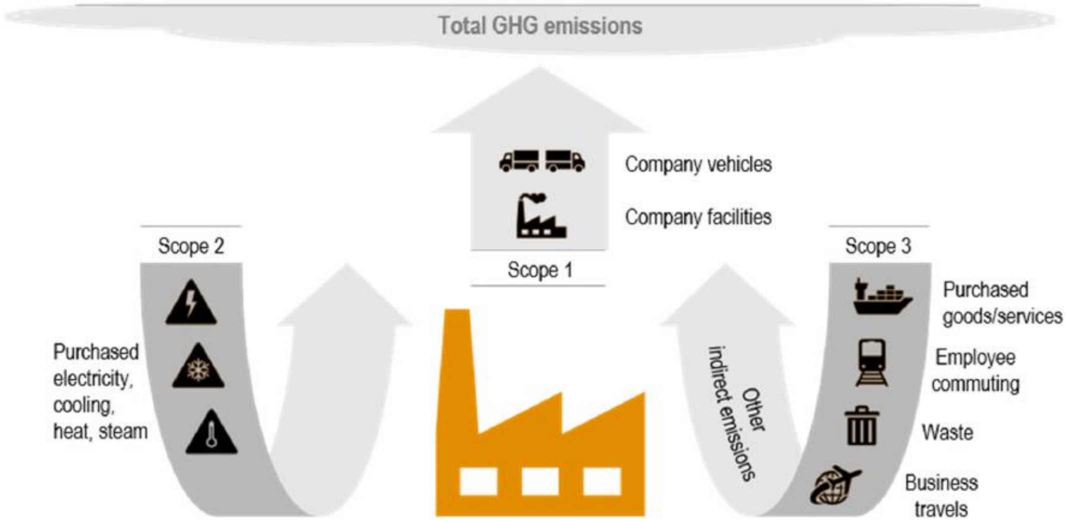

Figure 2.3. Classification of carbon and GHG emissions scopes (Source: (Buettner, 2022)).

According to Buettner (2022), the reduction of Scope 2 emissions is the easiest to achieve, as it essentially requires optimising the contract with the company's energy suppliers, which justifies the fact that most companies initially act on emissions related to energy supply. Next, Scope 1 emissions follow, as the company directly controls its activities. Finally, companies focus on Scope 3 since emissions from this scope are the most complex to reduce and address. Tackling Scope 3 emissions presents an additional layer of complexity that requires collaborative work with customers, supply networks, and industry groups (McKinsey & Company, 2021).

2.3.2. Drivers and Barriers

Decarbonising efforts are a priority and can constitute a structural change for developing sustainable organisational processes to attain NZE (Singh et al., 2022; Stern & Valero, 2021). However, the need for active participation in developing green SCM and large-scale production to meet the market's demands is a duality that faces difficulties implementing sustainable practices (Munten et al., 2021; Singh et al., 2022).

Being the SCM a complex process, the commitment to neutrality targets will face several barriers (Labanca et al., 2020). For Kumar et al. (2023), barriers are any situation, problem, or difficulty, perceived or actual, stopping a manager from planning and implementing measures. From Kumar et al. (2023) study, the priority rank of barriers is economic, infrastructure, operational, political, market, organisational governance, and environmental.

According to Zhang et al. (2022), customer demand and compliance with business and social norms are the most important external drivers, while sustainable business value and long-term economic benefits are relevant endogenous drivers. Based on the literature analysed, *Table 2.1.* was developed to summarise the main drivers and barriers to the decarbonisation of supply chains and the achievement of net-zero targets.

Table 2.1. Main drivers and barriers to the decarbonisation of supply chains.

	Description	***Sources***
Drivers	**Economic benefits:** The potential return on investments (ROI) from the emissions reduction projects should be proven to influence changes to more sustainable operations. Economic growth can be achieved by recycling or reusing materials/equipment/resources.	(Gurzawska, 2020; Singh et al., 2022; Sundarakani et al., 2021; Zhang et al., 2022)
	Regulatory pressures: Overseas customers from strong economies can influence national governments to strengthen laws and develop incentives to reduce the carbon footprint in supply chains and support cleaner production systems.	(Gurzawska, 2020; Singh et al., 2022; Zaid et al., 2018; Zhang et al., 2022)
	Social-environmental consciousness: Managers' solid environmental values, combined with the need to prove companies' "legitimacy" to customers, shareholders, and society, will generally force businesses to make neutrality commitments.	(Gurzawska, 2020; Singh et al., 2022; Zaid et al., 2018; Zhang et al., 2022)
	Quality focus: Organisations trying to reduce their carbon footprints will naturally develop products with higher lifespans, empowered workforces, and sustainable business models.	(Gong et al., 2018; Singh et al., 2022; Sundarakani et al., 2010; Zaid et al., 2018; Zhang et al., 2022)
Barriers	**Economic challenges:** This is the main obstacle to the adoption of LCSCM and achievement of NZE, as well as the most influential barrier in the decision-making process. Some causes of the economic challenges are the need for more private funds, high initial costs for implementing decarbonisation measures and technologies, low credit rating, or lack of awareness in some sectors.	(Das & Jharkharia, 2018; de Sousa Jabbour et al., 2019; Durugbo & Al-Balushi, 2022; Kumar et al., 2023; Mishra et

		al., 2022; Singh et al., 2022)
	Lack of operational/governance infrastructures: Management practices transformation, changes in energy sources, fleet electrification, and development of new capabilities are some examples of requirements for net-zero achievement that face severe resistance to change. That can only be overcome with investments in "green" training, R&D activities, voluntarily disclosing, and cooperation between organisations for effective planning and implementation. Efficient operational systems, by decarbonisation technologies and lean techniques applications, can allow net-zero emissions.	(Ball & Lunt, 2020; Gasbarro & Pinkse, 2016; Gong et al., 2018; Kumar et al., 2023; Mishra et al., 2022; Plambeck, 2012; Singh et al., 2022; Vimal et al., 2022)
	Policy and regulatory hindrances: Political and legal stability are essential to supporting the economic neutrality targets. The lack of political commitment to the SDG is the most influential political barrier. Long-term contracts and institutions to train people on the decarbonisation themes would promote sustainable and green SCM practices.	(Durugbo & Al-Balushi, 2022; Gasbarro & Pinkse, 2016; Kumar et al., 2023; Seto et al., 2021; Singh et al., 2022)
	Market-based obstacles: Knowing stakeholders' needs and expectations can help organisations make strategic decisions. The lack of communication and information about the specific stakeholder's roles will reduce the chances of successful net-zero achievement. The uncertainty caused by the general market, but mainly driven by competition, may put projects on hold.	(Das & Jharkharia, 2018; Kumar et al., 2023; Singh et al., 2022; Vimal et al., 2022)

2.4. Summary

Across the globe, the need for NZE, at both macro and micro levels, is evident (Kumar et al., 2023). So, most organisations have been taking steps to achieve neutrality targets through decarbonisation roadmaps (Buettner, 2022; Mishra et al., 2022).

Factors such as emission control taxes and policies, environmental management standards or carbon-auditing processes and pricing, environmental regulations awareness, and incentives to cover a firm's economic costs when adopting cleaner energy sources are examples of long-term programmes to be addressed by organisations to achieve climate neutrality targets (Kumar et al., 2023; Xu et al., 2023; Zou et al., 2020). Regulation, standardisation, experimentation, and data sharing must be promoted to encourage SCM members to implement decarbonisation technologies (Xu et al., 2023).

Most GHG emissions result from anthropogenic actions from population increase, industrialisation, and the growth of supply chains, and controlling these emissions in supply chains could respond to legal needs but also address the problem of climate change (Das and Jharkharia, 2018). Managers and shareholders should explore new initiatives for LCSCM adoption and innovative development (Kumar et al., 2023).

NZE means making communities more sustainable by conserving natural resources such as air, water, energy, or soil and promoting more skilled workforces (Kumar et al., 2023; Mishra et al., 2022). Decarbonising transport and energy through renewable sources significantly change fossil fuel resource flows, which are detrimental to achieving the desired targets (Mishra et al., 2022; Watari et al., 2021). Implementing technologies and managing resources effectively and sustainably are other tools in decarbonisation strategies (Mishra et al., 2022; Zhou et al., 2022). Industry 4.0 can be one of the possibilities to achieve low carbon emissions by rearranging value chains for circular economy solutions (Mishra et al., 2022).

A circular economy and NZE model could be possible if, when decarbonising the economy, investment in cleaner practices and technological innovation is made (Lee et al., 2017; Singh et al., 2022). Hence, net-zero targets' challenges require resolution for further emissions reductions and decarbonisation (Zhang et al., 2022). Achieving net-zero by 2050 is only feasible through developing business models focused on both people and nature and the profitability of organisations (Wehner et al., 2022). Some of the main stakeholders' concerns are the interoperability among digital platforms and the financial benefits of committing to decarbonisation investments (Zhou et al., 2022).

However, evidence shows that early movers in the commitment to carbon neutrality generate positive economic results (Zhang et al., 2022). In supply chains, freight transportation is a significant concern, and the most polluting industries should be addressed (Singh et al., 2022). With the growth of the maritime transport sector, caused by the increasing volume of global trade, a vast number of emissions such as CO2, GHG, and particulate matter (PM) are created, which arouse public concerns and put at severe risk coastal populations and ecosystems health (Corbett et al., 2007; Yang et al., 2019).

3. SYSTEMATIC LITERATURE REVIEW

From energy production to transportation, many are the sources of the increase in GHG emissions (*Figure 3.1.*), considered a significant cause of adverse effects on global warming, nature protection, water security, infectious diseases, and other social disruptions (Vimal et al., 2022). Reducing carbon emissions and energy consumption are key factors to combat climate change (Alzahrani et al., 2021). However, GHG emission reduction in the transport sector is a significant challenge for policymaking (Styhre et al., 2017).

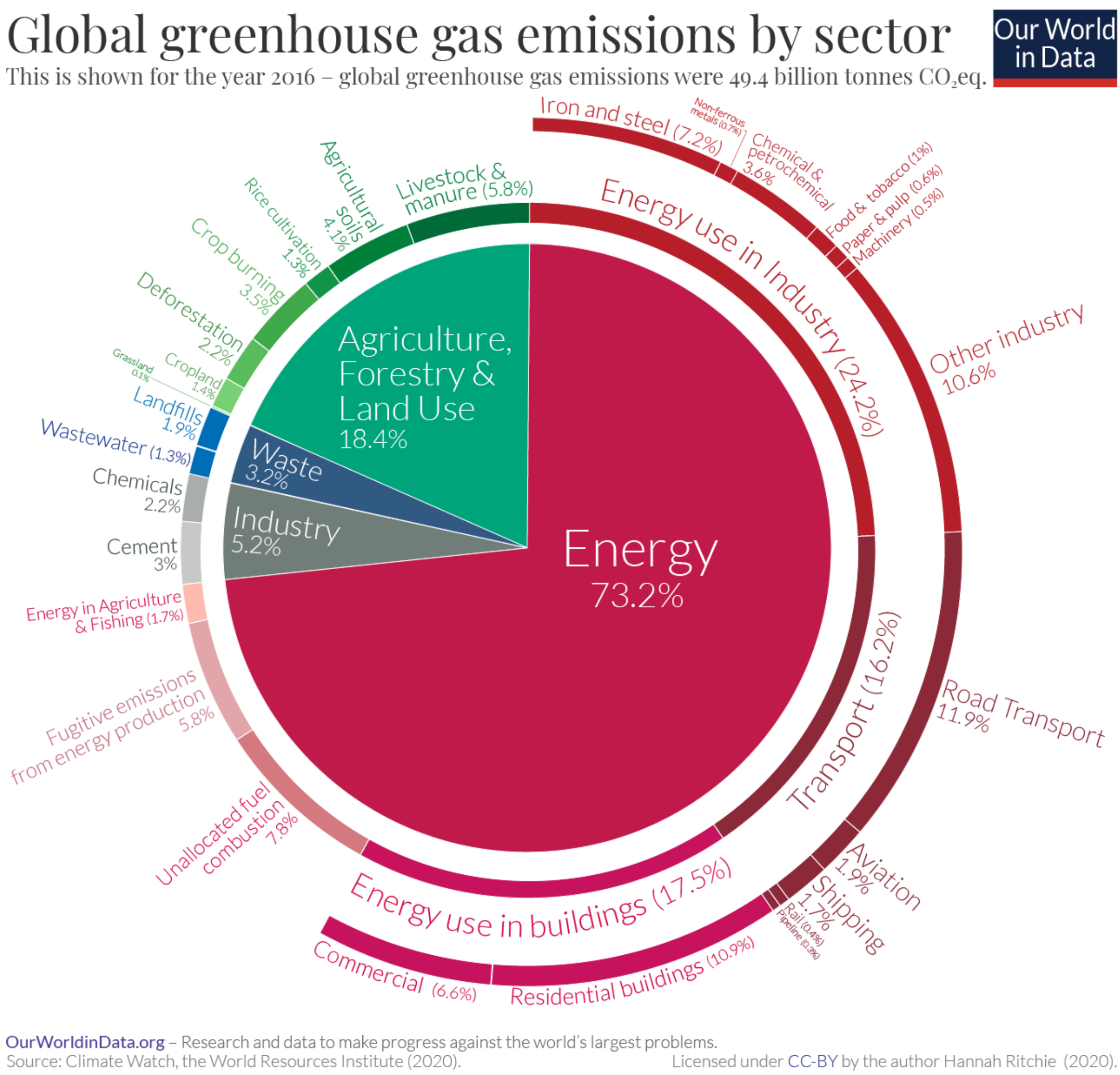

Figure 3.1. Emissions by sector (Source: (Ritchie, 2020)).

In supply chains, the most concerning factor of the high carbon emission rate is seen in freight transport, driven by production and consumption (Singh et al., 2022). The importance of shipping in globalisation and transportation of goods, its reputation as the most efficient mode of transportation, and the necessity for maritime terminal sustainability reinforce the significant role of seaports for net-zero goals (Alzahrani et al., 2021; dos Santos et al., 2022; Styhre et al., 2017; Zhou et al., 2022). Such importance is even easier to understand after several countries' commitment to decarbonisation roadmaps and being seaports responsible for handling 80% of global trade in volume and more than 70% in value (UNCTAD, 2017; Zhou et al., 2022).

Due to their location and exposure to climate change impacts, ports and other maritime/coastal structures are particularly interested in design guidelines and new practical approaches to incorporate trends and climate actions in new projects (Loza and Veloso-Gomes, 2023). The literature shows that the environmental impacts of sustainable container terminals and passenger seaports are very present (Balić et al., 2022). However, there is still a lack of general guidelines and standards for new climate change adaptation projects (Loza and Veloso-Gomes, 2023). Once maritime ports are considered a primary driver of the world economy and a core element of the industries of transportation, shipping, tourism, and fishing, ports' role as facilitators is under pressure to change to a more proactive energy efficiency role (Acciaro, Ghiara et al., 2014; Alzahrani et al., 2021).

International shipping is very problematic since oceans are international areas with laws specific to each country, making seaports essential players in the international cargo trade (dos Santos et al., 2022; Zhou et al., 2022), i.e., they are significant contributors to global economic growth, working as central hubs in the transport of goods (Acciaro, Ghiara et al., 2014; Alzahrani et al., 2021). Ports and terminals are essential in the maritime transport sector and critical infrastructure to world trade (Alamoush et al., 2020; Loza and Veloso-Gomes, 2023).

Due to the growth of ship sizes and numbers, the increased congestion from ships in ports causes tremendous logistical and technical difficulties in ports and their neighbouring cities experiencing substantial pollution levels (Alzahrani et al., 2021; Fruth and Teuteberg, 2017). As a result, 60,000 cancer deaths happen annually, most occurring in Europe, East Asia, and South Asia (Corbett et al., 2007). In this sense, when discussing sustainable development in the port context, the TBL concept must be present (Rosati and Faria, 2019), i.e., ports are critical economic systems with significant environmental and social impacts (Balić et al., 2022). Moreover, the maritime fossil fuel consumption in ports is responsible for 3% of global emissions, like GHG and other high-impacting emissions (sulphur oxides, nitrogen oxides, and PM), due to low-quality fuels (dos Santos et al., 2022; Misra, Panchabikesan, Gowrishankar et al., 2017).

Maritime transport has a less relevant carbon footprint than other means of transport (Boschiero et al., 2019; Singh, 2015). Despite this advantage, a relatively arduous problem might be found in the definition of a decarbonisation strategy (dos Santos et al., 2022). A single measure and a "one-size-fits-all" measure for port decarbonisation is unlikely to be effective, forcing identifying the best combination of measures (Alamoush et al., 2020).

Due to the complexity of the problem and the rise of new avenues of research, the decarbonisation of ports has received attention from all points of the globe. There are some reviews about the above-mentioned theme (*Table 3.1.*).

However, a proper identification of the leading topics for research still needs to be included. Also, a visualisation of how the main research topics are organised is required to understand the relationships between different research avenues. The fact that the current ports' decarbonisation literature lacks work to reduce complex multivariate data into smaller subsets can make research opportunities scattered. A summary and organisation of research opportunities through grouping, based on similarity, would improve chances of more efficiency in studying the decarbonisation of ports. Cluster analysis is a widely used analytical procedure to minimise within-group variance and to depict the path dynamics in research. (Lascialfari et al., 2022; Leonard and Droegem, 2008; Milcu et al., 2013).

The resulting research questions (RQs) are presented:

1) What are the main research topics concerning the decarbonisation of maritime ports, and how are they organised?
2) What are the research gaps concerning the decarbonisation of maritime ports?

Table 3.1. Reviews about the decarbonisation of ports.

References	***Title of the Document***	***Conclusions and Limitations***
Fruth and Teuteberg, 2017	Digitization in maritime logistics – What is there and what is missing?	The current level of digitisation in the maritime industry is studied, and existing problems and ways to improve them are identified. The authors

		concluded that it is essential to evaluate each digital technology to benefit from its advantages. As the first work in the digitisation of maritime logistics, it is likely that new avenues of research have emerged in the meantime. Another area for improvement is the focus on other types of measures and not just on digital solutions.
Bouman et al., 2017	State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review	By reviewing the CO2 emissions reduction potentials and measures, it was possible to identify promising areas, such as technologies and operational practices. The authors state that more than one measure is required to decarbonise the shipping sector. The focus on maritime transport forces the scope of research to expand to more points of the transport network and provide a bigger picture of its environmental impacts.
Alamoush et al., 2020	Ports' technical and operational measures to reduce greenhouse gas emission and improve energy efficiency: A review	This study systematically analyses diverse measures to reduce GHG emissions in ports and enhance energy efficiency. It categorises these measures into 7 main groups based on 214 studies. A combination of measures is essential for effective port decarbonisation. While the study offers valuable insights, it acknowledges limitations, including potential categorisation heterogeneity. However, this categorisation opens doors to further interpretation of the identified measures by identifying different clusters.
Alzahrani et al., 2021	Decarbonisation of seaports: A review and directions for future research	Initiatives to reduce seaport carbon emissions were reviewed, stressing the shift towards smarter and greener operations. This study advocates digital technologies like smart grids for effective decarbonisation. An adapted regulatory landscape is crucial to meet EU energy targets.

		The study addresses emerging cybersecurity concerns in seaport energy systems and suggests real-time LCA modelling. The components of green and smart seaports were identified, but how they relate could be more precise.
Sifakis and Tsoutsos, 2021	Planning zero-emissions ports through the nearly zero energy port concept	This review identifies several research opportunities to achieve a nearly Zero Energy Port concept. Port characteristics include high energy demands and the responsibility as a provider of supply activities. Besides, most measures are under-exploited in port but still have high value in decarbonisation. One conclusion is the need for more research regarding the less mature measures, like offset.
Raeesi et al., 2023	The synergistic effect of operational research and big data analytics in greening container terminal operations: A review and future directions	The unprecedented pressure to lower emissions led to operational research (OR), combined with Big Data Analytics (BDA) techniques as a solution to help in the quay and landside operations at ports, particularly container terminals. Interdisciplinary research to optimise port operations, improve energy management, and implement net-zero technology is an essential direction for future research. With this specific research goal in mind, a broader analysis of different technologies and measures was impossible to develop.
Oloruntobi et al., 2023	Sustainable transition towards greener and cleaner seaborne shipping industry: Challenges and opportunities	Technological innovations have been revolutionising the maritime sector and shipping operations. Information and communication technologies, unmanned autonomous vehicles, and low energy and emissions systems enhance port productivity, support energy transition, and improve operational flexibility and efficiency. However, the focus on new measures led to the need for clarity on how existing practices may influence the decarbonisation of ports.

A systematic literature review (SLR) will be adopted once it is one of the most used techniques to aggregate information, define the current level of knowledge about a subject area, and discover new unexplored themes (Carrera-Rivera et al., 2022). The SLR methodology emerged to review previous studies to bring a specific field closer together (Tranfield et al., 2003). Systematic reviews have multiple benefits, from updating researchers with the most critical and current literature about a subject to highlighting methodological issues in recent studies, always focusing on improving future research on a specific topic (Kitchenham et al., 2009).

Reviewing the current work on a research theme made future directions for further studies much clearer (Chalmers and Glasziou, 2009). A SLR is tailored to answer the RQs (Carrera-Rivera et al., 2022). Before implementing the SLR to find specific studies related to the RQs, a general overview should be set to introduce the theme and give some focus to the study (Carrera-Rivera et al., 2022).

3.1. General Review of Decarbonisation Measures for Ports

Smart and green ports (Alamoush et al., 2020; Iris and Lam, 2021; Styhre et al., 2017; Verhoeven et al., 2020) emerge as a group of initiatives to reduce seaport activities' emissions by integrating environmentally friendly operations and management practices (Alzahrani et al., 2021). Acciaro, Ghiara et al. (2014) concluded that port authorities must develop energy management practices to address environmental pressures by coordinating power generation, energy use, and implementation of renewable sources. Alamoush et al. (2020) justified that GHG reductions and energy efficiency are the pillars for green, sustainable, decarbonised ports.

Aligning the constant pursuit of operational efficiency with achieving sustainability goals makes seaports a key player in regional development and a vital part of the transport value chain (Zhou et al., 2022). In the last decades, ports have started to understand better and monitor energy-related activities, account for public environmental awareness, and consider the weight of sustainability in their strategies' definition (Acciaro, Ghiara et al., 2014). However, economic performance results are still the most significant goals for port authorities (Verhoeven et al., 2020). By considering ships' operations according to how often they revisit ports and their potential for emission reduction, Alzahrani et al. (2021) study demonstrates that to decarbonising seaports, it is necessary to install renewable energy sources, develop cost optimisation models, deploy smart technologies, and establish policies and regulations for green ports. Styhre et al. (2017) developed one of the first works on emission reduction, proposing essential technical and energy practices such as speed reduction in fairway channels, onshore power supply (OPS), berth turnaround time reduction, and alternative fuels.

Technical measures focus on improvements in energy, propulsion, and power efficiency, use of low-carbon fuels, use of renewable energy sources, or adoption of new technologies as part of an energy management strategy to achieve energy savings targets, improve ports competitive position, and identify possible strategic upgrades (Acciaro, Ghiara et al., 2014; dos Santos et al., 2022). That could be defined as a port Energy Management Plan (EMP), representing energy strategies centred on land planning, equipment, operations and transportation management, terminal design and operations, energy supply and delivery (Alamoush et al., 2020; Boile et al., 2016).

The International Maritime Organization (IMO) has proposed a strategy to reduce GHG emissions and several measures of energy efficiency requirements for ships (IMO, 2018). However, development is still needed (Alamoush et al., 2020; dos Santos et al., 2022). Ports must increasingly monitor and coordinate energy and power generation processes as a pillar for sustainability goals (Acciaro, Ghiara et al., 2014).

The IMO assumed that measures to reduce emissions must be implemented as early as possible (dos Santos et al., 2022). The need to achieve sustainable development, mitigate climate change, and promote ports' sustainability performance is clear (Alamoush et al., 2020). Ports' role in the net-zero achievement process to reduce in-port and at-sea GHG emissions is critical (Psaraftis and Zis, 2022). The lack of proper and well-defined strategies for maintaining environmental sustainability will lead to more pollution and emissions, being knowledge and information crucial among various firms to achieve sustainable growth (Kassaneh et al., 2021; Singh et al., 2022). Implementing measures to all ports, regardless of size or management practices, is necessary (Alamoush et al., 2020).

As stated earlier, a decarbonisation strategy can be a plan for CO2 emission reduction. That is particularly important in the port context since a significant share of CO2 emissions from the shipping industry are in the context of ships stay in ports, making ships emissions the largest source of pollution in ports, being ten times higher than ports' operations (Habibi and Rehmatulla, 2009; Styhre et al., 2017). So, land- and ship-based emissions must be considered for port emission inventory (Iris and Lam, 2019). By defining carbon management solutions, port authorities promote energy management and sustainable development (Acciaro, Ghiara et al., 2014). In addition, other activities have been proposed by the International Energy Agency, like the use of alternative fuels (dos Santos et al., 2022), or by the IMO, like the participation in the World Port Climate Initiative (WPCI) (Alamoush et al., 2020).

Although shipping transport is one of the best indicators of world economic growth, the complexity of decarbonising the sector discourages ports and their stakeholders (dos Santos et al., 2022). Different variables should be considered (cost, complexity, among others) to identify all possible measures, and factors like adaptability, reliability, sustainability, and, most importantly, should be considered to increase the likelihood of success (Alamoush et al., 2020; Loza and Veloso-Gomes, 2023). For example, some solutions can be implemented by retrofitting existing ships. Still, because this measure is costly, technical and energy practices (alternative fuels, OPS) are limited to new ships (Styhre et al., 2017). Besides, sector-wide emission reductions might find some setbacks due to the growth in maritime transport, requiring strong financial incentives to reach 2050 neutrality targets (Balcombe et al., 2019; Bouman et al., 2017).

Alamoush et al. (2020) have conducted a review and proposed a categorisation of portside activities and ship-port interface measures to decarbonise operations in ports through GHG emission reductions and energy efficiency improvements. In all the technical and operational measures identified, it is possible to derive a considerable dependence on ICT.

Considering that emissions are expected to increase by 40% by 2030 in seaports without any changes, and an ‘operational efficiency’ scenario could decrease emissions by 10%, measures to support efficient operations are critical (Winnes et al., 2015). Emerging technologies can facilitate the achievement of financial and non-financial objectives, as well as interconnection and integration with partners, requiring SCM systems to manage operational performance, environmental performance, and knowledge sharing (Wernick, 2008; Zhou et al., 2022). When it comes to port areas, smart technologies are part of the response to carbon emission reductions of around 75% by 2050, based on current technologies (Bouman et al., 2017; Misra, Panchabikesan, Gowrishankar et al., 2017).

According to Zhou et al. (2022), automation, electrification, and digitalisation are the three main topics in the transportation sector, including seaport terminals.

Automation replaces manual labour with automatised processes, facilitated by digitised technologies and coordinated by a central “brain”, a Terminal Operating System (TOS), for example. Electrification means adopting electrical power in an environmentally conscious and sustainable way. Digitalisation focuses on changes and improvements in communication to improve business activities within an entity and between stakeholders. Digitisation is simply converting information from a physical format into a digital one. Automation, electrification, and digitalisation are believed to support the transition towards NZE (Zhou et al., 2022).

Bouman et al. (2017) discuss several measures to maximise CO2 emissions reduction, such as hull design and maintenance, economy of scale achievement, power, propulsion, speed optimisation, alternative fuels and energy sources implementation, or weather-based routing and scheduling. Clean, affordable, and resilient energy systems are seen as potential measures to mitigate carbon emissions, limit the effects of global warming, and promote the NZE transition, but the variability in CO2 reduction potential for existing measures is still considerable (Bouman et al., 2017; Solomon et al., 2007).

In Winnes et al. (2015) work, three scenarios were developed (alternative fuels, ship design, and operations efficiency) to evaluate ships’ emissions from seaport measures. Like the previous, many other studies depend on optimisation and simulation models for various terminal designs (Gennitsaris and Kanellos, 2019; Styhre et al., 2017; Yun et al., 2018). Simulation is essential for investigating realistic and dynamic environments (Alamoush et al., 2020).

No global strategy can decarbonise ports (Alamoush et al., 2020). SCM members should take a long-term view in adopting low-carbon technologies because significant emission reductions require a combination of individual mitigation measures (Alamoush et al., 2020; Xu et al., 2023). A detailed explanation is provided in the following subsections to understand the different measures better.

3.1.1. Information Measures

Information measures include collecting data, tracking GHG emissions and energy consumption, and reporting these values over the years to develop and implement environmental measures while improving the port’s image (Alamoush et al., 2020). The culture of monitoring and auditing is believed to be well-established across EU ports (Sdoukopoulos et al., 2019). However, in 2019, the Vrije Universiteit Brussel surveyed seaport sustainability reporting practices. The survey gathered 97 responses, with European ports dominating the sample (around 61%). Some main conclusions are that a quarter of ports do not report on sustainability, and only 15% report according to international standards, like the Global Reporting Initiative (GRI). Indeed, 41% are unfamiliar with GRI, and 35% recognise a need for sector-specific standards (Verhoeven et al., 2020).

Instruments or devices measure energy consumption levels, while estimations are developed through calculations and perceptions. Real-time measuring of energy consumption values would allow high flexibility of the ports' energy management system. However, collection and control in real-time have increased costs, as it requires special equipment and software. The lack of registers of energy consumption levels makes implementing energy efficiency measures harder (Iris and Lam, 2019).

A Port Community System (PCS) is a platform for exchanging information between stakeholders to improve competitive positions in port communities by optimising, managing, and automating port processes (Verhoeven et al., 2020). A PCS is an open and neutral platform to promote the safe and effective exchange of information between multiple systems (Musolino et al., 2022). Seaports may cooperate with cities to achieve various climate mitigation goals, such as a circular economy concept, waste management strategies, and reuse of heat, steam, and CO2 (Alamoush et al., 2020). Also, ports should go beyond the technical and operational measures by having different green policies and programs (Winnes et al., 2015; Yen et al., 2023), such as a green procurement policy or, for example, a green commuting program to incentivise and encourage port employees to adopt green practices (Alamoush et al., 2020).

3.1.2. Alternative Fuels

Concerning port authorities and governments worldwide, low emission targets set a trend towards cleaner fuels. Alternative fuels, such as Liquefied Natural Gas (LNG), hydrogen, biodiesel, methanol, ammonia, and pyrolysis oil, are a low carbon energy source option (dos Santos et al., 2022). They place high pressure on the supply infrastructure, being ports responsible for the supply and further incentives for ships to use cleaner fuels (dos Santos et al., 2022; Gilbert et al., 2018; Styhre et al., 2017). Using alternative fuels to run seaport equipment is very interesting, too, mainly if production and supply infrastructures exist (Alamoush et al., 2020).

LNG was found to have a potential reduction of 20% to 30% of GHG and sulphur oxide emissions, while other options are not so present in the literature (Balcombe et al., 2019; dos Santos et al., 2022). The International Association of Ports and Harbors (IAPH) has created the IAPH Clean Marine Fuels Working Group to support the transition of the shipping industry towards neutrality targets, and one of the focuses of the group is the safe use and bunkering of LNG (Verhoeven et al., 2020).

However, the potential reductions in local air pollutants that the fuel shift entails cannot overshadow the adverse effects on global warming potential (Winnes et al., 2015). LNG has 25 times more warming potential than CO2 if slips of methane happen (Alamoush et al., 2020). Even though LNG is a relatively mature technology with commercial applications in the maritime industry, it probably will contribute little to the marine fuel mix. It will just have a transition role to achieve shipping neutrality targets (Xing et al., 2020). Other options, such as hydrogen and ammonia, are the worst due to energy consumed and high production costs (Law et al., 2021). They are expected to have difficulties entering some market segments, such as deep-sea shipping (Xing et al., 2020). Still, introducing these fuels could be motivated by lower emission levels of local air pollutants, the potential to gradually replace fossil fuels with renewable sources and being in line with goals of sustainability (Styhre et al., 2017; Winnes et al., 2015). Safety, security, supply, and market issues must be addressed to allow ports to develop all required infrastructures (Alamoush et al., 2020).

3.1.3. Renewable Energy

The energy required for ports' operations can be obtained through fuels or electricity. In the case of electricity, it can be obtained from the grid, or it can be produced within the port (Iris and Lam, 2019). Maritime port locations and various power capabilities potentiate renewable energy (RE) production. Even if production is not possible, there are several initiatives to buy clean electricity to reduce scope 2 emissions falling in the category of offset measures (Alamoush et al., 2020). In this last scenario, ports act like negotiators with energy suppliers and an intermediary for businesses around the port area (Iris and Lam, 2019).

RE are energy sources naturally restored on a short timescale. Solar energy production equipment is installed in open fields, nearby ports, or on buildings' rooftops and maybe photovoltaic (PV) or solar water heating (SWH). Wind energy production is very restricted by space availability, and because generators are typically too big, ports contract agreements with wind farm developers. The main types of ocean energy sources are tidal converters and wave converters, being both seriously hampered by ecological/environmental influences, navigational obstructions, high costs, low reliability, random variability of the ocean behaviour, and technological immaturity (Alamoush et al., 2020).

Considering that 20% of European ports have already implemented renewable energy sources, the percentage of energy from renewable sources can be an important KPI to monitor in sustainable ports (Acciaro, Vanelslander et al., 2014; Alamoush et al., 2020).

3.1.4. Energy Efficiency Measures

Energy efficiency measures reduce ports' energy consumption. Reducing emissions is directly proportional to the amount of fossil fuel saved (Acciaro, Ghiara et al., 2014; Styhre et al., 2017). In other words, energy efficiency measures minimise wasted energy by up to 90%, accounting for 57% of European ports' actions (Alamoush et al., 2020; Iris and Lam, 2019).

Several systems, technologies, and methods are available to implement an energy efficiency and saving strategy (Iris and Lam, 2019). Energy-saving examples are the use of LED, motion sensors, passive house design (designing buildings to minimise cooling/heating/illumination demand), sun protection roofs (if possible, with solar panels), eco-driving restrictions, and proper maintenance (Alamoush et al., 2020). Energy management systems and technologies could be energy management plans (EMP), energy storage systems (ESS), smart grids (centralised, automated systems to manage power flow from the grid to the points of consumption and overcome irregular power supply problems due to many energy sources), microgrids (controls energy resources, being capable of connect and disconnect from the grid), or smart load management (SLM) (management the variability in the electrical demand) (Acciaro, Ghiara et al., 2014; Bayindir et al., 2016).

Other technological systems could be impactful methods for energy efficiency, like automated mooring systems, start-stop engines, or reactive power compensation approaches. Engaged and attentive employees, through involvement right from the first stages, will increase the chances of success for any energy efficiency measure. As a result, ports should conduct in-depth technical, economic, and environmental analyses at the beginning of developing an energy efficiency strategy (Iris and Lam, 2019).

3.1.5. Operational Measures

Operational strategies aggregate operational methods focusing on energy consumption reductions, processing time reductions, non-peak hours practices, and energy price optimisation.

Equipment measures could be implemented by buying new equipment, replacing old equipment, repowering by changing old equipment or retrofitting measures to implement cleaner and energy-efficient technologies in buildings' lights and air conditioning, among others (Alamoush et al., 2020). Port authorities and stakeholders have recognised the benefits (economic, social, and environmental) of operational efficiency (Lim et al., 2019).

Digitalisation helps identify, monitor, and aggregate data to improve efficiency and protect the environment. Remote sensing and big data analytics reduce fuel consumption (Fruth and Teuteberg, 2017; Munim et al., 2020). Internet of Things (Ozturk et al., 2018; Yen et al., 2023) and cloud computing (Ranjan et al., 2020; Xia et al., 2021) can help manage logistics flows and reduce fuel consumption. Addictive manufacturing (3D printing) can be used to support maintenance and repair. Blockchain and centralised systems can potentially affect GHG reductions and increase security (Pu and Lam, 2021).

Container terminal automation and operation system (TOS) using AGV (Drungilas et al., 2023; Schmidt et al., 2015), automated machinery (Yen et al., 2023), drones, autonomous guided vessels (Oloruntobi et al., 2023), gate automation, scheduling yard trucks (Hong et al., 2023; Ranjan et al., 2020), and container tracking increases operational efficiency, reduces cost, and promotes environmental protection. Also, although equipment maintenance does not directly decrease emissions, it can save energy and reduce excess emissions, which can be potentiated if combined with predictive maintenance (Alamoush et al., 2020).

3.1.6. Land Transport Measures

Ports have 3 main areas: quayside, yardside, and landside. For the yardside, transport and stacking containers are the most important activities (Iris and Lam, 2019). The land transport measures suggest that reducing hinterland transport CO2 emissions will improve ports' green performance, even though they are few compared to the pollution caused by ships. Hinterland transport emissions are part of the ports' responsibility, and it is essential for the efficiency of the whole intermodal transportation chain (Behdani et al., 2020).

However, globally, only 20% of ports apply green hinterland emission reduction measures (monitoring programs, congestion prevention, and modal shifts, among others) (Gonzalez Aregall et al., 2018). Port terminal efficiency and reducing emissions are possible for intermodal transportation or modal shifts (moving cargo to rail, barges, short sea shipping or inland waterways) (Behdani et al., 2020; IMO, 2018). Dry ports or inland intermodal terminals emerge as a solution for ports' need to move to the hinterland to find the space they require for their operations, connecting seaports with intermodal transportation (Behdani et al., 2020).

Regarding truck emission reduction, replacement, retirement, repowering, or retrofit options result in using electric or hybrid trucks (Acciaro, Ghiara et al., 2014). Truck empty trips should also be addressed through truck-sharing opportunities (Islam et al., 2019).

On the other hand, seaports can promote freight transport efficiencies with a smart transportation system that plans efficient schedules, truck routing, pickup, and dispatching through operational research methods (Raeesi et al., 2023). An intelligent inter-terminal transportation schedule, a truck appointment system (TAS) combined with an automated gate processing system, and a peak hour's traffic mitigation fee (TMF) are some measures that would allow trucks to select a specific schedule to enter the terminal decreasing congestion outside the ports' gates while decreasing overall ports' emissions (Alamoush et al., 2020; He et al., 2013).

3.1.7. Onshore Power Supply

Globally, ship CO2 emissions in maritime ports could go up to almost 70%, about 18 million tonnes, and grow at least 4 times by 2050 (Styhre et al., 2017). Ship-port interface needs to be a top priority for decarbonisation strategies in seaports. Considering that the use of onshore power supply (OPS) can reduce ships' emissions by up to 70%, OPS is one of the essential ship-port interface measures recommended to reduce CO2 emissions in port areas and one of the most discussed in the literature (Alamoush et al., 2020). Onshore power supply (OPS), cold ironing, shore-side electricity, or shore-side power means ships in ports can turn off their auxiliary engines because they are connected to the electric grid while at berth to reduce emissions (Williamsson et al., 2022).

The GHG emissions reduction could be very high but depends on the electric power source (Styhre et al., 2017). The best results are when the energy sources come from RE, like solar, wind or ocean (Winnes et al., 2015). OPS has been identified as crucial for maritime transport electrification and one of the most viable technologies for ports' emissions reductions (Williamsson et al., 2022).

A systematic literature review by Williamsson et al. (2022) presents a framework for categorising barriers and drivers to the implementation of OPS, divided into four key categories (technology and operations, institutional elements, economic elements, and stakeholder elements) and three main areas of concern (port, transmission, and vessel), with several key components for OPS implementation (*Figure 3.2.*). The review indicates that research on OPS was limited until 2019, when interest increased considerably, coinciding with stakeholder concerns and regulatory pressure.

	Port	Transmission	Vessel
Key components	Berth design—space for sub-stations, cable reels, etc. Positioning of connection point(s). Local power production and storage.	Main substation (connecting to national grid). Port grid. Shore-side substation. Fixed or mobile connection point at berth. Cable (dimensions, and length) and cable reel at berth. Converter Safety protocols	Cable Cable-management system Switchboard Final step-down transformer

Figure 3.2. Key components for OPS implementation (Source: (Williamsson et al., 2022)).

Besides its potential and the gaining momentum of implementation of OPS, the adoption rate is still low, with the European continent leading in the implementation of high voltage OPS facilities (*Figure 3.3.*) (Verhoeven et al., 2020). The complexity of OPS implementation requires collaborative and collective approaches (Williamsson et al., 2022) from ports, ship operators, ship manufacturers and other stakeholders to make joint investments because of high costs (Styhre et al., 2017). Introducing OPS is highly contextual due to institutional, regulatory, and stakeholder aspects. Policies, incentives, and monetary charges are needed to encourage the share of costs associated with emissions (Williamsson et al., 2022).

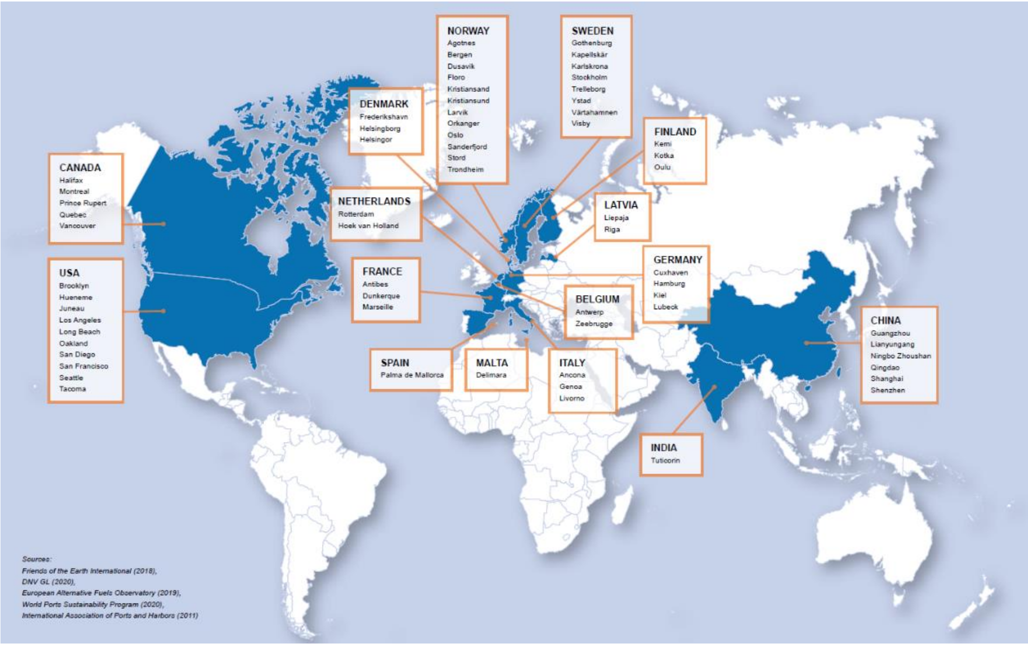

Figure 3.3. Map of high voltage OPS facilities (Source: (Verhoeven et al., 2020)).

3.1.8. Ship Turnaround Time

The GHG emissions from ships at berth can contribute to between 60% and 88% of the total emissions in ports (Styhre et al., 2017). Thus, reduced turnaround time (TAT) for the ships at berth would directly affect the total emissions. The turnaround time can be enhanced by increased productivity, reduced waiting time to start loading/unloading, reduced congestion, more efficient clearance procedures, longer operating hours, crane equipment efficiency, and berth availability (Styhre et al., 2017; Winnes et al., 2015). Further, reducing TAT can be achieved through information sharing, using information communication technologies (ICT), electronic data interchange (EDI), port community system (PCS), or vessel traffic management (VTM) (Alamoush et al., 2020). Reducing TAT also allows shipping companies to increase transport work, reduce the speed at sea, and increase the berth capacity for the port (Styhre et al., 2017).

If ships reduce TAT by 30%, it is possible to reduce CO2 emissions by 37%, while if TAT increases by 30%, emissions may increase by 30.7% (Moon and Woo, 2014). Also, TAT reduction, while at berth, by four hours to one hour provides a 2% to 8% energy saving (Johnson and Styhre, 2015).

Usually, ships berth on a first-come-first-served basis, which increases the total TAT and CO2 emissions. Ports can provide enhanced alternative service policies, like booking berths before arrival and assuring berths on arrival (Alamoush et al., 2020). By combining information sharing, technological innovation, and alternative policy schemes, measures to reduce TAT can be defined. Terminal berth allocation, yard allocation and scheduling of crane equipment, automated mooring systems, and midstream operations (loading and unloading of cargo containers between ships at non-berth locations) are some examples of practices to reduce TAT and GHG emissions (Díaz-Ruiz-Navamuel et al., 2018; Misra, Panchabikesan, Gowrishankar et al., 2017).

3.1.9. Just-in-Time Berth and Vessel Speed Reduction

Through information sharing, it is possible to bring all stakeholders together on just-in-time (JIT) berthing, vessel speed reduction (VSR), and slow steaming, yielding up to a 27% saving in fuel consumption (Gibbs et al., 2014). These measures can significantly contribute to GHG emission reductions in ports (Alamoush et al., 2020). Generally, operational measures have low investment costs and can substantially affect the fleet quickly (Styhre et al., 2017). Operational research methods could optimise practices like berth and mooring scheduling, stacking, and container storage (Raeesi et al., 2023).

Contractual issues clarification is required for ports to succeed in managing JIT berthing, demanding collaboration with various stakeholders. Several authors have recommended the benefits of this measure to reduce shipping emissions (Alamoush et al., 2020; Misra, Panchabikesan, Gowrishankar et al., 2017; Poulsen et al., 2018). An international alliance for the JIT arrival of ships is being developed to support an energy-efficient and low-carbon maritime transport sector (Verhoeven et al., 2020). By reducing the time a ship stays in ports, a vessel can reduce its speed at sea (Johnson and Styhre, 2015).

When vessels reduce speed while approaching ports, they can reduce fossil fuel consumption and lower emissions (Gibbs et al., 2014; Poulsen et al., 2018; Winnes et al., 2015). CO2 emissions can be reduced by 50% only with VSR implementation and up to 91% by combining OPS with VSR (Alamoush et al., 2020). A well-elaborated strategy of slow steaming among all parties in the shipping sector could result in a considerable GHG reduction (Armstrong, 2013). Mainly, ships with significant power installed in their main engines will contribute more to emission reduction (Styhre et al., 2017).

3.1.10. Offset Programmes

Offsetting is a mechanism for compensating emissions through direct prevention of the release of, reduction in, or removal of, an amount of GHG emissions outside the operational boundaries of the organisation or indirectly through the purchase of carbon credits generated by a third party (ISO/TR 14069:2013). Port authorities and other stakeholders could offer clients the possibility to invest in verified and reliable projects capable of reducing or preventing emissions from GHG or other substances. Some initiatives could be reforestation, end-of-pipe solutions in industrial processes, or investments in renewable energy sources (Hellenic and International Shipping, 2021)

Offset programmes widen the impact of port climate change mitigation, with potentially high emission reduction and relatively low investment (Alamoush et al., 2020). Offset programmes should always be considered additional support, forcing seaports to adopt new technologies, even though they may require more resources (time, money, infrastructure, and knowledge). Still, having partners to improve the quality of a decarbonisation strategy is very important, and finding the proper organisation for that support can be challenging (EIT InnoEnergy, 2022).

3.1.11. Carbon Capture and Utilisation and Sequestration

Like the offset programs, carbon capture and utilisation and sequestration (CCU/CCS/CCUS) programmes can have significant carbon reductions with low investment compared to other technologies (Alamoush et al., 2020). Carbon capture and storage technologies can also serve as a substitution for conventional marine fuels. However, large-scale applications are still early once future developments depend on technological improvements and regulatory support (Xing et al., 2020). The next generation of ports can serve as CCU/CCS/CCUS facilities (Iris and Lam, 2019).

Right now, commercial CCU/CCS/CCUS implementations handle vast quantities of CO2 (in order of tens of thousands of tonnes), and, unfortunately, many system developers, operators, or regulators may lack an understanding of the properties of CO2 (as a gas and as a liquid) and how these can lead to major accidents. If a significant CO2 leak happens, it could result in widespread loss of life and create barriers to the acceptance of CCU/CCS/CCUS projects, particularly in seaports or near-shore areas (Holt and Simms, 2021).

Nature-based solutions, like trees and grass plantations in the port area or controlled algae production on the shoreside, may improve air conditions, water quality, and general landscape (Tsai et al., 2018; Wang et al., 2023). These are potential carbon capture programmes and a source for other products (raw materials) and services (ecosystem services). Mahmood et al. (2022) and Ostrow et al. (2022) have focused on models to complement design guidelines based on nature-based solutions.

3.2. Methods

Various articles, reviews, reports, and other literature types have been consulted for net-zero, decarbonisation strategies, decarbonisation of supply chains, and decarbonisation of maritime ports themes. In this section, a methodology to answer the initial RQs is developed. The methodological procedure is presented in *Figure 3.4.* and it follows a Systematic Literature Review (SLR) method. For Denyer and Tranfield (2009), SLR consists of identifying, selecting, analysing, and summarising the research on a particular topic.

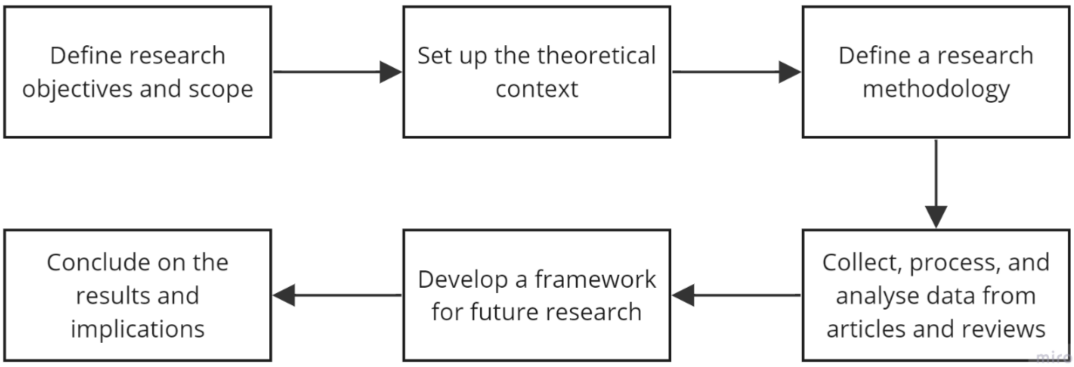

Figure 3.4. Flowchart for research methodology.

A SLR is an extensive research method and a complete practice than other review forms (Kumar et al., 2023). For Paul et al. (2021), the 3 pillars of SLR are “assembling” (select and acquire the literature), “arranging” (organise and refine the literature), and “assessing” (assess and report the literature). The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) technique (Moher et al., 2009) was used to define the literature selection and data analysis. The PRISMA guidelines assure valid and reliable results.

Based on De Felice and Petrillo (2021) and Kumar et al. (2023) studies, the PRISMA technique consists of a 4-phase process:

- Identification: Variables, like keywords, databases, and periods, are used to find the first group of papers.
- Screening: Duplicated papers and non-relevant subject areas are eliminated. The primary language or languages should be chosen.
- Eligibility: After screening, the publications are evaluated by their titles, abstracts, and full content if necessary. Quality criteria, like applicability to the research, scientific journal, and number of citations, among others, are considered too.
- Inclusion: At this stage, the author or authors should verify if any necessary documents are missing and include any relevant papers through the snowball technique.

Through a SLR methodology, peer-reviewed scientific journal literature written in English and registered in the *Scopus* database was obtained. In the following sections, the defined methods will be implemented. Bibliometric, content, and cluster analyses of the selected papers will be carried out in *Section 3.4. Data Analysis and Results*.

3.3. Data Collection and Processing

The literature was collected using an appropriate, credible, and valid database. The database chosen was the Scopus database, the most acknowledged online scientific database on different subject areas and frequently used for searching the literature (Culot et al., 2020; Guz and Rushchitsky, 2009). Also, documents are continually expanded and updated (Levine-Clark and Gil, 2008).

After that, a group of keywords were selected and combined, according to the relevance of the terms to the research, to identify high-quality peer-reviewed papers about the decarbonisation of ports. Different sets of keywords were developed and utilised for a combined search ("OR" to aggregate keywords within the sets; "AND" to group the sets). The list of keywords and how they were aggregated and grouped is presented in *Table 3.2*.

Table 3.2. List of keywords used during documents' search.

Strings of keywords	**1. Measures**	renewable energy OR alternative fuel* OR low carbon fuel* OR renewable fuel OR state of the art technologies OR end-to-end maritime transport OR industry 4.0 OR information system* OR ict OR internet of thing* OR cloud computing OR ai OR big data OR blockchain* OR pcs OR virtual reality OR electric vehicle OR electrification
	2. Objectives	decarboni* OR net-zero OR energy efficien* OR low carbon emission* OR greenhouse gas* reduction* OR ghg reduction* OR greenhouse gas* emission OR ghg emission*
	3. Area of Application	maritime sector OR shipping sector OR international shipping sector OR maritime transport* OR seaport OR port OR harbour OR container
Number of results	3420 documents in *Scopus* database	

Set 1 of keywords is the "Measures" group, which aggregates 18 concepts that can be applied to the decarbonisation of ports, from overarching broad concepts to specific technological applications. The group "Objectives" includes 8 ideas about the significant goals of ports' decarbonisation strategies. Finally, for group 3, 8 keywords related to the "Area of Application" of the decarbonisation measures were used. The sets of keywords were based on Alamoush et al. (2020), dos Santos et al. (2022), and Xu et al. (2023) studies. These keywords were searched in the titles, abstracts, and keywords of the papers.

Figure 3.3. shows the PRISMA application for this study. In the first search, 3420 documents were obtained using the keywords, covering the period until May 2023.

After, only English language articles and reviews were selected, and Physics and Astronomy, Chemical Engineering, Materials Science, Chemistry, Medicine, Biochemistry, Genetics and Molecular Biology, Arts and Humanities, Pharmacology, Toxicology and Pharmaceutics, Immunology and Microbiology, and Neuroscience subject areas were excluded. 1470 results were achieved for this first round of screening. A preliminary eligibility analysis was performed on these articles by checking the titles and if needed, the abstracts. 442 papers were selected, and their information was exported in a *.cvs* type file, with essential information for each document, like authors, title, abstract, and keywords. The resulting file was converted to an *Excel* file for further analysis.

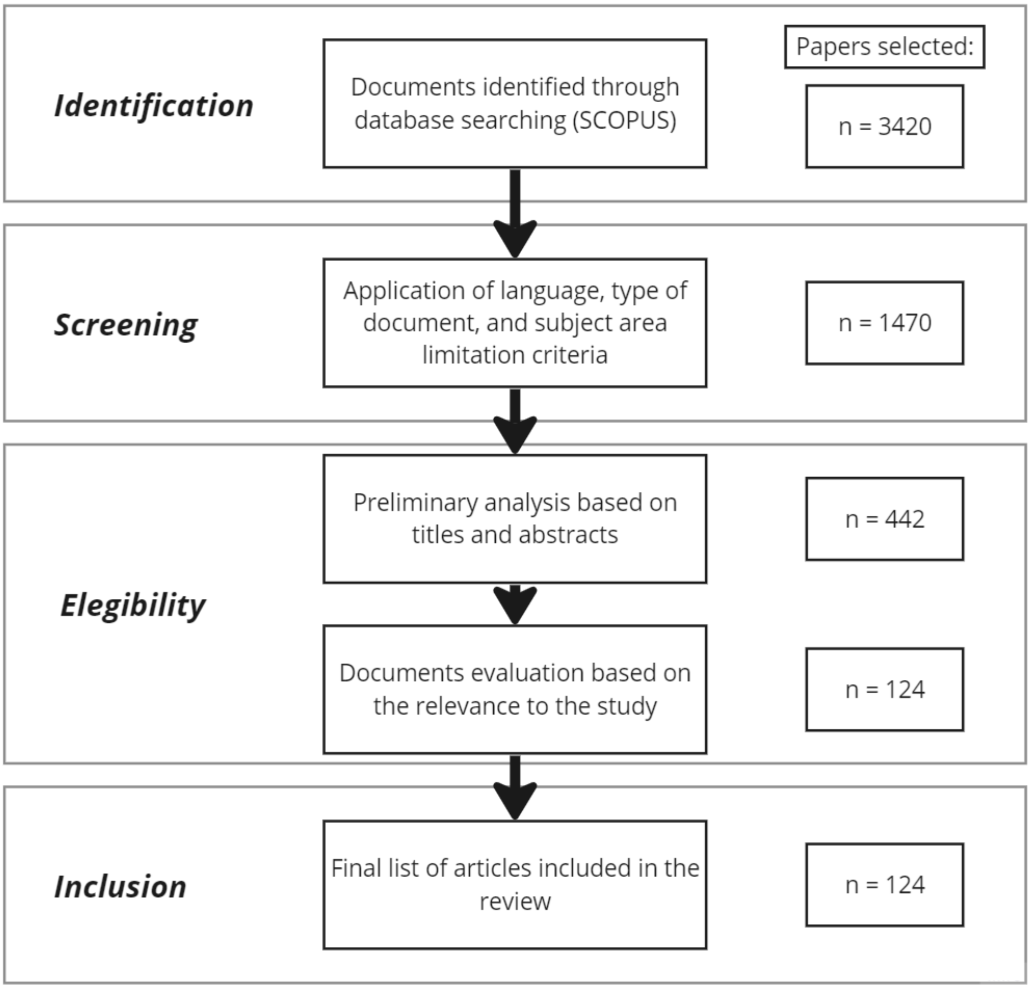

Figure 3.5. Document selection process, following the PRISMA approach.

To the resulting *Excel* file, 3 columns were added for the 3 researchers' evaluations, each with a separate column. The assessment was made separately, individually, and without knowing each other's opinions to avoid influences and ensure the process's reliability. The possible responses were the following: "Yes" for papers with relevance for the study, "No" for papers without significance for the study, and "Doubt" if it was not clear the relevance or lack of relevance for the study. Relevant studies were, for example, articles or reviews about measures for the decarbonisation of ports. The assessment was made according to the title, the abstract, and the full text when necessary.

After each researcher conducted the evaluation individually, the papers and articles were selected or excluded from the study based on agreement between all. Papers were excluded if it was clear the lack of relevance for the research or if it was not clear if the article had something to add to the study. The goal was to assess each other's opinions and potentially include relevant papers instead of eliminating them without discussion. Articles whose full text was unavailable online were eliminated after approval from all researchers.

Finally, 124 English-language articles and reviews about the decarbonisation of ports between 2011 and 2023 were selected.

With the sample obtained, the selected papers were analysed. First, each contribution was analysed in *Section 3.4.1. Bibliometric Analysis* based on bibliometric indicators like year of publication, first author, geography of affiliation of the first author, source of publication, and citations. More information about the selected papers can be consulted in *Appendix A*.

After that, the content of each publication was carefully scanned. A synthetic view is presented in *Section 3.4.2. Content Analysis* and the full results are listed in *Appendix B* and *Appendix C*. Since researchers use different terminology for the same concepts, an inductive approach was adopted (Culot et al., 2020; Mittal et al., 2016). The measures mentioned in the publications were grouped by similarity, resulting in 4 categories and 11 measure groups, represented in *Figure 3.12.* The several types of methodologies identified are listed below in *Table 3.3.*, as well as the most investigated geographies in *Figure 3.11.*

3.4. Data Analysis and Results

3.4.1. Bibliometric Analysis

3.4.1.1. Distribution of Papers by Year of Publication

The distribution of the 124 papers by year of publication is presented in *Figure 3.6.*, which shows an apparent increase in the number of documents since 2019. The high number of publications in 2021 and 2022 demonstrates a growing interest in decarbonisation measures for ports as a very current topic with many opportunities for future works. The graph shows that 2011 was the year of the first publication selected.

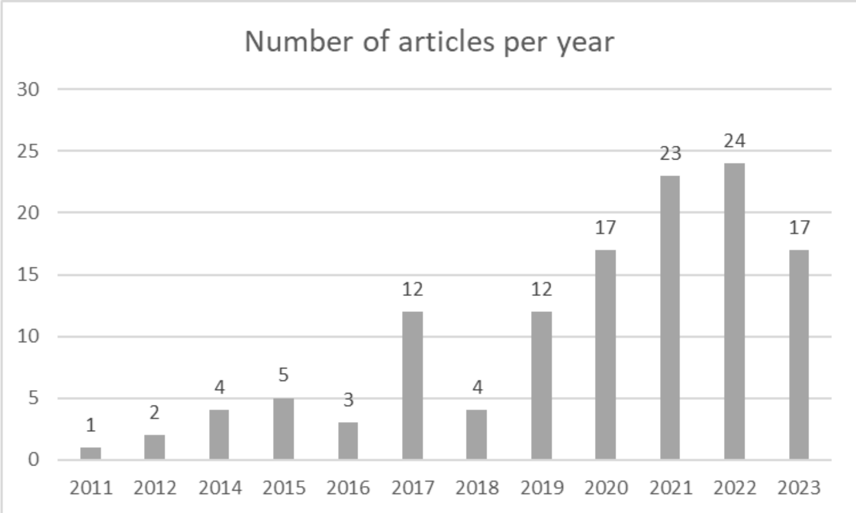

Figure 3.6. Number of articles per year.

3.4.1.2. Distribution of Papers by Source of Publication

The papers collected in this review were distributed in 64 different journals, and the most relevant are presented in *Figure 3.7*. The most pertinent journals represent 19% of the total number of sources, and together, they represent more than 53% of the papers selected in the study. These journals cover mainly energy-related topics, but some focus on sustainability, transportation, and maritime themes.

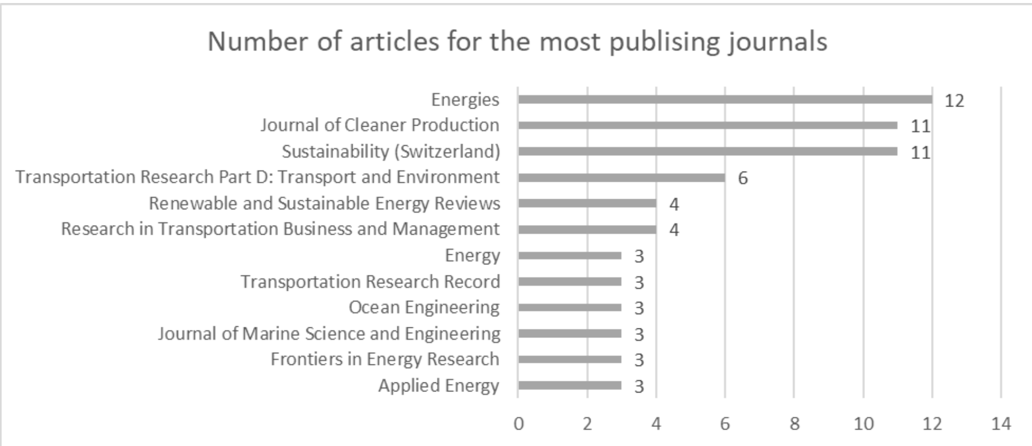

Figure 3.7. Number of articles for the most publishing journals.

3.4.1.3. Distribution of Papers by Main Authors

By analysing the first authors' productivity, in a total of 114 first authors, we can identify in *Figure 3.8.*, 7 researchers with more than one paper published. We can also conclude that in 124 articles, the 7 authors identified are responsible for a relatively low number of only 17 documents. In this sense, it is possible to state that the investigation on the decarbonisation of ports is very spread out regarding primary researchers' figures.

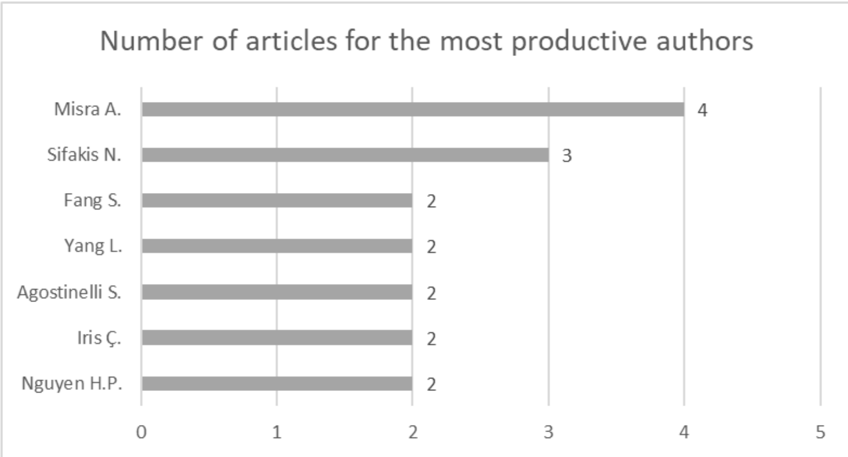

Figure 3.8. Number of articles for the most productive authors.

3.4.1.4. Distribution of Papers by Citations

In terms of citations, the top 10 most cited articles are represented in *Figure 3.9*. Only 2 of these articles are signed by 2 authors identified as the most productive. By further analysing, it is possible to conclude that 5 of the most cited articles were published in journals interested in transportation-related themes (Bouman et al., 2017; Fagerholt et al., 2015; Fang et al., 2020; Styhre et al., 2017; Winnes et al., 2015).

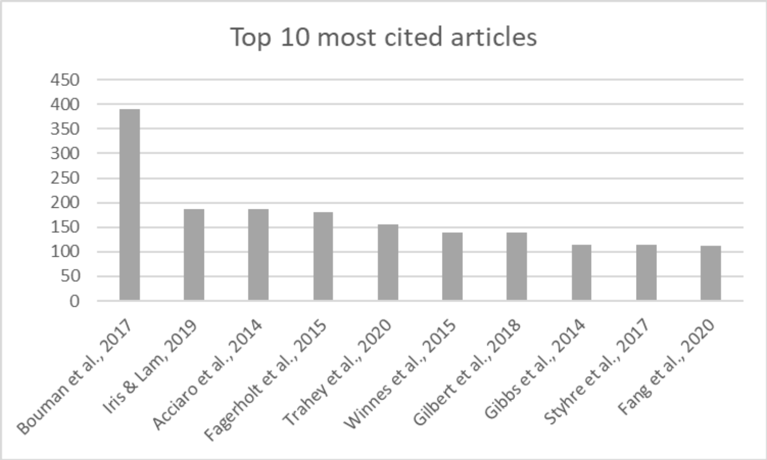

Figure 3.9. Top 10 most cited articles.

3.4.1.5. Distribution of Papers by Geography

When analysing the geography of affiliation of the first authors of each paper, it is possible to identify 9 countries with 5 or more occurrences *Figure 3.10*. China leads with a significant difference from other countries, with 18 documents. Italy and Greece follow, with 9 and 8 articles, respectively. The United States, the United Kingdom, and India are accountable for 7 papers. There are 6 papers, with the first authors affiliated with Norwegian institutions. Finally, Germany and Sweden produced 5 documents.

Figure 3.10. Countries with the most papers produced.

Thanks to China, Asian countries are making tremendous efforts to decarbonise maritime ports. Still, the European continent is very upfront in researching port decarbonisation measures. Countries from Oceania, South America, and Africa continents still have much work to be done in terms of research.

3.4.2. Content Analysis

3.4.2.1. Geographies Studied

Due to the usual disagreement between authors' affiliations and studied geographies, compiling the several countries mentioned along the 124 documents collected through the SLR methodology was necessary. A country was considered if its country or region was used for a case study, as an example in a review, or had participants in a survey or an interview study.

The results can be seen in *Appendix C*. The top 15 countries that studied the decarbonisation of their ports are summarised in Figure 3.11., according to their occurrences in the papers selected, as shown in *Section 3.4.1.5. Distribution of Papers by Geography* the European countries are very upfront in researching decarbonisation measures for ports in general, but now we conclude that, too, relative to the European ports. Germany has the most studies about decarbonising its ports, with 19 studies. Netherlands and Italy with 13 studies, the United Kingdom and Spain with references in 11 papers, Sweden with 10 studies, Belgium with 8 articles, France, Greece, and Norway with 7 investigations produced, and Denmark with 6 references.

Some of the most studied European ports are the port of Hamburg (Acciaro, Ghiara et al., 2014; Holly et al., 2020; Schmidt et al., 2015), the port of Gothenburg (Styhre et al., 2017; Winnes et al., 2015), the port of Rotterdam (Bosman et al., 2018; Schneider et al., 2020), and the port of Genoa (Acciaro, Ghiara et al., 2014; Castellano et al., 2020; Lavidas et al., 2020).

Besides the European countries, Chinese ports can be identified in 18 documents, as well as the United States. The San Pedro Bay Port Complex, which includes the ports of Los Angeles and Long Beach in southern California, is a case study investigated (Amar et al., 2017; Kim et al., 2012; Zhu et al., 2022). Singapore and India are the last 2 countries in the top 15, with 8 and 6 references, respectively.

Figure 3.11. Top 15 geographies studied.

3.4.2.2. Methodologies Implemented

The first conclusion of this analysis is related to the prevalence of quantitative methods to study the decarbonisation of maritime ports. Almost 70% of the papers selected through the SLR method used a quantitative method, and only 5 of the 124 documents considered used a mixed method strategy. Because of how vital mixed methods are, authors should apply methods concerning both quantitative and qualitative techniques (Bryman, 2006; Venkatesh et al., 2016), particularly in the theme of port decarbonisation. Also, only 3 studies performed a survey as a strategy of investigation (Argyriou et al., 2022; Spaniol and Hansen, 2021; Szymanowska et al., 2023). Since surveys are especially critical when working on beliefs, attitudes, or opinions, once they offer a complete vision than other approaches, more studies should be conducted using this investigation strategy (Bennett et al., 2011). For more details, the *Appendix C* can be consulted.

Table 3.3. Summary of methodologies used in the study of decarbonisation of ports.

Methods	***Strategy of investigation***	***Number of papers***
Mixed Methods	Mixed Strategies	5
Qualitative	Archival Research	30
	Ethnographic Observation	1
Quantitative	Case Study	85
	Survey	3
	Total	124

Of the 30 studies that used Archival Research as a strategy of investigation, 8 of them conducted Systematic Literature Reviews (Alamoush et al., 2020; Bouman et al., 2017; Fruth and Teuteberg, 2017; Mansoursamaei et al., 2023; Munim et al., 2020; Oloruntobi et al., 2023; Raeesi et al., 2023; Sifakis and Tsoutsos, 2021), and 4 of them performed a Bibliometric Analysis (Alamoush et al., 2020; Ampah et al., 2021; Liao et al., 2023; Munim et al., 2020). The decarbonisation of ports was studied 6 times while using interviews as one of the techniques of investigation (Islam et al., 2019; Klopott et al., 2023; Mańkowska et al., 2021; Poulsen and Sampson, 2020; Schneider et al., 2020; Sinha and Roy Chowdhury, 2022).

For quantitative techniques, a total of 7 papers applied a CFA (Gibbs et al., 2014; Mańkowska et al., 2021) or a LCA (Foretich et al., 2021; Gilbert et al., 2018; Holly et al., 2020; Kim et al., 2012; Taneja et al., 2021). Simulation, optimisation, and computation, using, for example, Machine Learning, are the most used techniques. Those techniques were identified 60 times along with the selected documents.

3.4.2.3. Measures Investigated

Figure 3.12. summarise the classification of measures followed in this work. In *Appendix B*, it is possible to identify in more detail which works studied which measures. By far, the energy system practices and the information measures are the most studied in 68 and 62 papers, respectively. After that, energy efficiency measures, with 43 references; renewable energy utilisation, with 42 references; alternative fuel sources, with 36 references; equipment measures, with 30 references; and ship-port interface measures, with 27 references, appear. Finally, offset, and carbon capture and sequestration measures are the less studied measures, with 10 and 4 works, respectively.

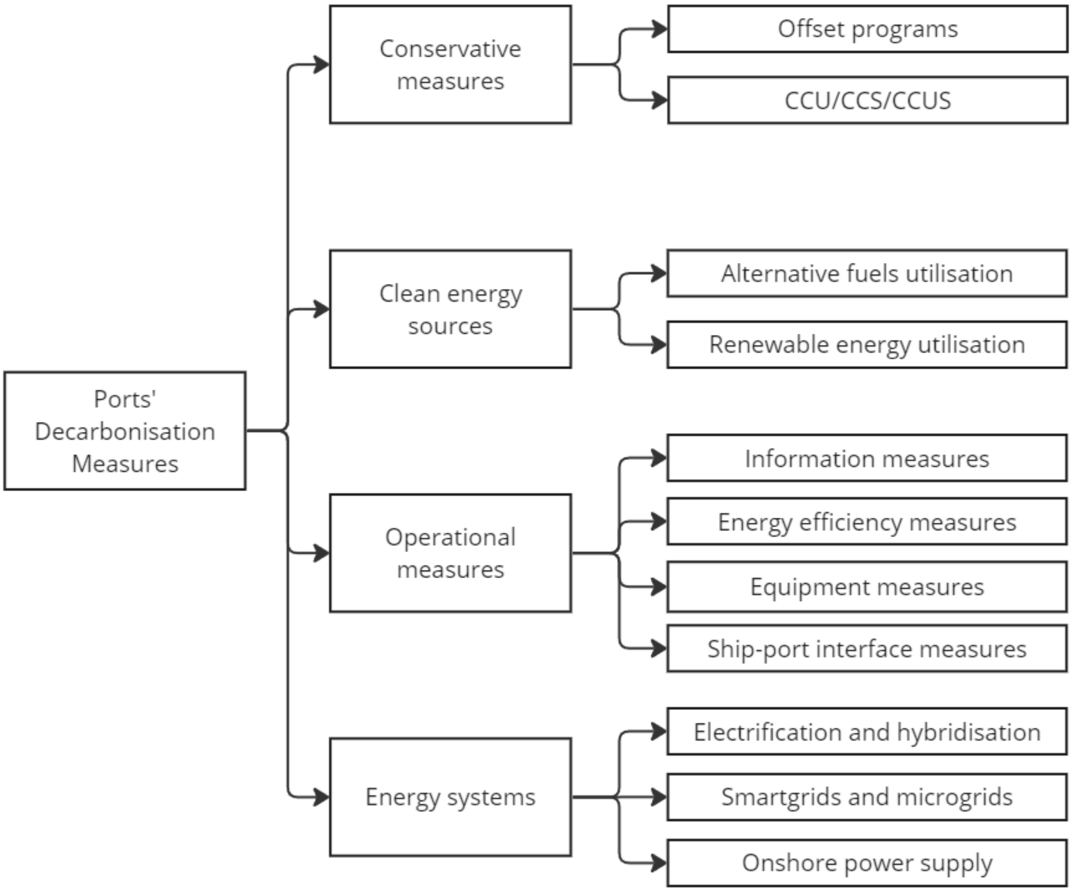

Figure 3.12. Categorisation of measures.

For the conservative practices, both offset and carbon capture and sequestration measures were considered. Offset measures are relatively low investment mitigation strategies with potentially high emission reduction (Misra, Panchabikesan, Gowrishankar et al., 2017). It can be adapted depending on the willingness to pay (Argyriou et al., 2022). Some examples can be carbon pricing (Yang et al., 2019), port charges based on their productivity levels and stakeholders' performance (Iris & Lam, 2021), penalties for vessels that use non-clean fuel (Kim, 2022), discounts for shippers transporting cargo by intermodal transport, like rail and barges (Sinha and Roy Chowdhury, 2022). CCU/CCS/CCUS are emission prevention programs, meaning that emissions may happen eventually (Xing et al., 2020). Carbon capture and sequestration measures are being studied as potential alternatives to integrate with cleaner fuels to reduce shipping emissions further, even if they are not presently at the centre of stakeholders' attention due to the slow growth in the energy sector acceptability (Mukherjee et al., 2020).

Clean energy sources include 2 crucial measures for the decarbonisation of ports: alternative fuel utilisation and renewable energy utilisation. Alternative fuels, like LNG, hydrogen, biodiesel, and ammonia, are the most mentioned in the literature. However, ethanol, nuclear, methanol, and methane are some other fuels with the potential to replace heavy fuels with low-sulphur fuels (Alamoush et al., 2020; Ampah et al., 2021; Mallouppas and Yfantis, 2021). Alternative fuels could be considered in mixtures to increase their reduction potential (Foretich et al., 2021; Taneja et al., 2021). Renewable energy utilisation can be considered individually (solar, wind, wave, tidal, geothermal, biomass) or combined (Balbaa and El-Amary, 2017; Rolan et al., 2019; Spaniol and Hansen, 2021). A renewable energy community is a new concept to be studied, which could escalate the potential for reducing GHG emissions in ports (Agostinelli, Neshat et al., 2022).

Information, energy efficiency, equipment, and ship-port interface measures are the most relevant operational measures. Information measures focus mainly on collecting, tracking, and reporting data (Gibbs et al., 2014). However, they can also include management of port community systems (PCS) (Alzahrani et al., 2021), integrating port-city objectives (Bosich et al., 2023), development and fulfilment of green policies, environmental regulations, targets, and standards in ports (Bouman et al., 2017; Winnes et al., 2015), and promote digitalisation (Fruth and Teuteberg, 2017), through digital twins (Agostinelli, Cumo, et al., 2022), IoT (Ullah Khan et al., 2022), among others techniques. Developing new contracts with emissions reduction commitment plans, ensuring well-connected port infrastructure for efficient and reliable port services, and transparent port funding are very important (Boile et al., 2016) and should be measured and controlled by environmental management KPIs to best communicate with the public (Di Vaio et al., 2019).

Energy efficiency measures are operational practices that ensure energy-saving measures (Alasali et al., 2019) and energy management systems and technologies are implemented (Iris and Lam, 2021). Energy management plans, virtual power plants, smart load management, diversification of energy sources, pick shaving (levelling out picks of demanded energy) are essential for efficient and resilient power system, and lastly, minimising overall energy consumption (Acciaro, Ghiara et al., 2014; Alzahrani et al., 2021; Iris and Lam, 2019).

Some examples of equipment measures are intermodal transportation (Kurtulus & Cetin, 2019), truck appointment (Poulsen and Sampson, 2020), AGVs (Drungilas et al., 2023), container terminal automation (Al-Fatlawi and Jassim Motlak, 2023), cleaning and waste management systems (Di Vaio et al., 2019), radio frequency identification (RFID) (Choi et al., 2012), unmanned aerial vehicle (UAV) (drones) assisted data (Oloruntobi et al., 2023), wireless signals (Ozturk et al., 2018), engine technical development (Foretich et al., 2021), equipment maintenance, replacement, or retrofitting (Alamoush et al., 2020). They can result in truck emission reduction, truck congestion reduction (Islam et al., 2019), PM reductions, empty container movement improvements (Kurtulus & Cetin, 2019) and improvement in container movement scheduling (Pei et al., 2021), shifting processes to off-peak hours (Schmidt et al., 2015).

The last group of operational practices are the ship-port interface measures. One of the most studied measures is the ship turnaround time reduction through berth allocation, yard allocation and scheduling, automated mooring systems, and mid-stream operations (Alamoush et al., 2020; Mao et al., 2022; Styhre et al., 2017). Virtual arrival (Sinha and Roy Chowdhury, 2022), JIT berthing (Gibbs et al., 2014), and VSR (Yun et al., 2018) are other critical measures. Engine technical development, environmentally friendly ship's hull cleaning, use of compressors to clear quayside ice, electric shore-side pumps for bulk liquids, and burning of more polluting fuels at high seas (Alamoush et al., 2020) can also result in improvements in the efficiency of loading and unloading (Yang et al., 2017), higher security in operation, less response time (Ozturk et al., 2018), and strategy thinking for the capacities of a ship (Reusser and Pérez, 2020). Ship design and vessel handling (speeds and utilisation) should be adapted in a regional way to limit ecosystem impacts (Lindstad et al., 2015).

Energy system practices focus primarily on electrification and hybridisation (Daniel et al., 2022) of electric cargo handling equipment (Iris and Lam, 2021; Taneja et al., 2021), like cranes (Alasali et al., 2019), and vehicles, like entirely electric or all-electric ships (AES) (Bakar et al., 2021; Fang et al., 2020; Kumar et al., 2019), trucks (Amar et al., 2017; Hong et al., 2023), railways (Kurtulus and Cetin, 2019), or AGVs (Drungilas et al., 2023).

Another prevalent measure in the literature is the use of OPS as a means for ships in ports to reduce emissions because they can turn off their auxiliary engines while connected to the electric grid at berth (Sciberras et al., 2016; Yun et al., 2018). The adaptation of OPS forces drastic changes in the energy system of ports, with high investment costs that should be supported for as many stakeholders as possible (Acciaro, Ghiara et al., 2014; Lu and Huang, 2021).

Intelligent energy networks in harbour grid configurations, like smartgrids (Alzahrani et al., 2021; Kanellos et al., 2019; Rolan et al., 2019) and microgrids (Kinnon et al., 2021; Misra, Venkataramani et al., 2017; Parise et al., 2016), are essential to electrify ports, incorporate energy storage systems (Sifakis et al., 2021; Trahey et al., 2020; Vahabzad et al., 2021), and create revenue streams with extra electrical energy produced (Balbaa and El-Amary, 2017).

3.4.3. Clusters Analysis

After the bibliometric analysis and the content analysis of the most relevant indicators and aspects of the papers selected for the SLR, the most important research topics were identified and grouped. The *VOSviewer Software* is a tool for representing bibliometric maps (Van Eck and Waltman, 2010). The *VOSviewer Software* allows the analysis of research topics, elaborates on co-occurrence networks, and identifies research clusters (Jimenez et al., 2022; Souza Piao et al., 2023). Being easy to use and providing multiple features has made *VOSviewer Software* a tool present across different areas of knowledge and diverse audiences (Orduña-Malea and Costas, 2021).

A co-word analysis was conducted using the *VOSviewer Software* to create a conceptual structure using the Titles and the Abstracts of the 124 documents. The words in those fields were considered to establish links and build a bibliographic map, representing a network of themes and their relationships within a specific subject area (Zupic and Čater, 2015). The wider the connecting line, the stronger the link between the concepts is. The terms considered had a minimum of 10 occurrences and were selected according to their relevance to the study. The first iteration is shown in *Figure 3.13*.

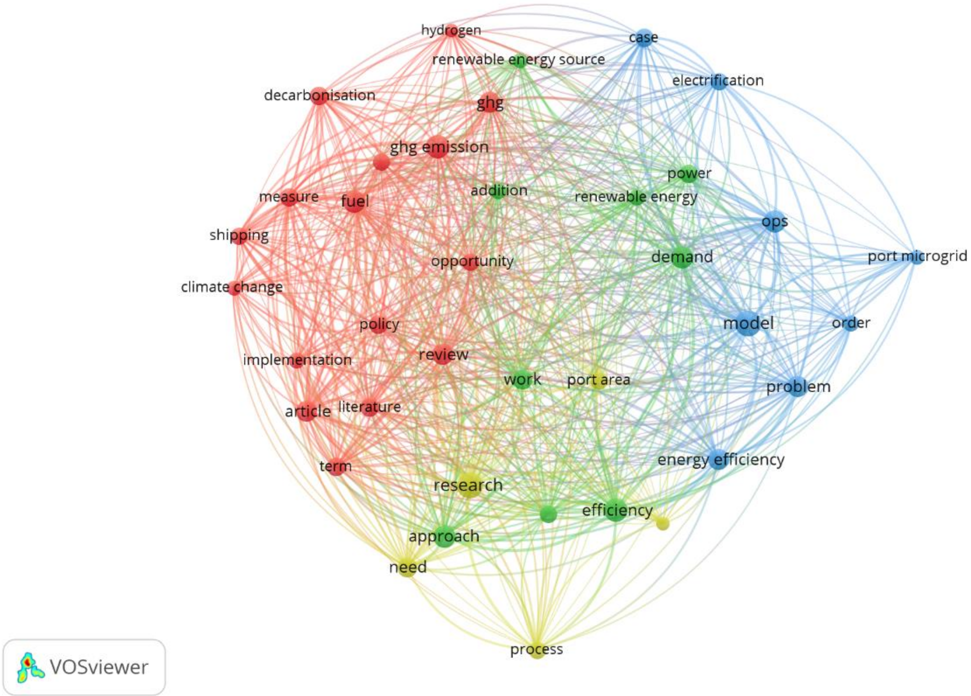

Figure 3.13. The first map of concepts.

Some concepts were standardised to achieve this first iteration (*Table 3.4.*). The goal was to avoid repeating ideas because some were in a plural form, others in a singular form, or because some were written in British and others in American English. Also, some concepts can be written in different ways, with words written in a complete form and others presented through an acronym.

Table 3.4. Standardisation of concepts.

Standardisation criteria	***Words to be replaced***	***Final words***
Plural forms replaced by singular forms	ports	port
	energies	energy
	GHGes or GHGs	GHG
	emissions	emission
American English forms replaced by British English forms	decarbonization	decarbonisation
	harbor	harbour

Different words for the same concept	onshore power supply, cold ironing, shore-side power, shore-side electricity	OPS
	seaport	port
	carbon dioxide, carbon, CO_2	CO2
Full-form words replaced by an acronym	greenhouse gas	GHG
	internet of things	IoT
	liquefied natural gas	LNG
	automated guided vehicle	AGVs

By analysing the concept map above in *Figure 3.13.*, it is already possible to identify some clusters, more specifically 4 clusters. In this sense, the method effectively visualised relationships between different research topics through the co-occurrence of keywords (Yu et al., 2021). However, this solution was still raw. Some concepts do not add value to the answer we were looking for. For example, concepts too vague, like need, order, or process; ideas repeated when a complete form already exists, like fuel or renewable energy; and concepts not relevant to answer the objectives and research questions of the work, like review, literature, or model. The goal was to use the literature to identify specific measures, so they were the focus of the final on the map. The concepts removed are listed below in *Table 3.5*.

Table 3.5. Concepts excluded and their exclusion criteria.

Exclusion Criteria	***Concept***
Concepts too vague	"work", "term", "implementation", "addition", "opportunity", "demand", "need", "approach", "power", "problem", "process", "case", "order"
Concepts repeated	"fuel", "renewable energy", "ghg", "efficiency"
Concepts not relevant	"review", "research", "literature", "article", "model"

The proposed final solution of the concept map for the decarbonisation of ports is represented in *Figure 3.14*. It has 3 main clusters and 15 items.

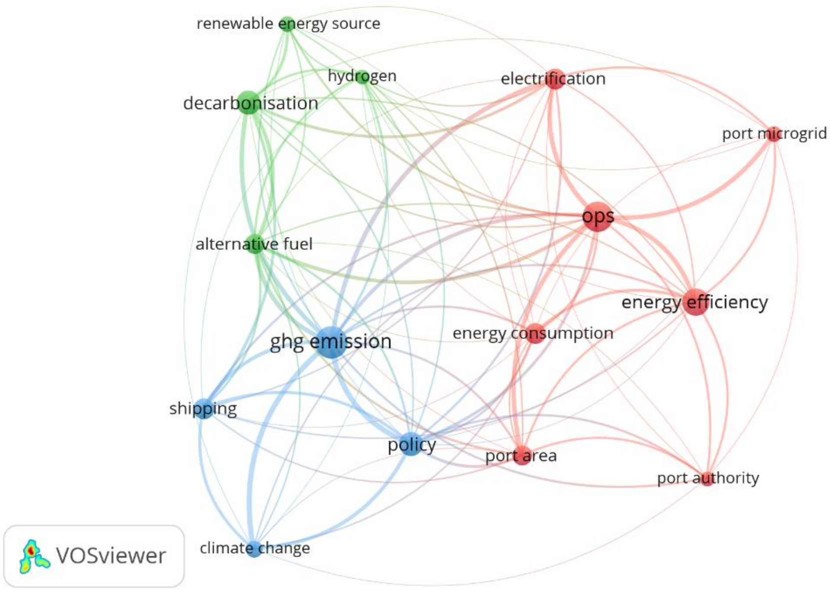

Figure 3.14. The final map of the clusters of investigation.

To summarise, it is possible to identify 3 clusters. The red one includes the concepts of "electrification", "energy consumption", "energy efficiency", "ops", "port area", "port authority", and "port microgrid". The terms "climate change", "ghg emission", "policy", and "shipping" make the blue cluster. The last cluster is the green cluster, which combines the occurrences of "alternative fuel", "decarbonisation", "hydrogen", and "renewable energy source". In *Appendix D*, it is possible to verify which papers selected for the SLR contribute to each cluster.

Using the *VOSviewer Software*, it is possible to do one other analysis, the density map. The density map shows the concepts' intensity and extensiveness and how they relate to their neighbouring terms. In *Figure 3.15.* we identify a clear "U" shape main path from "renewable energy source" to "electrification", passing by terms like "decarbonisation", "policy", or "ops". The lack of proximity of the word "electrification" to the neighbouring concepts "hydrogen" and "renewable energy source" indicates a weak relationship between these concepts, meaning that more research could be done on the use of renewable energy sources and hydrogen to electrify port infrastructures.

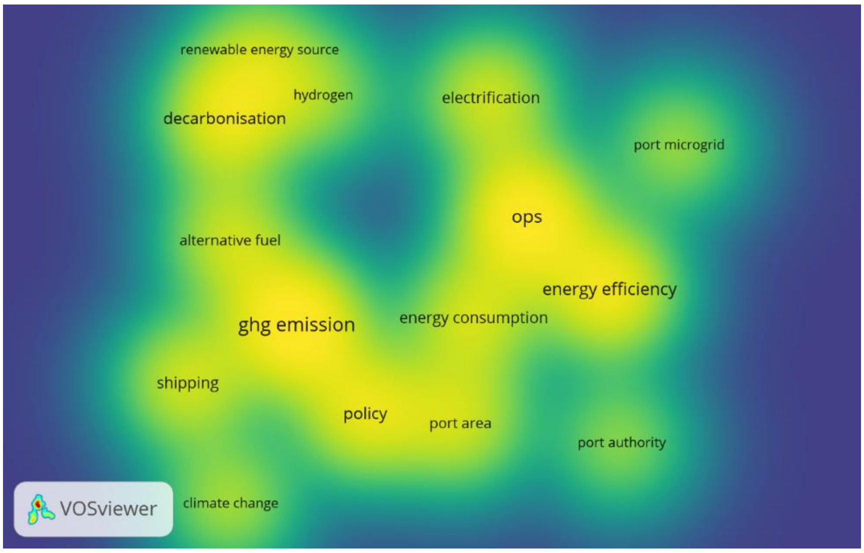

Figure 3.15. Map of the density of concepts.

Also, the concepts of “shipping”, “climate change”, “port authority”, and “port microgrid” seem disconnected from the main central path. It is possible to state that more studies could be made to increase the strength of those concepts with critical targets, like decarbonisation, reduction of GHG emissions, and improvement of energy efficiency.

For a more in-depth look at the 3 clusters of investigation identified through the co-word analysis, 3 subsections will follow, one for each cluster, with a detailed explanation of the research in each group. The steps proposed by Bashir (2022) and Souza Piao et al. (2023) were followed. The top 10 research papers, according to the number of citations, in every cluster were selected to reduce the sample of analysis and propose more concrete conclusions, which is a common practice in systematic and bibliometric studies (Fahimnia et al., 2015). The 15 concepts of the final map of clusters were searched in the Title and Abstract of the 124 documents selected for the SLR to identify the top 10 researched papers for each group.

3.4.3.1. Cluster 1 (red): “electrification”, “energy consumption”, “energy efficiency”, “ops”, “port area”, “port authority”, and “port microgrid”

The shipping sector is expected to improve energy efficiency parameters and reduce GHG emissions (Xing et al., 2020). Despite the current technological improvements, the mere development of technical solutions will not have effects until diffusion across the shipping industry has happened (Munim et al., 2020). That means it is necessary to bring all stakeholders together to combine efforts to adopt decarbonisation measures widely.

Ports are required to manage their electrical power distribution in microgrids, that is, a proper system that plans and monitors power demands and generations across all port locations, considering them unique customers. Moreover, the energy management of a port area is a commercial opportunity for the port authority (Parise et al., 2016). A roadmap to manage a grid in ports smartly and efficiently is essential. It should be based on 4 pillars: energy supply, energy storage, energy demand management, and optimal management and communication (Iris and Lam, 2019). The management of a port is becoming a complex multi-microgrid coordination problem. In port microgrids, various issues can be resolved by technical and operational measures, such as power-sharing, increased power quality, and voltage regulation rules (Fang et al., 2020).

When compared to traditional designs, port microgrids or smart grids implementation results in considerable cost savings due to the consideration of demand response mechanisms, like power sharing or peak shaving, and can escalate when ESS is deployed since they help to store energy for later utilisation or sell back to the main grid at higher prices (Iris and Lam, 2021). New KPIs should be suggested for energy efficiency measures and to facilitate the comparison of sustainable energy management practices, focusing on operational optimisation, like peak shaving, because it may lead to energy savings and emissions reductions (Iris and Lam, 2019). Like in any other business, management principles have a vital impact on the system's performance throughout its life cycle. One of those principles is operational efficiency, which in port microgrids implies reorganisation of the electrical distribution system to connect all users and to facilitate the implementation of innovations (Parise et al., 2016).

Ports are increasingly under pressure to reduce their environmental footprint (Acciaro, Ghiara et al., 2014; Parise et al., 2016). Electrification of all equipment and use of electricity as the primary energy source are the first steps for many seaports that want to contribute to mitigating climate change issues (Iris and Lam, 2021). With the trend of electrification in seaports, the connections between the landside and ships are no longer limited to a logistic vision but also expanded to an energy optimisation problem (Fang et al., 2020). The use of big data and AI can serve as a step for the digital transformation required to address energy efficiency problems (Munim et al., 2020).

OPS could reduce CO_2 emissions substantially, particularly in ports with a large share of high-frequency shipping lines (Styhre et al., 2017). OPS is an excellent measure to reduce GHG emissions and can be enhanced if a renewable source is used (Winnes et al., 2015). Ports should invest in electrification projects, which may include setting up conditions for port microgrids and all-electric ships (AESs), as feasible measures to enhance the overall system flexibility and mitigate environmental issues (Fang et al., 2020; Lindstad et al., 2015).

The importance of the port authority in the port area is pivotal when selecting decarbonisation measures. Port authorities must engage in energy management practices, like coordinating power generation, energy use, and implementing new renewable sources to diversify and respond to environmental pressure, and not just promote energy efficiency measures and stimulate energy conservation (Acciaro, Ghiara et al., 2014).

Since most of the identified measures and technologies need high investments, port authorities and operators need to perform an economic analysis to support the decision-making process because, depending on the size of the port, some investments might not be profitable (Iris and Lam, 2021). Port authorities should also consider the locations and the equipment within the port area with the highest potential for emissions reduction (Winnes et al., 2015). Moreover, the potential to reduce GHG emissions in the port area depends on how often a ship revisits a port (it is easier to implement decarbonisation measures for high-frequent lines in ports, while less frequent ship visitors (10 times or less) contribute significantly to emissions in ports) (Styhre et al., 2017).

Collaborations with partners and neighbouring stakeholders might help to adopt an optimal energy management plan (Iris and Lam, 2021). That also means that port energy management plans should be strongly linked to the neighbouring city strategies. In the end, energy management appears as a part of the strategic positioning of the port as a response to societal pressure and regulation or as a new alternative revenue source to improve the competitive position of the port due to the substantial efficiency gains (Acciaro, Ghiara et al., 2014). Increasing efficiency will eliminate unnecessary redundancy and energy waste while promoting central services for security, safety, administration, and automation (Parise et al., 2016).

3.4.3.2. Cluster 2 (blue): “climate change”, “ghg emission”, “policy”, and “shipping”

To reach sustainability goals, reduce the impact of climate change, turn around the tendency to increase GHG emissions, and ensure the sustainability of the shipping sector in the short, medium, and long term are the focus of the second cluster. Ports should provide infrastructures to reduce global shipping emissions while reducing their emissions once the required efforts result in environmental benefits (Gibbs et al., 2014).

With the international commitment to limit the effects of climate change, the shipping sector also started facing the challenge of reducing its emissions (Bouman et al., 2017). Models to minimise costs for a ship and determine sailing paths and speeds along a given sequence of ports are developed (Fagerholt et al., 2015). Programmes and policies for ports to address GHG emissions have been introduced. Still, international cooperation towards stricter regulations cannot be missing, and to overcome local issues, a port-city perspective could be more important than a global vision (Winnes et al., 2015). For example, even with a limited number of ports being certified for the ISO 50001 implementation, ports can start locally developing corporate policies for energy management and efficiency (Iris and Lam, 2019). Emerging digital technologies, like BDA, would promote more reliable and efficient management systems across the shipping industry (Fruth and Teuteberg, 2017).

The efforts implemented by ports need to be quantified in terms of potential reductions of ships' emissions to best select a group of measures in a decarbonisation strategy once the most significant potential for reduction is at fairway channels or at berth (Winnes et al., 2015). Bouman et al. (2017) reported a substantial variation in emissions reduction potentials across studies, meaning that decarbonisation measures must be chosen from a case-by-case perspective and that no single action is sufficient to achieve neutrality targets. They also conclude that operational practices are the most promising groups. If those measures are appropriately combined, based on current state-of-the-art technologies, emissions can be reduced by around 75% by 2050 if policies are developed to help adopt and implement the selected measures.

Reductions in GHG emissions and local pollutant levels are vital challenges, and to understand the full implications of emissions reductions, a complete life-cycle perspective should be adopted besides adopting measures like ESS (Gilbert et al., 2018; Trahey et al., 2020). Unfortunately, as Winnes et al. (2015) concluded in their study, there are severe difficulties in achieving the GHG emission levels desired for ports by 2030. For example, because a significant percentage of emissions in ports caused by ships are produced by low frequent visitors (less than 10 visits per year), who may not be interested in adopting measures in partnership with specific ports (Styhre et al., 2017).

As a result, operational measures which are insufficient to achieve neutrality targets may look more attractive once ports have difficulties offering incentives for measures requiring high investment costs, such as fuel shifts, OPS, or design improvements (Styhre et al., 2017; Winnes et al., 2015).

Therefore, the port's opportunity to offer incentives and infrastructure for decarbonisation measures with high investment costs (alternative fuels, OPS, among others) is at risk. Collective action is critical, and the lack of it can mislead industry policymakers and regulators, which has severe consequences (Gilbert et al., 2018). A clear example can be found in the adoption of digitalisation techniques. Industry 4.0 measures have several benefits at a relatively low cost, like efficiency, safety, and energy saving. However, risks, such as data abuse or cybercrime, must be considered collectively and internationally (Fruth and Teuteberg, 2017).

3.4.3.3. Cluster 3 (green): "alternative fuel", "decarbonisation", "hydrogen", and "renewable energy source"

The third cluster mentions some of the most essential measures to decarbonise seaports: alternative fuels, hydrogen, and renewable energy sources. Alternative fuels as a cleaner practice, RE utilisation as a significant cost-saving measure, and hydrogen as an emerging solution are globally recognised to reduce shipping emissions (Ampah et al., 2021; Gilbert et al., 2018; Iris and Lam, 2019). The uptake in the port sector of innovative technologies, such as alternative fuels or renewable energy installations in port areas, demands more attention to energy matters within ports' management (Acciaro, Ghiara et al., 2014).

Ports worldwide need to assess each measure's potential for implementation and identify where crucial barriers may be located (Gilbert et al., 2018; Iris and Lam, 2019). Also, the interest and level of adoption of measures, such as alternative fuels, from the shipowners' perspective would help identify barriers and ways to tackle them (Ampah et al., 2021). One thing is clear: a complete analysis should be performed to understand the advantages and the limitations of the exploitability of the chosen practice. For example, several parameters should be considered when using a renewable source to conclude the feasibility of exploiting such measures, such as energy outputs, site-specific efficiency, availability, and capacity factors (Ramos et al., 2014).

Unconventional alternative energy sources, like the use of nuclear energy in ships, seem unlikely to be accepted, but further consideration and investigation are worthwhile because current research on nuclear applications could be more extensive. Fuel cell technology is an essential mechanism for cleaner fuels such as hydrogen and ammonia but requires more research, too (Xing et al., 2020).

By decarbonising energy inputs and feedstock materials using renewable sources, GHG emissions reductions are possible if stakeholders in the shipping industry, like ports, do not have an individual approach when addressing significant barriers (Gilbert et al., 2018). Measures to decarbonise ports, like renewable energy sources and alternative fuels, are highly effective measures to reduce emissions (Winnes et al., 2015). Still, in the end, the targets of decarbonisation defined by the IMO (2018) will only be possible to achieve if all stakeholders of the shipping industry fulfil their while taking shared investments and developing collaborative partnerships (Ampah et al., 2021).

Besides the measures already mentioned that can cause structural changes in ports, other measures can be highly efficient for CO2 reductions and achieving decarbonisation targets. Vessel speed reductions to and from the port or time at berth reductions are examples of those measures (Styhre et al., 2017). ESS are a crucial pillar of modern society, and they can help in addressing the variability in renewable energy production, increasing the efficiency of storage and distribution of energy (Trahey et al., 2020). No isolated and individual measure will be sufficient to achieve the objectives of low-carbon and zero-carbon shipping defined in the Initial Strategy of the IMO (2018) (Xing et al., 2020).

3.5. Discussion of Results

To properly close the analysis of results from the SLR, future research opportunities will be presented. The goal is to understand the most critical lines for future work.

3.5.1. Future Research Opportunities for the Cluster 1 (red)

Future research directions for the first cluster can explore simulations to integrate OPS with optimal berth allocation and alternative fuels, consider autonomous and electrified equipment with scheduling decisions for energy storage devices charging, or combine electrification with hydrogen fuel cells (Iris and Lam, 2019). Stakeholders' participation in adequate scenario building and high-quality models, mainly due to the diverse conditions that ports experience, is also significant (Winnes et al., 2015). This results in the need for customisation and tailoring of a set of decarbonisation measures based on the specifications of each port, helping port authorities better implement a decarbonisation strategy (Styhre et al., 2017).

A distributed control framework, adaptive energy management techniques, and efficient ESS management are some problems to address in future research about port electrification and microgrids (Fang et al., 2020). In addition, hybrid power solutions should be developed once they have a lower environmental impact and annual fuel bill than standard combustion systems (Lindstad et al., 2015).

Technology development should be balanced with more research on legal, cultural, commercial, and collaboration issues, for example, by identifying drivers and barriers to increasing transparency and trust to overcome legal obstacles, such as cybersecurity and data ownership within a digital network (Munim et al., 2020). The barriers and opportunities for decarbonisation measures should be identified and analysed, as well as economic and environmental performance analysis for smart grid through simulation (Iris & Lam, 2019). There is a need to clarify where and how the port authority can operate to increase energy efficiency in the port area while investigating the port industry from a benchmarking perspective, particularly for energy management as a sustainable and innovative practice due to the lack of awareness of its importance in ports (Acciaro, Ghiara et al., 2014).

3.5.2. Future Research Opportunities for the Cluster 2 (blue)

For future research directions, it is recommended to use more precise data from each scope of emission for studies that will assess the emissions of ports and test decarbonisation solutions before going into "industrial" levels (Gilbert et al., 2018; Winnes et al., 2015). Also, limiting GHG emissions needs to be tested when using environmentally differentiated port charges and when offering clean sources of energy supply (Styhre et al., 2017).

Research on policies and regulatory frameworks for ports and the implications for public authorities should be developed, and improvements in collaborations for shipping-related themes between different institutions, countries, or authors should be facilitated (Ampah et al., 2021). Incentives for further enhancements in maritime transport energy efficiency are recurrent in the industry. However, they are not always implemented due to existing barriers, like restricting contracts, lack of proper information, and lack of control over operations. Barriers that should be studied once they prevent economic benefits by stopping investments in energy efficiency technologies (Styhre et al., 2017).

3.5.3. Future Research Opportunities for the Cluster 3 (green)

Some future research directions identified in the documents selected for this cluster are operational, technological, economic, and environmental analyses of renewable energy sources and hydrogen fuel cells for viability and applicability assessment or technological developments, feasibility analysis and pilot projects for maritime applications of renewable energy sources (Iris and Lam, 2019; Xing et al., 2020).

Modelling a port energy management system based on renewable energy sources, under uncertainty (disruptions, natural events, among other events), and combined with other technologies, like diesel generators, would be critical (Iris and Lam, 2021). However, besides the perspective of the implementation of decarbonisation measures, other requirements need to be investigated, such as installation and maintenance costs, ESS facilities, and impacts on the marine environment (Ramos et al., 2014).

It is also necessary to conduct studies on combustion characteristics and performance for stakeholders to evaluate the complete feasibility of alternative fuels or advancements of other measures (power and propulsion systems, efficient hull design, speed optimisation, marine fuel mix, among others) (Ampah et al., 2021). As well as improve the knowledge in the developing and manufacturing batteries to best respond to high-emergent demands and fulfil their role as essential applications to decarbonise maritime shipping (Trahey et al., 2020). Just like the diversification of the types of ships, the decentralisation and diversification of ship power systems are inevitable until 2100, making prospects depend on sustainable technological improvements and policy support (Xing et al., 2020).

Also, efforts must be made internationally to help policy development for alternative fuels, considering that a method to conduct international benchmarking studies more easily is required to make meaningful comparisons of ship emissions in ports (Styhre et al., 2017; Winnes et al., 2015). Economic considerations and regulatory obstacles are currently the main challenges, which entail more research on legal requirements, market-based measures, and voluntary programs (Xing et al., 2020).

3.6. Summary

The "Initial IMO Strategy" set targets for 2030 (40% CO2 reduction compared to 2008 levels) and for 2050 (50% GHG reduction compared to 2008 levels) (IMO, 2018). Alamoush et al. (2020) conclude that electrification, hybridisation, and alternative fuels have the most significant potential of all measures to decarbonise seaports and achieve neutrality targets, especially if renewable energies are the energy source of those measures. The lack of skilled workforce and the increase in cargo volume stimulate disruptive technological solutions – automation, electrification, and digitalisation – in the port industry (Zhou et al., 2022).

The 1.5ºC limit for the global temperature rise set by the Intergovernmental Panel on Climate Change (IPCC) forces the maritime industry to adopt zero-emission fuels and emerging technologies, besides operational and energy efficiency measures. The average lifetime of vessels is 20 to 30 years, which causes the shipping sector to promote secure, operational, and optimised commercial trade routes and zero-emission vessel development and implementation (Energy Transitions Commission, 2020).

The COVID-19 pandemic affected business and market growth expectations for container transport companies and ceased many terminal investment plans. However, the maritime transport industry is recovering, and emissions levels have returned to pre-pandemic levels (UNCTAD, 2021; Zhou et al., 2022). Accounting that 86% of business leaders invest in sustainability to protect their organisations from disruptions (Gartner, 2022), incentives and initiatives must be put into action to increase investors' motivation to invest in the development of green and sustainable seaports and achieve potential marketing benefits (Alzahrani et al., 2021; Styhre et al., 2017).

In the port area, ship-port interface measures have great potential because the fair channel and berth have the highest potential for emissions reduction in different scenarios (Winnes et al., 2015). Operational efforts should be combined with port-city integration, cooperation among other ports, as well as implementation of green policies, like the FeulEU Maritime initiative, and achievement of international requirements, like the European Green Deal (Alamoush et al., 2020; Psaraftis & Zis, 2022). Implementing technological solutions to comply with international regulations can decarbonise seaports and supply chains (Alamoush et al., 2020; Xu et al., 2023).

Since 2018, the World Ports Sustainability Program (WPSP) has been developing a portfolio and a global database of port-related projects on sustainable development (Verhoeven et al., 2020). In terms of geographical representation, European port projects dominate, which agrees with the findings from this work. With the commitment for Europe to be the first carbon-neutral continent, the lack of available reports from the European seaports is a concern (Balić et al., 2022; European Commission, 2023).

Climate change, as the most significant contributor to the uncertainty in sustainable port design, requires international policies and regulations that are currently missing, which increases the resistance to new options to decarbonise the maritime sector (dos Santos et al., 2022; Loza and Veloso-Gomes, 2023). Worldwide, with only 1% of ports fully automated and 2% semi-automated, the maritime sector has a long path to becoming fully automated (Alamoush et al., 2020).

No universal solution to decarbonise ports is sufficient to reduce GHG emissions substantially. Even with many decarbonisation options, various limitations can be identified in each measure, making none the best pathway (Tai and Chang, 2022; Xing et al., 2020). Solutions must be customer-tailored for specific ports and involve a combination of measures (Styhre et al., 2017; Xing et al., 2020). If significant barriers, like economic and public acceptance, are overcome, electrification, digitalisation, and alternative energy sources will be the pathway to decarbonise maritime ports (Balcombe et al., 2019; Xing et al., 2020).

Developing an instrument to evaluate each port's best mix of measures is critical, and it is the only way to establish a decarbonisation strategy. A benchmarking tool could be set to evaluate actions and their level of implementation across a region or the entire globe. The purpose should be to understand which measures and practices are most used and at which level of adoption. With that, it would be possible to compare the most studied decarbonisation measures and the most implemented ones. This tool should consider the stakeholders' insights into ports' decarbonisation process and their roles in the strategy definition.

4. CONCLUSIONS

After data analysis and subsequent discussion, essential conclusions were drawn regarding how ports should decarbonise and can be summarised in one sentence: "There is no universal and single measure to decarbonise maritime ports". As a final chapter, the key insights are presented, limitations of the study are identified, and future research endeavours are suggested. That ensures ongoing investigations will continue to contribute knowledge to the theme.

This work has first delved into the theme of decarbonisation strategies, offering an extensive exploration of key concepts, like net-zero, low-carbon, and scopes of emissions. An overview of the decarbonisation of supply chains was conducted to understand the strategies, challenges, and drivers. By doing so, the baselines for the study of the decarbonisation of seaports are set once seaports play a critical role in global supply chains and world trade of goods.

Through a SLR and comprehensive analysis, it has become evident that while the literature on decarbonisation measures and their adoption is burgeoning, there was a need for more representation of the most important clusters of investigation of this topic. The research has highlighted the urgent need for increased focus on adopting innovative technologies to curtail greenhouse gas emissions within the maritime sector and a way to learn which are the biggest motivations for ports to decarbonise operations.

The findings have illuminated the multifaceted nature of the barriers to decarbonisation, such as economic, regulatory, operational, and market-based dimensions. That empowers the conclusion of the need for collaborative initiatives among stakeholders to address these challenges collectively. Furthermore, the synthesis of diverse viewpoints and strategies presented in the literature underscores the complexity of port decarbonisation and the necessity for tailored solutions that align with local contexts and specific operational requirements.

The insights gleaned from this study have practical implications for maritime industry practitioners, policymakers, and researchers alike. As the world accelerates its pursuit of a sustainable future, it is evident that the shipping sector's role in global decarbonisation efforts is paramount. The maritime industry can be a vanguard of change in the journey towards a carbon-neutral future by fostering cross-disciplinary collaboration, encouraging innovative technologies, and streamlining regulatory frameworks.

To answer the RQs proposed, a summary for each question is presented below:

1) Through the cluster analysis, using the *VOSviewer Software*, the main topics of research are “electrification”, “energy consumption”, “energy efficiency”, “ops”, “port area”, “port authority”, “port microgrid”, “climate change”, “ghg emission”, “policy”, “shipping”, “alternative fuel”, “decarbonisation”, “hydrogen”, and “renewable energy source”. The main topics of research are organised in 3 clusters. Cluster 1, the red one, includes the concepts of “electrification”, “energy consumption”, “energy efficiency”, “ops”, “port area”, “port authority”, and “port microgrid”. The terms “climate change”, “ghg emission”, “policy”, and “shipping” make the second cluster. The last cluster is the green cluster, which combines the occurrences of “alternative fuel”, “decarbonisation”, “hydrogen”, and “renewable energy source”.
2) The critical directions for future research for each cluster are detailed above. Generally, the new insights described above indicate a benchmarking opportunity to understand the level of decarbonisation in ports. More simulation and optimisation studies are needed to set the best mix of measures in specific ports. The participation of more ports’ stakeholders in the decarbonisation process and identifying drivers and barriers to adopting measures should be pursued. Policy and regulations definition is critical for this area.

Like all other scientific projects, this work also has its limitations. The research scope constraint and the field’s dynamic nature demand ongoing vigilance to remain current and relevant. There is also the possibility that some relevant articles to the work were not selected because of the keywords chosen. That could happen due to the definition of inappropriate keywords, alternative names for the same concept, and other imposed exclusion criteria like language and subject area. The articles’ selection, inclusion, categorisation, and analyses were influenced by the bias of the authors’ subjectivity.

As the decarbonisation of seaports is developed with this work, the foundations for new perspectives of research opportunities are summarised, allowing a transformation within the maritime industry.

More research is needed globally, especially in African, South American, and Oceanic countries. Also, more research in European and Asian countries is vital to compare countries on the same continent. That is essential once neighbouring countries have different political, ethical, cultural, environmental, and economic positions that may drastically change ports' decarbonisation.

In terms of methodologies used, action research, ethnographic observation, or surveys are essential to implement in the future, once they are very little present or not present in the literature collected for the SLR. Mixed strategies can give broader perspectives because they combine different research methodologies, so increasing the number of works using this strategy is crucial.

Finally, conservative practices need to be studied in the context of the decarbonisation of ports as soon as possible. Unfortunately, most sustainability and net-zero targets are impossible or difficult to achieve in the expected timeline. However, offset and carbon capture and sequestration measures can be a solution for a short-term and medium-term decarbonisation pathway because of their high emission reduction potential in the short-term and with relatively low efforts. In general, more studies on the possibility of reduction of emissions when several measures are combined, can benefit port stakeholders' when choosing the best combination of measures because one single measure is insufficient for a decarbonisation strategy.

Moreover, the level of implementation of each measure, the impact on ports' strategy and performance, or the perceived barriers/benefits from adopting the several types of techniques, standards, and actions are opportunities for future work. Such future work could be materialised in a survey to understand how ports combine different efforts, the requirements to select those specific measures, and the impacts of measures implementation in the different emission scopes.

In conclusion, synthesising existing literature, empirical insights, and strategic perspectives presents a compelling case for embracing technological advancements to curtail greenhouse gas emissions in maritime ports. Our collective responsibility is to usher in an era of sustainable practices that safeguard our planet for future generations. The maritime sector stands poised to play a pivotal role in this crucial endeavour.

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APPENDIX A

Reference	Title	Source title	Cited by
Colodner et al., 2011	Port authority of New York and New Jersey criterion pollutant and greenhouse gas emission inventory	Transportation Research Record	
Choi et al., 2012	Design and implementation of practical asset tracking system in container terminals	International Journal of Precision Engineering and Manufacturing	11
Kim et al., 2012	Life-Cycle Emissions from Port Electrification: A Case Study of Cargo Handling Tractors at the Port of Los Angeles	International Journal of Sustainable Transportation	26
Pavlic et al., 2014	Sustainable port infrastructure, practical implementation of the green port concept	Thermal Science	54
Acciaro, Ghiara et al., 2014	Energy management in seaports: A new role for port authorities	Energy Policy	186
Gibbs et al., 2014	The role of sea ports in end-to-end maritime transport chain emissions	Energy Policy	115
Ramos et al., 2014	A port towards energy self-sufficiency using tidal stream power	Energy	62
Fagerholt et al., 2015	Maritime routing and speed optimization with emissions control areas	Transportation Research Part C: Emerging Technologies	180
Winnes et al., 2015	Reducing GHG emissions from ships in port areas	Research in Transportation Business and Management	140
Lindstad et al., 2015	Maritime shipping and emissions: A three-layered, damage-based approach	Ocean Engineering	64
Schmidt et al., 2015	Using battery-electric AGVs in container terminals - Assessing the potential and optimizing the economic viability	Research in Transportation Business and Management	47
Ölçer and Ballini, 2015	The development of a decision making framework for evaluating the trade-off solutions of cleaner seaborne transportation	Transportation Research Part D: Transport and Environment	35
Parise et al., 2016	Wise port and business energy management: Port facilities, electrical power distribution	IEEE Transactions on Industry Applications	77

Sciberras et al., 2016	Cold ironing and onshore generation for airborne emission reductions in ports	Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment	30
Boile et al., 2016	Developing a port energy management plan: Issues, challenges, and prospects	Transportation Research Record	22
Bouman et al., 2017	State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review	Transportation Research Part D: Transport and Environment	391
Styhre et al., 2017	Greenhouse gas emissions from ships in ports – Case studies in four continents	Transportation Research Part D: Transport and Environment	114
Fruth and Teuteberg, 2017	Digitization in maritime logistics — What is there and what is missing?	Cogent Business and Management	77
Yang et al., 2017	A carbon emission evaluation for an integrated logistics system-a case study of the port of Shenzhen	Sustainability (Switzerland)	36
Lindstad et al., 2017	Batteries in offshore support vessels – Pollution, climate impact and economics	Transportation Research Part D: Transport and Environment	29
Misra, Venkataramani et al., 2017	Renewable Energy Based Smart Microgrids—A Pathway To Green Port Development	Strategic Planning for Energy and the Environment	28
Misra, Panchabikesan, Gowrishankar et al., 2017	GHG emission accounting and mitigation strategies to reduce the carbon footprint in conventional port activities–a case of the Port of Chennai	Carbon Management	22
Balbaa and El-Amary, 2017	Green energy seaport suggestion for sustainable development in Damietta Port, Egypt	WIT Transactions on Ecology and the Environment	7
Yarova et al., 2017	Economic assessment of the alternative energy sources implementation for port enterprises	Economic Annals-XXI	7
Misra, Panchabikesan, Ayyasamy et al., 2017	Sustainability and Environmental Management: Emissions Accounting for Ports	Strategic Planning for Energy and the Environment	4
Amar et al., 2017	Development of a duty cycle for the design and optimization of advanced, heavy-duty port drayage trucks	Transportation Research Record	3
Misra, Tajudeen et al., 2017	Role of biodiesel with nanoadditives in port owned trucks and other vehicles for emissions reduction	Thermal Science	2
Gilbert et al., 2018	Assessment of full life-cycle air emissions of alternative shipping fuels	Journal of Cleaner Production	138

Yun et al., 2018	A simulation-based research on carbon emission mitigation strategies for green container terminals	Ocean Engineering	50
Bosman et al., 2018	Carbon lock-out: Leading the fossil port of Rotterdam into transition	Sustainability (Switzerland)	25
Ozturk et al., 2018	Energy-Aware Smart Connectivity for IoT Networks: Enabling Smart Ports	Wireless Communications and Mobile Computing	23
Iris and Lam, 2019	A review of energy efficiency in ports: Operational strategies, technologies and energy management systems	Renewable and Sustainable Energy Reviews	187
Kanellos et al., 2019	Power management method for large ports with multi-agent systems	IEEE Transactions on Smart Grid	44
Rolan et al., 2019	Integration of Cold Ironing and Renewable Sources in the Barcelona Smart Port	IEEE Transactions on Industry Applications	33
Gutierrez-Romero et al., 2019	Implementing Onshore Power Supply from renewable energy sources for requirements of ships at berth	Applied Energy	33
Gennitsaris and Kanellos, 2019	Emission-Aware and Cost-Effective Distributed Demand Response System for Extensively Electrified Large Ports	IEEE Transactions on Power Systems	29
Yang et al., 2019	Choice of technology for emissions control in port areas: A supply chain perspective	Journal of Cleaner Production	27
Di Vaio et al., 2019	Management Control Systems in port waste management: Evidence from Italy	Utilities Policy	23
Kumar et al., 2019	Design and analysis of new harbour grid models to facilitate multiple scenarios of battery charging and onshore supply for modern vessels	Energies	18
Kurtulus and Cetin, 2019	Assessing the environmental benefits of dry port usage: A case of inland container transport in Turkey	Sustainability (Switzerland)	17
Alasali et al., 2019	A comparative study of energy storage systems and active front ends for networks of two electrified RTG cranes	Energies	8
Islam et al., 2019	Minimization of empty container truck trips: insights into truck-sharing constraints	International Journal of Logistics Management	8
Verma and Gupta, 2019	Efficient docker container scheduling using ABC optimization technique	International Journal of Innovative Technology and Exploring Engineering	
Trahey et al., 2020	Energy storage emerging: A perspective from the Joint Center for Energy Storage Research	Proceedings of the National Academy of Sciences of the United States of America	156
Fang et al., 2020	Toward Future Green Maritime Transportation: An Overview of Seaport Microgrids and All-Electric Ships	IEEE Transactions on Vehicular Technology	113

Munim et al., 2020	Big data and artificial intelligence in the maritime industry: a bibliometric review and future research directions	Maritime Policy and Management	104
Xing et al., 2020	A comprehensive review on countermeasures for CO2 emissions from ships	Renewable and Sustainable Energy Reviews	68
Alamoush et al., 2020	Ports' technical and operational measures to reduce greenhouse gas emission and improve energy efficiency: A review	Marine Pollution Bulletin	34
Castellano et al., 2020	Evaluating the economic and environmental efficiency of ports: Evidence from Italy	Journal of Cleaner Production	32
Poulsen and Sampson, 2020	A swift turnaround? Abating shipping greenhouse gas emissions via port call optimization	Transportation Research Part D: Transport and Environment	23
Lee et al., 2020	Estimation of the non-greenhouse gas emissions inventory from ships in the port of Incheon	Sustainability (Switzerland)	23
Roy et al., 2020	Design, sizing, and energy management of microgrids in harbor areas: A review	Energies	22
Oliveira-Pinto and Stokkermans, 2020	Marine floating solar plants: An overview of potential, challenges and feasibility	Proceedings of the Institution of Civil Engineers: Maritime Engineering	22
Kermani et al., 2020	Ultracapacitors for port crane applications: Sizing and techno-economic analysis	Energies	17
Mukherjee et al., 2020	A Perspective on Biofuels Use and CCS for GHG Mitigation in the Marine Sector	iScience	16
Ranjan et al., 2020	Energy-Efficient Workflow Scheduling Using Container-Based Virtualization in Software-Defined Data Centers	IEEE Transactions on Industrial Informatics	13
Seddiek, 2020	Application of renewable energy technologies for eco-friendly sea ports	Ships and Offshore Structures	11
Schneider et al., 2020	Risks and opportunities associated with decarbonising Rotterdam's industrial cluster	Environmental Innovation and Societal Transitions	8
Holly et al., 2020	Flexibility management and provision of balancing services with battery-electric automated guided vehicles in the Hamburg container terminal Altenwerder	Energy Informatics	7
Lavidas et al., 2020	Blue growth development in the mediterranean sea: Quantifying the benefits of an integrated wave energy converter at Genoa harbour	Energies	4
Ampah et al., 2021	Reviewing two decades of cleaner alternative marine fuels: Towards IMO's decarbonization of the maritime transport sector	Journal of Cleaner Production	72
Iris and Lam, 2021	Optimal energy management and operations planning in seaports with smart grid while harnessing renewable energy under uncertainty	Renewable and Sustainable Energy Reviews	63

Mallouppas and Yfantis, 2021	Decarbonization in Shipping industry: A review of research, technology development, and innovation proposals	Journal of Marine Science and Engineering	54
Sifakis and Tsoutsos, 2021	Planning zero-emissions ports through the nearly zero energy port concept	Journal of Cleaner Production	29
Ortiz-Imedio et al., 2021	Power-to-Ships: Future electricity and hydrogen demands for shipping on the Atlantic coast of Europe in 2050	Energy	22
Sifakis et al., 2021	Hybrid renewable energy system optimum design and smart dispatch for nearly Zero Energy Ports	Journal of Cleaner Production	20
Foretich et al., 2021	Challenges and opportunities for alternative fuels in the maritime sector	Maritime Transport Research	16
Wan et al., 2021	Evaluation of emission reduction strategies for berthing containerships: A case study of the Shekou Container Terminal	Journal of Cleaner Production	15
Reusser and Pérez, 2020	Evaluation of the emissions impact of cold-ironing power systems, using a bi-directional power flow control strategy	Sustainability (Switzerland)	13
Široka et al., 2021	A novel approach for assessing the ports' environmental impacts in real time – The IoT based port environmental index	Ecological Indicators	11
Vahabzad et al., 2021	Optimal energy scheduling of a solar-based hybrid ship considering cold-ironing facilities	IET Renewable Power Generation	11
Mańkowska et al., 2021	Biomass sea-based supply chains and the secondary ports in the era of decarbonization	Energies	10
Pu and Lam, 2021	Greenhouse gas impact of digitalizing shipping documents: Blockchain vs. centralized systems	Transportation Research Part D: Transport and Environment	10
Garcia et al., 2021	Net Zero for the International Shipping Sector? An Analysis of the Implementation and Regulatory Challenges of the IMO Strategy on Reduction of GHG Emissions	Journal of Environmental Law	9
Alzahrani et al., 2021	Decarbonisation of seaports: A review and directions for future research	Energy Strategy Reviews	9
Kinnon et al., 2021	The role of fuel cells in port microgrids to support sustainable goods movement	Renewable and Sustainable Energy Reviews	8
Bakar et al., 2021	A review of the conceptualization and operational management of seaport microgrids on the shore and seaside	Energies	8
Lu and Huang, 2021	Optimization of shore power deployment in green ports considering government subsidies	Sustainability (Switzerland)	7
Vicenzutti and Sulligoi, 2021	Electrical and energy systems integration for maritime environment-friendly transportation	Energies	3
Pei et al., 2021	Robust multi-layer energy management and control methodologies for reefer container park in port terminal	Energies	1
Taneja et al., 2021	Sustainability performance of port infrastructure—a case study of a quay wall	Sustainability (Switzerland)	1

Spaniol and Hansen, 2021	Electrification of the seas: Foresight for a sustainable blue economy	Journal of Cleaner Production	1
Xia et al., 2021	Power Dispatching of Transportable Energy Storage System for Post-disaster Restoration Scheme of Port: The AES-Based Joint Restoration Scheme	Frontiers in Energy Research	
Hoang et al., 2022	Energy-related approach for reduction of CO2 emissions: A critical strategy on the port-to-ship pathway	Journal of Cleaner Production	59
Mao et al., 2022	Optimal scheduling for seaport integrated energy system considering flexible berth allocation	Applied Energy	15
Vichos et al., 2022	Challenges of integrating hydrogen energy storage systems into nearly zero-energy ports	Energy	12
Agostinelli, Cumo et al., 2022	Renewable Energy System Controlled by Open-Source Tools and Digital Twin Model: Zero Energy Port Area in Italy	Energies	8
Zhang et al., 2022	Optimal Port Microgrid Scheduling Incorporating Onshore Power Supply and Berth Allocation Under Uncertainty	Applied Energy	8
Daniel et al., 2022	Shore power as a first step toward shipping decarbonization and related policy impact on a dry bulk cargo carrier	eTransportation	7
Zhu et al., 2022	Assessment of the greenhouse gas, Episodic air quality and public health benefits of fuel cell electrification of a major port complex	Atmospheric Environment	5
Nguyen, Nguyen et al., 2022	Green Port Strategies in Developed Coastal Countries as Useful Lessons for the Path of Sustainable Development: A Case study in Vietnam	International Journal of Renewable Energy Development	5
Dai et al., 2022	UAV-assisted data offloading for smart container in offshore maritime communications	China Communications	4
Kurtuluş, 2023	Optimizing Inland Container Logistics and Dry Port Location-Allocation from an Environmental Perspective	Research in Transportation Business and Management	3
Pivetta et al., 2022	Multi-Objective Optimization of a Hydrogen Hub for the Decarbonization of a Port Industrial Area	Journal of Marine Science and Engineering	3
Tai and Chang, 2022	Reducing pollutant emissions from vessel maneuvering in port areas	Maritime Economics and Logistics	3
Fang et al., 2022	Optimal power scheduling of seaport microgrids with flexible logistic loads	IET Renewable Power Generation	3
Sinha and Roy Chowdhury, 2022	A framework for ensuring zero defects and sustainable operations in major Indian ports	International Journal of Quality and Reliability Management	2
Zhou and Zhang, 2022	Choice of Emission Control Technology in Port Areas with Customers' Low-Carbon Preference	Sustainability (Switzerland)	2

Nguyen, Pham et al., 2022	Technical-Environmental Assessment of Energy Management Systems in Smart Ports	International Journal of Renewable Energy Development	2
Sifakis et al., 2022	Introducing the cold-ironing technique and a hydrogen-based hybrid renewable energy system into ports	International Journal of Energy Research	2
Kim, 2022	Characteristics of Economic and Environmental Benefits of Shore Power Use by Container-Ship Size	Journal of Marine Science and Engineering	1
Argyriou et al., 2022	Challenging a sustainable port. A case study of Souda port, Chania, Crete	Case Studies on Transport Policy	1
Ullah Khan et al., 2022	Cyber Secure Framework for Smart Containers Based on Novel Hybrid DTLS Protocol	Computer Systems Science and Engineering	
Shan et al., 2022	Polymorphic Distributed Energy Management for Low-Carbon Port Microgrid With Carbon Capture and Carbon Storage Devices	Frontiers in Energy Research	
Teng et al., 2022	Distributed low-carbon energy management method for port microgrid based on we-energies under polymorphic network	Frontiers in Energy Research	
Agostinelli, Neshat et al., 2022	Integrating Renewable Energy Sources in Italian Port Areas towards Renewable Energy Communities	Sustainability (Switzerland)	
Sogut and Erdoğan, 2022	An investigation on a holistic framework of green port transition based on energy and environmental sustainability	Ocean Engineering	
Yen et al., 2023	How smart port design influences port efficiency – A DEA-Tobit approach	Research in Transportation Business and Management	3
Kumar et al., 2023	Synergy of green hydrogen sector with offshore industries: Opportunities and challenges for a safe and sustainable hydrogen economy	Journal of Cleaner Production	2
Liao et al., 2023	Knowledge Mapping Analysis of Intelligent Ports: Research Facing Global Value Chain Challenges	Systems	1
Drungilas et al., 2023	Deep reinforcement learning based optimization of automated guided vehicle time and energy consumption in a container terminal	Alexandria Engineering Journal	1
Kovalishin et al., 2023	Using Artificial Intelligence (AI) methods for effectively responding to climate change at marine ports	Journal of International Maritime Safety, Environmental Affairs, and Shipping	
Mansoursamaei et al., 2023	Machine Learning for Promoting Environmental Sustainability in Ports	Journal of Advanced Transportation	
Vidović et al., 2023	Systematic Overview of Newly Available Technologies in the Green Maritime Sector	Energies	
Raeesi et al., 2023	The synergistic effect of operational research and big data analytics in greening container terminal operations: A review and future directions	European Journal of Operational Research	

Potapenko et al., 2023	Renewable Energy Potential for Micro-Grid at Hvide Sande	Sustainability (Switzerland)	
Hong et al., 2023	The Integrated Scheduling Optimization for Container Handling by Using Driverless Electric Truck in Automated Container Terminal	Sustainability (Switzerland)	
Bosich et al., 2023	Cold Ironing Integration in City Port Distribution Grids: Sustainable electrification of port infrastructures between technical and economic constraints	IEEE Electrification Magazine	
Klopott et al., 2023	Seaports' Role in Ensuring the Availability of Alternative Marine Fuels—A Multi-Faceted Analysis	Energies	
Oloruntobi et al., 2023	Sustainable transition towards greener and cleaner seaborne shipping industry: Challenges and opportunities	Cleaner Engineering and Technology	
Al-Fatlawi and Jassim Motlak, 2023	Smart ports: towards a high performance, increased productivity, and a better environment	International Journal of Electrical and Computer Engineering	
Abu Bakar et al., 2023	Electrification of onshore power systems in maritime transportation towards decarbonization of ports: A review of the cold ironing technology	Renewable and Sustainable Energy Reviews	
Szymanowska et al., 2023	Seaport innovation trends: Global insights	Marine Policy	
Qi et al., 2023	Surveillance practice and automatic data algorithm of sniffing telemetry for SO2 emissions from ship exhaust in Tianjin Port	Journal of Cleaner Production	

APPENDIX B

	Conservative		Clean energy sources		Operational practices				Energy systems		
	Offset	Carbon capture	Alternative fuels	Renewable energies	Information measures	Energy efficiency	Equipment measures	Ship-port interface measures	Electrification and hybridisation	Smart and microgrids	OPS
Colodner et al., 2011					X						
Choi et al., 2012							X				
Kim et al., 2012				X					X		
Pavlic et al., 2014					X	X					
Acciaro, Ghiara et al., 2014				X		X			X		X
Gibbs et al., 2014					X			X			
Ramos et al., 2014				X							
Ölçer & Ballini, 2015						X					
Fagerholt et al., 2015			X					X			
Schmidt et al., 2015							X				
Winnes et al., 2015			X		X			X			
Lindstad et al., 2015			X		X			X	X		
Boile et al., 2016				X	X	X					
Parise et al., 2016					X				X	X	
Sciberras et al., 2016			X							X	
Amar et al., 2017							X		X		
Fruth & Teuteberg, 2017					X						
Balbaa & El-Amary, 2017				X					X		
Misra, Tajudeen et al., 2017			X								
Lindstad et al., 2017									X		
Misra, Panchabikesan, Gowrishankar et al., 2017	X				X		X				
Yang et al., 2017			X		X			X			X
Bouman et al., 2017					X	X	X	X			
Misra, Panchabikesan, Ayyasamy et al., 2017				X	X	X					
Styhre et al., 2017			X					X			X
Misra, Venkataramani et al., 2017				X						X	
Yarova et al., 2017				X	X	X					
Ozturk et al., 2018					X	X	X	X		X	
Gilbert et al., 2018			X	X							
Bosman et al., 2018					X						
Yun et al., 2018			X		X			X			X
Kumar et al., 2019						X			X		X
Di Vaio et al., 2019					X		X				
Kanellos et al., 2019						X			X	X	X
Alasali et al., 2019						X			X		
Islam et al., 2019							X				
Verma & Gupta, 2019					X						
Iris & Lam, 2019	X		X	X	X	X			X	X	X
Rolan et al., 2019				X						X	X
Gennitsaris & Kanellos, 2019				X					X		X
Kurtulus & Cetin, 2019							X		X		
Gutierrez-Romero et al., 2019				X							X
Yang et al., 2019	X		X								X
Munim et al., 2020					X	X					
Fang et al., 2020									X	X	
Kermani et al., 2020						X			X		

Schneider et al., 2020					X						
Trahey et al., 2020				X	X	X			X		
Lavidas et al., 2020				X							
Poulsen & Sampson, 2020							X	X			
Holly et al., 2020				X		X	X				
Lee et al., 2020			X		X		X	X			X
Roy et al., 2020					X	X			X	X	X
Castellano et al., 2020					X						
Seddiek, 2020				X							
Alamoush et al., 2020					X	X	X	X			
Mukherjee, et al., 2020		X	X								
Oliveira-Pinto & Stokkermans, 2020				X							
Ranjan et al., 2020					X	X					
Xing et al., 2020		X	X			X		X			
Foretich et al., 2021			X		X		X	X			
Reusser & Pérez, 2021					X			X			X
Široka et al., 2021					X						
Vahabzad et al., 2021				X					X		X
Lu & Huang, 2021			X								X
Garcia et al., 2021	X		X								
Sifakis & Tsoutsos, 2021				X						X	
Mańkowska et al., 2021				X							
Mallouppas & Yfantis, 2021			X	X				X			
Wan et al., 2021			X				X				
Pu & Lam, 2021					X						
Pei et al., 2021					X		X		X		
Ortiz-Imedio et al., 2021			X	X					X		
Sifakis et al., 2021				X		X	X		X		
Kinnon et al., 2021			X	X		X				X	
Iris & Lam, 2021	X			X		X	X	X	X	X	X
Xia et al., 2021					X			X		X	
Ampah et al., 2021			X								
Vicenzutti & Sulligoi, 2021				X	X			X	X		X
Taneja et al., 2021			X	X	X				X		
Alzahrani et al., 2021				X	X	X				X	
Spaniol & Hansen, 2021				X					X		
Bakar et al., 2021							X			X	X
Kurtuluş, 2022	X						X		X		
Khanet et al., 2022					X						
Dai et al., 2022					X		X				
Pivetta et al., 2022			X	X					X		
Daniel et al., 2022					X	X			X		X
Mao et al., 2022								X	X		X
Vichos et al., 2022			X	X	X	X					X
Agostinelli, Cumo et al., 2022				X	X	X					
Zhu et al., 2022			X		X						
Kim, 2022	X				X						X
Zhang et al., 2022						X		X	X	X	X
Hoang et al., 2022		X	X	X		X				X	
Shan et al., 2022		X			X	X				X	
Teng et al., 2022			X	X	X	X				X	
Sinha & Roy Chowdhury, 2022	X				X		X	X			
Tai & Chang, 2022			X		X			X			X
Fang et al., 2022						X	X		X	X	
Zhou & Zhang, 2022			X								X
Agostinelli, Neshat et al., 2022				X							
Nguyen, Pham et al., 2022					X		X				
Nguyen, Nguyen et al., 2022					X						
Sifakis et al., 2022			X	X		X			X		
Argyriou et al., 2022	X			X	X						

Sogut & Erdoğan, 2022						X					
Kovalishin et al., 2023				X	X	X			X	X	X
Mansoursamaei et al., 2023					X	X					
Vidović et al., 2023	X		X		X			X	X		
Raeesi et al., 2023					X	X	X				
Yen et al., 2023					X	X	X	X	X		
Kumar et al., 2023			X	X					X		
Liao et al., 2023					X						
Potapenko et al., 2023				X					X		
Hong et al., 2023						X	X		X		
Bosich et al., 2023				X	X				X		
Drungilas et al., 2023					X	X	X		X		
Klopott et al., 2023			X		X						
Oloruntobi et al., 2023					X	X	X	X			
Al-Fatlawi & Motlak, 2023					X	X	X				
Abu Bakar et al., 2023			X		X				X	X	X
Szymanowska et al., 2023			X		X	X			X		
Qi et al., 2023					X			X			

APPENDIX C

Reference	Country of 1st author affiliation	Geographies studied	Methods	Research strategy
Colodner et al., 2011	United States	United States	Quantitative	Case Study
Choi et al., 2012	South Korea	South Korea	Quantitative	Case Study
Kim et al., 2012	United States	United States	Quantitative	Case Study
Pavlic et al., 2014	Slovenia	Slovenia	Quantitative	Case Study
Acciaro, Ghiara et al., 2014	Germany	Germany / Italy	Quantitative	Case Study
Gibbs et al., 2014	United Kingdom	United Kingdom	Quantitative	Case Study
Ramos et al., 2014	Spain	Spain	Quantitative	Case Study
Fagerholt et al., 2015	Norway	Indonesia / United Kingdom / Norway / Spain / Canada / United States / Belgium / Germany / Sweden / France / Italy	Quantitative	Case Study
Winnes et al., 2015	Sweden	Sweden	Quantitative	Case Study
Lindstad et al., 2015	Norway	United States / Canada / Germany / Belgium / Sweden / Finland / Norway / Poland / United Kingdom / France	Quantitative	Case Study
Schmidt et al., 2015	Germany	Germany	Quantitative	Case Study
Ölçer and Ballini, 2015	Sweden	Denmark	Quantitative	Case Study
Parise et al., 2016	Italy		Qualitative	Archival Research
Sciberras et al., 2016	United Kingdom	Spain	Quantitative	Case Study
Boile et al., 2016	Greece	Spain / France / Italy / Slovenia / Croatia	Quantitative	Case Study
Bouman et al., 2017	Norway		Qualitative	Archival Research
Styhre et al., 2017	Sweden	Sweden / United States / Japan / Australia	Quantitative	Case Study

Fruth and Teuteberg, 2017	Germany	United States	Qualitative	Archival Research
Yang et al., 2017	China	China	Quantitative	Case Study
Lindstad et al., 2017	Norway		Quantitative	Case Study
Misra, Venkataramani et al., 2017	India	India	Quantitative	Case Study
Misra, Panchabikesan, Gowrishankar et al., 2017	India	India	Quantitative	Case Study
Balbaa and El-Amary, 2017	Egypt	Egypt	Quantitative	Case Study
Yarova et al., 2017	Ukraine	Ukraine	Quantitative	Case Study
Misra, Panchabikesan, Ayyasamy et al., 2017	India	India	Quantitative	Case Study
Amar et al., 2017	United States	United States	Quantitative	Case Study
Misra, Tajudeen et al., 2017	India	India	Quantitative	Case Study
Gilbert et al., 2018	United Kingdom		Quantitative	Case Study
Yun et al., 2018	China	Algeria	Quantitative	Case Study
Bosman et al., 2018	Netherlands	Netherlands	Quantitative	Case Study
Ozturk et al., 2018	United Kingdom	Netherlands / Germany / Belgium / Spain	Quantitative	Case Study
Iris and Lam, 2019	Singapore	Singapore	Qualitative	Archival Research
Kanellos et al., 2019	Greece	Germany	Quantitative	Case Study
Rolan et al., 2019	Spain	Spain	Quantitative	Case Study
Gutierrez-Romero et al., 2019	Spain	Spain	Quantitative	Case Study
Gennitsaris and Kanellos, 2019	Greece	Germany / Belgium	Quantitative	Case Study
Yang et al., 2019	China		Quantitative	Case Study
Di Vaio et al., 2019	Italy	Italy	Quantitative	Case Study
Kumar et al., 2019	Finland		Quantitative	Case Study
Kurtulus and Cetin, 2019	Turkey	Turkey	Quantitative	Case Study
Alasali et al., 2019	United Kingdom	United Kingdom	Quantitative	Case Study
Islam et al., 2019	Canada	Bangladesh	Mixed Methods	Mixed Strategies
Verma and Gupta, 2019	India		Quantitative	Case Study
Trahey et al., 2020	United States		Quantitative	Case Study
Fang et al., 2020	Singapore	Singapore / China	Qualitative	Archival Research
Munim et al., 2020	Norway	China	Qualitative	Archival Research

Xing et al., 2020	China		Qualitative	Archival Research
Alamoush et al., 2020	Sweden		Qualitative	Archival Research
Castellano et al., 2020	Italy	Italy	Quantitative	Case Study
Poulsen and Sampson, 2020	Denmark	United States / Poland / Latvia / Germany	Qualitative	Ethnographic Observation
Lee et al., 2020	South Korea	South Korea	Quantitative	Case Study
Roy et al., 2020	France	United States	Qualitative	Archival Research
Oliveira-Pinto and Stokkermans, 2020	Norway	United Kingdom	Qualitative	Archival Research
Kermani et al., 2020	Italy	United States	Quantitative	Case Study
Mukherjee et al., 2020	Netherlands	Netherlands / Sweden	Qualitative	Archival Research
Ranjan et al., 2020	India		Quantitative	Case Study
Seddiek, 2020	Egypt	Egypt	Quantitative	Case Study
Schneider et al., 2020	Germany	Netherlands	Mixed Methods	Mixed Strategies
Holly et al., 2020	Germany	Germany	Quantitative	Case Study
Lavidas et al., 2020	Netherlands	Italy	Quantitative	Case Study
Ampah et al., 2021	China	United States / United Kingdom / China / Sweden / Finland / Egypt / Taiwan / Italy / Denmark / Saudi Arabia	Qualitative	Archival Research
Iris and Lam, 2021	Singapore	Singapore / Netherlands / Germany / Spain	Quantitative	Case Study
Mallouppas and Yfantis, 2021	Cyprus	Japan / Denmark / Norway	Qualitative	Archival Research
Sifakis and Tsoutsos, 2021	Greece		Qualitative	Archival Research
Ortiz-Imedio et al., 2021	Spain	United Kingdom / France / Spain / Ireland	Quantitative	Case Study
Sifakis et al., 2021	Greece	Greece	Quantitative	Case Study
Foretich et al., 2021	United States		Mixed Methods	Mixed Strategies
Wan et al., 2021	China	China	Quantitative	Case Study
Reusser and Pérez, 2020	Chile		Quantitative	Case Study
Široka et al., 2021	Croatia	France / Italy / Greece	Quantitative	Case Study
Vahabzad et al., 2021	Iran	Sweden / Finland / Estonia	Quantitative	Case Study
Mańkowska et al., 2021	Poland	Poland	Mixed Methods	Mixed Strategies
Pu and Lam, 2021	Singapore	Singapore / China	Quantitative	Case Study
Garcia et al., 2021	Australia	Norway / United Kingdom	Qualitative	Archival Research

Alzahrani et al., 2021	United Kingdom	United Kingdom	Qualitative	Archival Research
Kinnon et al., 2021	United States	United States	Quantitative	Case Study
Bakar et al., 2021	Denmark	United States / Australia / Singapore / New Zealand / Germany	Qualitative	Archival Research
Lu and Huang, 2021	China	Netherlands / Germany / Belgium / Spain	Quantitative	Case Study
Vicenzutti and Sulligoi, 2021	Italy	Croatia	Quantitative	Case Study
Pei et al., 2021	China		Quantitative	Case Study
Taneja et al., 2021	Netherlands	Netherlands	Quantitative	Case Study
Spaniol and Hansen, 2021	Denmark	Norway / Scotland / Denmark / Sweden / Germany / Netherlands	Quantitative	Survey
Xia et al., 2021	China	China	Quantitative	Case Study
Hoang et al., 2022	Vietnam	Japan / Vietnam / Chile / United States / Nigeria / Malaysia / China / Spain / Canada / Germany / Taiwan / Norway / France / Belgium / Sweden / United Kingdom / Italy	Qualitative	Archival Research
Mao et al., 2022	China	China / United States	Quantitative	Case Study
Vichos et al., 2022	Greece	Greece	Quantitative	Case Study
Agostinelli, Cumo, et al., 2022	Italy	Italy	Quantitative	Case Study
Zhang et al., 2022	China	China	Quantitative	Case Study
Daniel et al., 2022	Canada	United States / Greece / Canada	Quantitative	Case Study
Zhu et al., 2022	United States	United States	Quantitative	Case Study
Nguyen, Nguyen et al., 2022	Vietnam	Vietnam	Quantitative	Case Study
Dai et al., 2022	China	China	Quantitative	Case Study
Kurtuluş, 2023	Turkey	Turkey	Quantitative	Case Study
Pivetta et al., 2022	Italy	Italy	Quantitative	Case Study
Tai and Chang, 2022	Taiwan	Taiwan	Qualitative	Archival Research
Fang et al., 2022	Hong Kong	China	Quantitative	Case Study
Sinha and Roy Chowdhury, 2022	India	India	Mixed Methods	Mixed Strategies
Zhou and Zhang, 2022	China	China	Quantitative	Case Study
Nguyen, Pham et al., 2022	Vietnam	Netherlands / Germany	Qualitative	Archival Research
Sifakis et al., 2022	Greece	Greece	Quantitative	Case Study

Kim, 2022	South Korea	South Korea	Quantitative	Case Study
Argyriou et al., 2022	Greece	Greece	Quantitative	Survey
Ullah Khan et al., 2022	Pakistan		Quantitative	Case Study
Shan et al., 2022	China	China	Quantitative	Case Study
Teng et al., 2022	China	China	Quantitative	Case Study
Agostinelli, Neshat, et al., 2022	Italy	Italy	Quantitative	Case Study
Sogut and Erdoğan, 2022	Turkey	Turkey	Quantitative	Case Study
Yen et al., 2023	Taiwan	China / Singapore / Dubai / Malaysia / Belgium / Vietnam / South Korea / Netherlands / Germany / USA / Taiwan	Quantitative	Case Study
Kumar et al., 2023	Australia		Qualitative	Archival Research
Liao et al., 2023	China		Qualitative	Archival Research
Drungilas et al., 2023	Lithuania	Lithuania	Quantitative	Case Study
Kovalishin et al., 2023	Russian Federation		Qualitative	Archival Research
Mansoursamaei et al., 2023	Iran	Germany / Netherlands / Singapore	Qualitative	Archival Research
Vidović et al., 2023	Croatia		Qualitative	Archival Research
Raeesi et al., 2023	United Kingdom		Qualitative	Archival Research
Potapenko et al., 2023	Sweden	Denmark	Quantitative	Case Study
Hong et al., 2023	China		Quantitative	Case Study
Bosich et al., 2023	Italy	Italy	Quantitative	Case Study
Klopott et al., 2023	Poland	Poland	Qualitative	Archival Research
Oloruntobi et al., 2023	Malaysia		Qualitative	Archival Research
Al-Fatlawi and Jassim Motlak, 2023	Iraq	Netherlands / Germany	Qualitative	Archival Research
Abu Bakar et al., 2023	Denmark		Qualitative	Archival Research
Szymanowska et al., 2023	Poland	Albania / Saudi Arabia / Argentina / Australia / Azerbaijan / Belgium / Belize / Brazil / Chile / China / Croatia / Cote D'Ivoire / Cyprus / Montenegro / Denmark / Philippines / Finland / France / Germany / Greece / Hungary / Ireland / Israel / India /	Quantitative	Survey

		Jamaica / Colombia / Malaysia / Mozambique / Netherlands / Norway / Oman / Poland / Portugal / Russia / South Africa / Serbia / Singapore / Slovenia / Sri Lanka / Sweden / Togo / Turkey / United Kingdom / United Arab Emirates		
Qi et al., 2023	China	China	Quantitative	Case Study

APPENDIX D

Reference	Cluster 1 (red)	Cluster 2 (blue)	Cluster 3 (green)
Colodner et al., 2011	X	X	
Choi et al., 2012	X	X	
Kim et al., 2012	X	X	X
Pavlic et al., 2014	X		
Acciaro, Ghiara et al., 2014	X		X
Gibbs et al., 2014		X	
Ramos et al., 2014			X
Fagerholt et al., 2015		X	
Winnes et al., 2015	X	X	X
Lindstad et al., 2015	X	X	
Schmidt et al., 2015			
Ölçer and Ballini, 2015			
Parise et al., 2016	X		
Sciberras et al., 2016	X		X
Boile et al., 2016	X	X	
Bouman et al., 2017		X	
Styhre et al., 2017	X	X	X
Fruth and Teuteberg, 2017		X	
Yang et al., 2017	X		
Lindstad et al., 2017			
Misra, Venkataramani et al., 2017		X	X
Misra, Panchabikesan, Gowrishankar et al., 2017		X	
Balbaa and El-Amary, 2017			
Yarova et al., 2017			
Misra, Panchabikesan, Ayyasamy et al., 2017	X	X	
Amar et al., 2017	X	X	
Misra, Tajudeen et al., 2017		X	
Gilbert et al., 2018		X	X
Yun et al., 2018	X	X	X
Bosman et al., 2018	X		
Ozturk et al., 2018	X		
Iris and Lam, 2019	X	X	X
Kanellos et al., 2019	X		

Rolan et al., 2019	X		
Gutierrez-Romero et al., 2019	X	X	X
Gennitsaris and Kanellos, 2019	X		X
Yang et al., 2019	X	X	
Di Vaio et al., 2019	X		
Kumar et al., 2019	X		
Kurtulus and Cetin, 2019	X	X	
Alasali et al., 2019	X		
Islam et al., 2019		X	
Verma and Gupta, 2019	X		
Trahey et al., 2020		X	X
Fang et al., 2020	X		
Munim et al., 2020	X		
Xing et al., 2020	X	X	X
Alamoush et al., 2020	X	X	X
Castellano et al., 2020		X	
Poulsen and Sampson, 2020		X	
Lee et al., 2020	X	X	X
Roy et al., 2020	X	X	
Oliveira-Pinto and Stokkermans, 2020			X
Kermani et al., 2020	X		
Mukherjee et al., 2020		X	X
Ranjan et al., 2020	X		
Seddiek, 2020			
Schneider et al., 2020	X	X	X
Holly et al., 2020			
Lavidas et al., 2020		X	X
Ampah et al., 2021		X	X
Iris and Lam, 2021	X	X	X
Mallouppas and Yfantis, 2021		X	X
Sifakis and Tsoutsos, 2021	X		
Ortiz-Imedio et al., 2021		X	X
Sifakis et al., 2021	X	X	
Foretich et al., 2021		X	X
Wan et al., 2021			
Reusser and Pérez, 2020	X	X	
Široka et al., 2021	X	X	
Vahabzad et al., 2021	X	X	
Mańkowska et al., 2021			X
Pu and Lam, 2021		X	X
Garcia et al., 2021		X	X
Alzahrani et al., 2021			X

Kinnon et al., 2021	X		
Bakar et al., 2021	X		
Lu and Huang, 2021	X	X	
Vicenzutti and Sulligoi, 2021	X	X	
Pei et al., 2021	X	X	
Taneja et al., 2021			X
Spaniol and Hansen, 2021	X	X	X
Xia et al., 2021	X		
Hoang et al., 2022	X	X	X
Mao et al., 2022	X	X	
Vichos et al., 2022	X		X
Agostinelli, Cumo et al., 2022	X	X	
Zhang et al., 2022	X		
Daniel et al., 2022	X	X	X
Zhu et al., 2022	X	X	X
Nguyen, Nguyen et al., 2022		X	
Dai et al., 2022			
Kurtuluş, 2023	X		
Pivetta et al., 2022			X
Tai and Chang, 2022	X	X	
Fang et al., 2022	X		
Sinha and Roy Chowdhury, 2022	X	X	
Zhou and Zhang, 2022	X		
Nguyen, Pham et al., 2022	X	X	
Sifakis et al., 2022	X		X
Kim, 2022	X	X	
Argyriou et al., 2022	X	X	
Ullah Khan et al., 2022	X		
Shan et al., 2022	X		
Teng et al., 2022	X		
Agostinelli, Neshat et al., 2022	X		X
Sogut and Erdoğan, 2022	X		
Yen et al., 2023		X	
Kumar et al., 2023		X	X
Liao et al., 2023		X	
Drungilas et al., 2023	X		
Kovalishin et al., 2023	X	X	X
Mansoursamaei et al., 2023	X	X	
Vidović et al., 2023			X
Raeesi et al., 2023			
Potapenko et al., 2023			X

Hong et al., 2023	X	X	
Bosich et al., 2023	X		X
Klopott et al., 2023		X	X
Oloruntobi et al., 2023	X	X	
Al-Fatlawi and Jassim Motlak, 2023	X	X	
Abu Bakar et al., 2023	X		X
Szymanowska et al., 2023	X		
Qi et al., 2023			