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# Decarbonisation of shipping: A state of the art survey for 2000-2020

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## Abstract

In the global effort to reduce Green House Gases and carbon emissions, there is great importance for the shipping industry to decarbonise and move forward into a greener future. However, there is a lack of academic commentary on how attempts at various decarbonisation methods reported in research articles have developed over the 21st century. This paper analyses how the shipping industry has decarbonised by utilising 294 papers from 2000-2020. By analysing 20 years' worth of research, this paper delivers a comprehensive review of shipping decarbonisation research and analyses the evolution of its themes as a function of time. It therefore aids to develop a greater understanding and comparison of governmental, economic and academic perspectives (and their potential alignment) for the industry to decarbonise. For 2017-20 the key shipping decarbonisation technologies were summarised and their advantages, disadvantages and current academic literature applications are revealed. Furthermore, the analysis of the evolution of shipping decarbonisation research themes reveals clear research gaps in the current literature and guides the development of a future research agenda with the prediction of future opportunities and potential for shipping decarbonisation research developments for the shipping industry.

*Keywords:* decarbonisation, shipping, emissions, air quality

## 1.0. Introduction

To achieve climate change objectives and reduce Green House Gases (GHGs), the shipping industry must significantly decarbonise to move forward into a greener future (Deloitte, 2020). Major international protocols, events, governmental and academic priorities all have their roles in triggering and responding to the challenges that this sector faces towards becoming more environmentally conscious and sustainable. Understanding the meaning of 'decarbonisation' is important as it is a term that is utilised for 'reduction or even total removal of Carbon Dioxide ($CO_2$) emissions'. An example of these attempts is demonstrated within the International Maritime Organisation (IMO) Fourth GHG Study in August 2020. This study set out key targets for the shipping industry for a 50% comparative drop in annual GHG emissions by 2050 compared to 2008 levels(IMO, 2020).

In terms of understanding what the industry has accomplished to combat these issues and offer solutions for decarbonisation, academics have put more of a focus on considering review articles which addressed: emission type quantification and analysis (Viana et al., 2008; Streets et al., 2013; Endres et al., 2018), development and utilisation of new technologies (Sun, Zwolinska and Chmielewski, 2016; Wang, Zhou and Wang, 2017; McCarney, 2020) and location specific emission analysis (Holland et al., 2014; Keuken et al., 2014; Zhang et al., 2017; Zhang et al., 2019; Pastorcic et al., 2020). quantity of these review papers is very low and in the past, the only other specific reviews on decarbonisation demonstrate a critical overview of IMO GHGs reduction strategies (Serra and Fancello, 2020) and vessel design optimization (Armstrong, 2013). More recently, a greater focus has began to emerge for a more holistic and all-encompassing approach to decarbonisation. Demonstrated in a review by Balcombe et al. (2019) which offers the most recent literature comparison within the field. Other decarbonisation review papers offer insight from multiple different perspectives such as global warming (Little, Sheppard and Hulme, 2021), shipping network configuration (Liu et al., 2021), emission calculation (Jing et al., 2021) and prediction and shipping power systems(Xu et al., 2021).

What is also evident from these previous studies is that there is a lack of academic commentary on how these decarbonisation methods and research articles have developed over the 21st century. By analysing such a large time span, this paper aims to conduct a comprehensive review of research themes to identify the gaps in current research and analyse the future trends in shipping decarbonisation. The novelty within this review paper is twofold. Firstly, this paper provides a state-of-the-art review of decarbonisation methods used in shipping from 2000 – 2020. As a function of time, the findings of this paper reveal the evolution the main research themes and criticises the advantages and disadvantages of the decarbonisation methods along the analysis of author name, author location, key words, journal popularity, publication frequency, and author collaboration networks. Secondly, this paper utilises the literature to understand and compare governmental, economic and academic perspectives and their consequential alignment towards decarbonisation. Where these pillars of the sector do not align, recommendations for policy are suggested to improve cohesion between them.

The structure of this paper is as follows: Section 2 outlines the methodology for inclusion of articles within this review and scope of the paper. Section 3 demonstrates the results of this search and Section 4 describes in-depth the findings, focusing on the discussion of research themes, their evolution and a summary of the ‘latest’ decarbonisation methods from 2017-2020. Section 5 highlights future development directions and implications. Finally, Section 6 concludes the paper with the key findings and their implications.

## 2.0. Methodology and scope of review

### 2.1. Search Criteria

To understand the shipping industry’s actions towards decarbonisation, a systematic review was undertaken (making use of published academic literature). Utilising a widely used methodology (as demonstrated in Tukamuhabwa et al. (2015) and Wan et al. (2017)), the Web of Science (WoS) (Core Collection) database was utilised to gather research papers. This search was conducted in August 2020 and the associated search strings included all “Topic” and “OR” functions within the WoS databased were: “Ship* and carbon emission”, “Ship* and decarbonisation”, “Ship* and decarbonization”, “Ship* and decarbonising” and “Ship* and decarbonizing”.

### 2.2. Selection of Articles

After an initial search using the search strings, there were 1,165 papers. Among them, only peer reviewed journal papers written in English between the years of 2000-2020 (inclusively) were accepted. By ensuring all results were those from peer reviewed journals, this review analysis guarantees a high quality of results. Any conference proceedings, book chapters, reports or case studies were therefore excluded from the search. This limited the results to 943 research items. To ensure the relevancy of papers within the review was maintained, the title, keywords and abstracts were first examined. Only journal articles that specifically covered the topics of how the maritime and shipping industry had attempted to decarbonise were accepted (excluding any articles on other maritime vessels such as submarines, oceanographic vehicles, sailing wind turbines and aircraft carriers). To ensure the scope of this paper was specifically only for the reduction of carbon emissions, any articles reducing specifically NOx and SOx emissions would be excluded. However, when considering Emission Control Areas (ECAs) these would be included as by reducing emissions would include the potential implementation of decarbonising technologies.  After these papers were screened, this reduced the total number of papers to 532. A further examination of papers was conducted which considered the introduction and conclusion of papers were reviewed to further ensure applicability for this review. Once all papers had been further evaluated, 294 articles were retained and utilised for this research paper.

## 3.0. Results and Discussion

To understand the data for the twenty years included within this review, the papers were grouped into 4 years (inclusive) time intervals. These were as follows: 2000-04, 2005-08, 2009-12, 2013-16 and 2017-20. Due to the extended time frame within this review and large quantity of papers within it, these groups were selected as they would reasonably represent the different phases of increasing popularity for decarbonising the shipping sector. By reviewing the current literature and analysing authorship and analytics associated with each paper, gives a greater insight into the current literature landscape. Also, this statistical analysis focuses on the changes/evolution of the reviewed papers against different criteria (e.g. main research themes and topics) with a function of time, revealing the findings that are discussed to generate new insights in both qualitative and quantitative forms.

### 3.1. Distribution of publications by year

Considering the year each article was published, the distribution of papers can be found in Figure 1. This figure also demonstrates that in the 21st century, there was a clear continual rise in research interest for this broad research sector. This growth is continual and due to this literature search taking place in August, it is presumed that the growth in quantity of papers would continue to rise throughout the rest of 2020. Figure 1 also demonstrates that the ‘interest’ in this research topic was negligible until approximately 2008. Before this time, between 2000-07 in this eight-year span, there was a cumulative total of only 5 papers. Policies or the legislative reasoning behind this abrupt increase in research interest will be further explored within Section 4. In addition, by understanding industrial events that may have lead to such a dramatic increase in publications from 2008, this will provide further enrichment to the analysis of literature that follows. Most significantly, in 2008, the International Maritime Organisation (IMO) created the working group for ‘*Greenhouse Gas Emissions from Ships’* and during this meeting in Oslo, Norway started the proceedings to technically tackle and reduce shipping emissions. Consequentially, this working group would go on to provide tangible emission reducing mechanisms for all green house gas emissions. Because of this active approach to emission reduction, 2008 would therefore become a ‘benchmark’ for emission quantification and analysis. Moving forward, by measuring emissions in 2008, the implementation of any reduction measures, policies or mechanisms going forward can then be adequately assessed. It is clear that this working group was extremely impactful to the maritime sector and therefore would act as a catalyst for driving real change within the industry – which is demonstrated by such a large increase in quantity of academic literature.

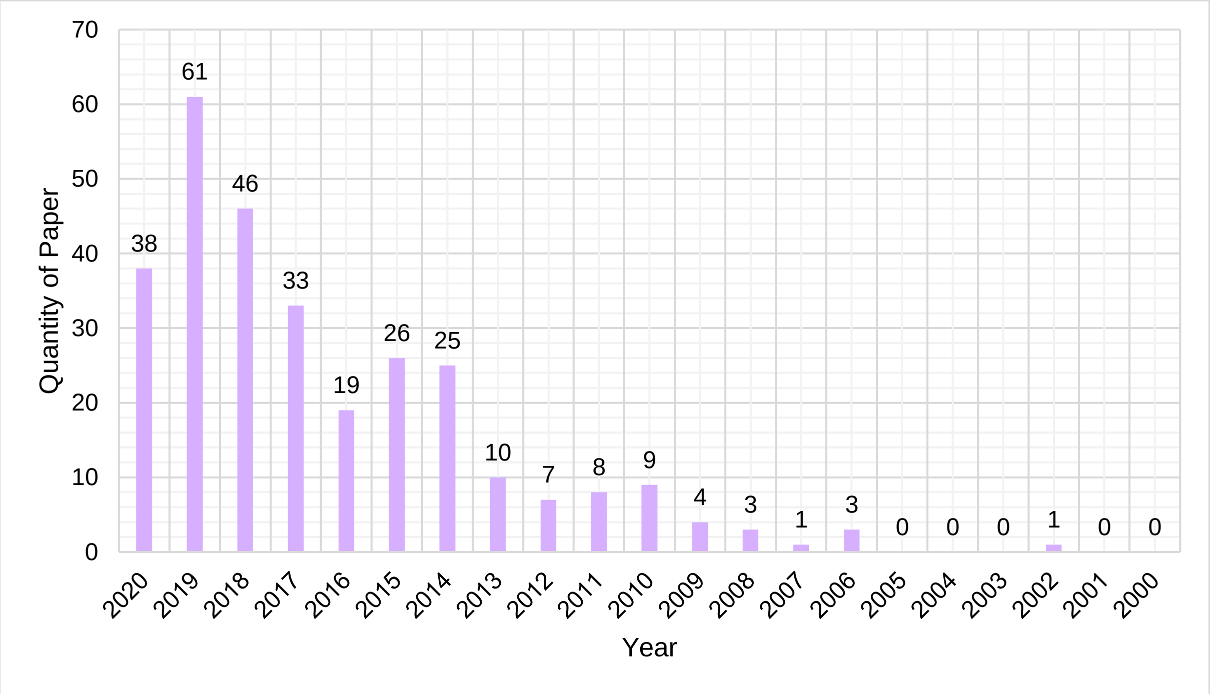

**Figure 1.** Distribution of relevant papers by year from 2000 to 2020.

### 3.2. Distribution of journals

For all papers included in this review, there were 118 different contributing journals. After collating all 294 papers, the top 10 journals with the most articles published demonstrated within Table 1. The most prevalent journal is '*Atmospheric Chemistry and Physics'.* Interestingly, this collection of top 10 journals also accounts for approximately 40% of all the papers within this review (117 papers).

**Table 1.** Distribution of top 10 journals

| Number | Journal Name | Number of Journals |
|---|---|---|
| **1** | Atmospheric Chemistry and Physics | 22 |
| **2** | Atmospheric Environment | 15 |
| **3** | Transportation Research Part D – Transport and Environment | 14 |
| **4** | Environmental Science and Technology | 11 |
| **5** | Journal of Cleaner Production | 11 |
| **6** | Ocean Engineering | 10 |
| **7** | Sustainability | 10 |
| **8** | Marine Policy | 9 |
| **9** | Energy | 8 |
| **10** | Science of the Total Environment | 7 |

Considering the journals within Table 1, the evolution of how vast the different research areas and therefore contributing journals to the field has greatly developed. This is exhibited within Table 2 where the quantity of papers within 2017-20 by comparison to 2000-04 has increased significantly.

**Table 2.** Development for the quantity of papers and journals from 2020-2000.

| Year | Quantity of Papers | Quantity of Unique Journals |
|---|---|---|
| 2020-17 | 178 | 94 |
| 2016-13 | 80 | 46 |
| 2012-09 | 28 | 16 |
| 2008-05 | 7 | 4 |
| 2004-00 | 1 | 1 |

To represent the development of the diversification of journals from Table 2, Figure 2 demonstrates (within each 4 year time block) the extensive range and specific names of contributing journals. By understanding the different journals that have accepted research on the decarbonising methodology or research development within shipping, it enabled a greater understanding how research topics within this particular area have formed. Figure 2 demonstrates that whilst the quantity of journals has increased, the shear breadth and range of methodologies of research areas that have also developed. This multidisciplinary approach develops as a function of time, which in turn, enriches the sector.

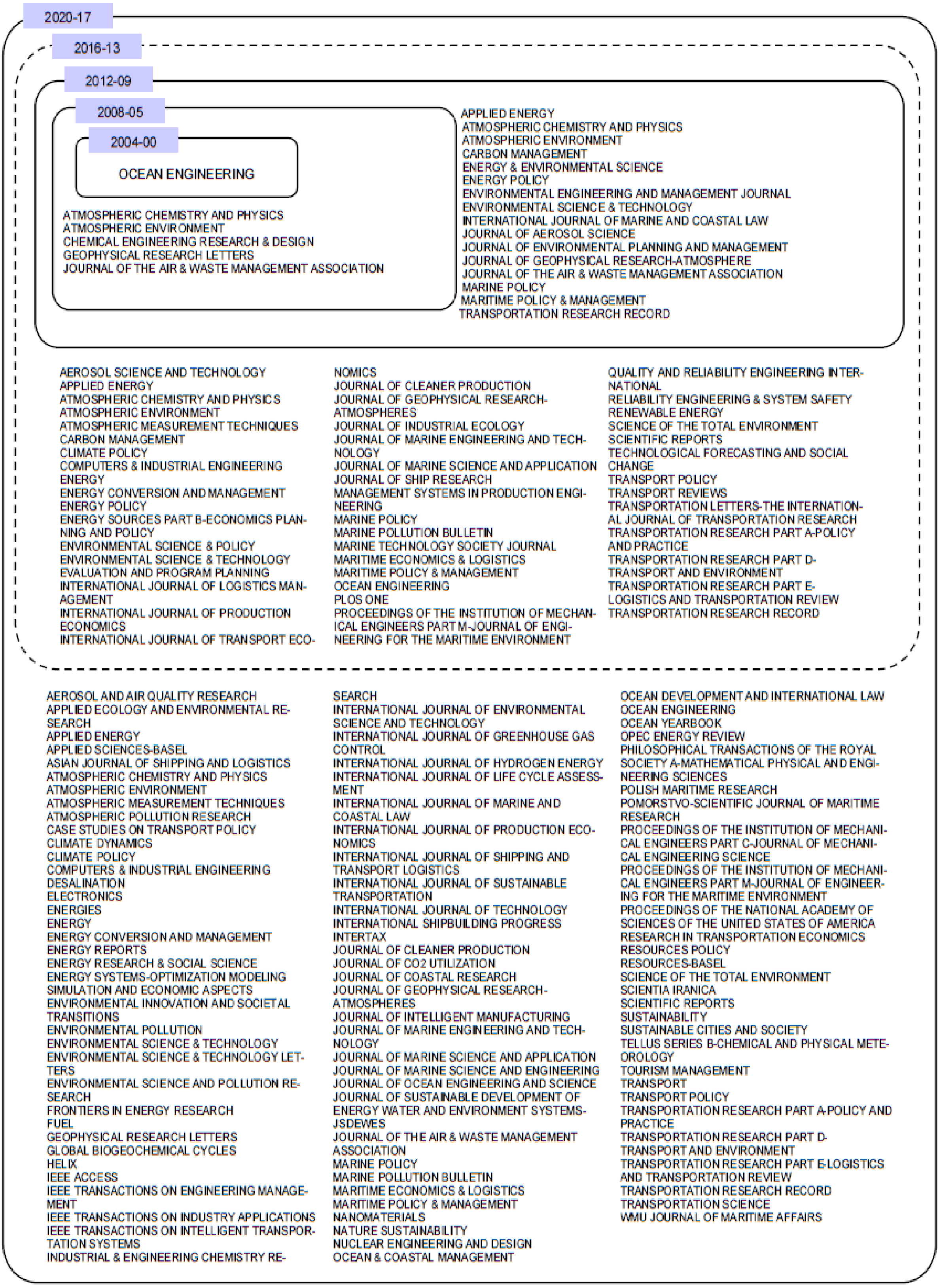

**Figure 2.** Development of contributing journals from 2000-2020.

### 3.3. Location of authors

When reviewing the papers, the location of authors was considered. For all 294 papers, the continent where all authors are from were categorised and is demonstrated within **Error! Reference source not found.**. Where the authorship team is from a combination of continents, the first authors location is utilised. **Error! Reference source not found.** also demonstrates that most papers are produced from Europe (49.7%) and the least papers are being published from Oceania (1.4%), South America (0.7%) and Africa (0.3%). However, what **Error! Reference source not found.** does not represent is how the location of authors changes and develops as a function of time. To determine how time affects the publication of papers from different locations, author location and quantity of papers produced within each time block are presented within Table 3.

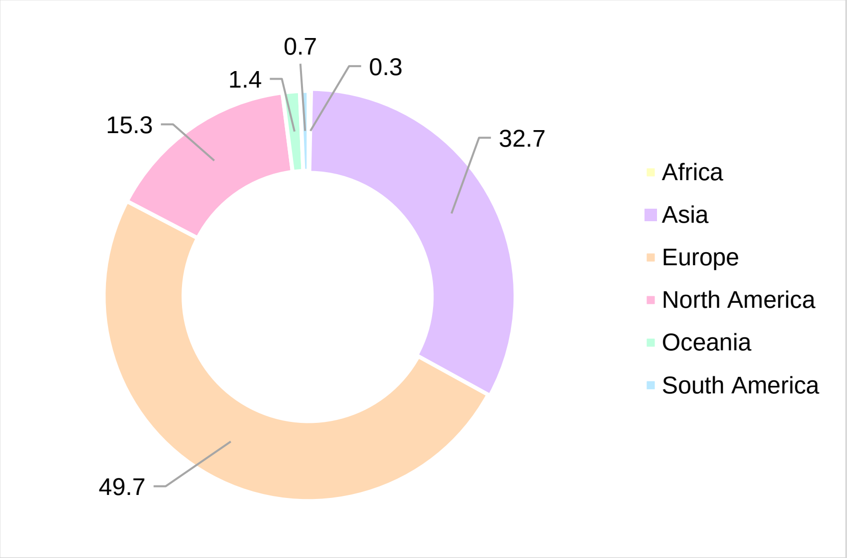

**Figure 3.** Location of each author as a percentage of all papers.

Over the time period from 2000-08 there was no contributions from any institutions aside from 1 paper from Asia. From 2009-2020, European and Norther American contributed the only research items with 3 and 4 papers (respectively). Between 2009-12, European researchers published the most papers with North American also having a large contribution. However, from 2013 onwards, there is a large uptake in publications from Asian based researchers within. Whereas from 2017, papers from Asian, European and North American universities continued to increase.

**Table 3.** Author location development from 2000-20.

| **Continent** | **Year** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **2000-04** | | **2005-08** | | **2009-12** | | **2013-16** | | **2017-20** | |
| | Quantity | Percentage of total papers from time period (%) | Quantity | Percentage of total papers from time period (%) | Quantity | Percentage of total papers from time period (%) | Quantity | Percentage of total papers from time period (%) | Quantity | Percentage of total papers from time period (%) |
| Africa | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Asia | 1 | 100 | 0 | 0 | 0 | 0 | 15 | 19 | 80 | 45 |
| Europe | 0 | 0 | 3 | 43 | 17 | 61 | 49 | 60 | 79 | 44 |
| North America | 0 | 0 | 4 | 57 | 10 | 36 | 16 | 20 | 15 | 8 |
| Oceania | 0 | 0 | 0 | 0 | 1 | 4 | 0 | 0 | 3 | 2 |
| South America | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| **Total Quantity Papers** | 1 | | 7 | | 28 | | 81 | | 179 | |

### 3.4. Author names and research collaboration networks

Another methodology of investigating these papers is via the linkages and professional networks that are driven by collaboration on journal articles. This enables an identification of research communities and established network connections (Newman, 2010). As demonstrated in Wang et al. (2020), by utilising Netminer 4.3 (a social media network analysis programme) the links between authors can be identified. By using this type of analysis, it considers all authors to have equal “weighting” despite their position in the authorship list. All authors from all papers and the key research collaborative networks are identified in Figure 4.

**Figure 4.** Co-authorship networks from 2000-20.

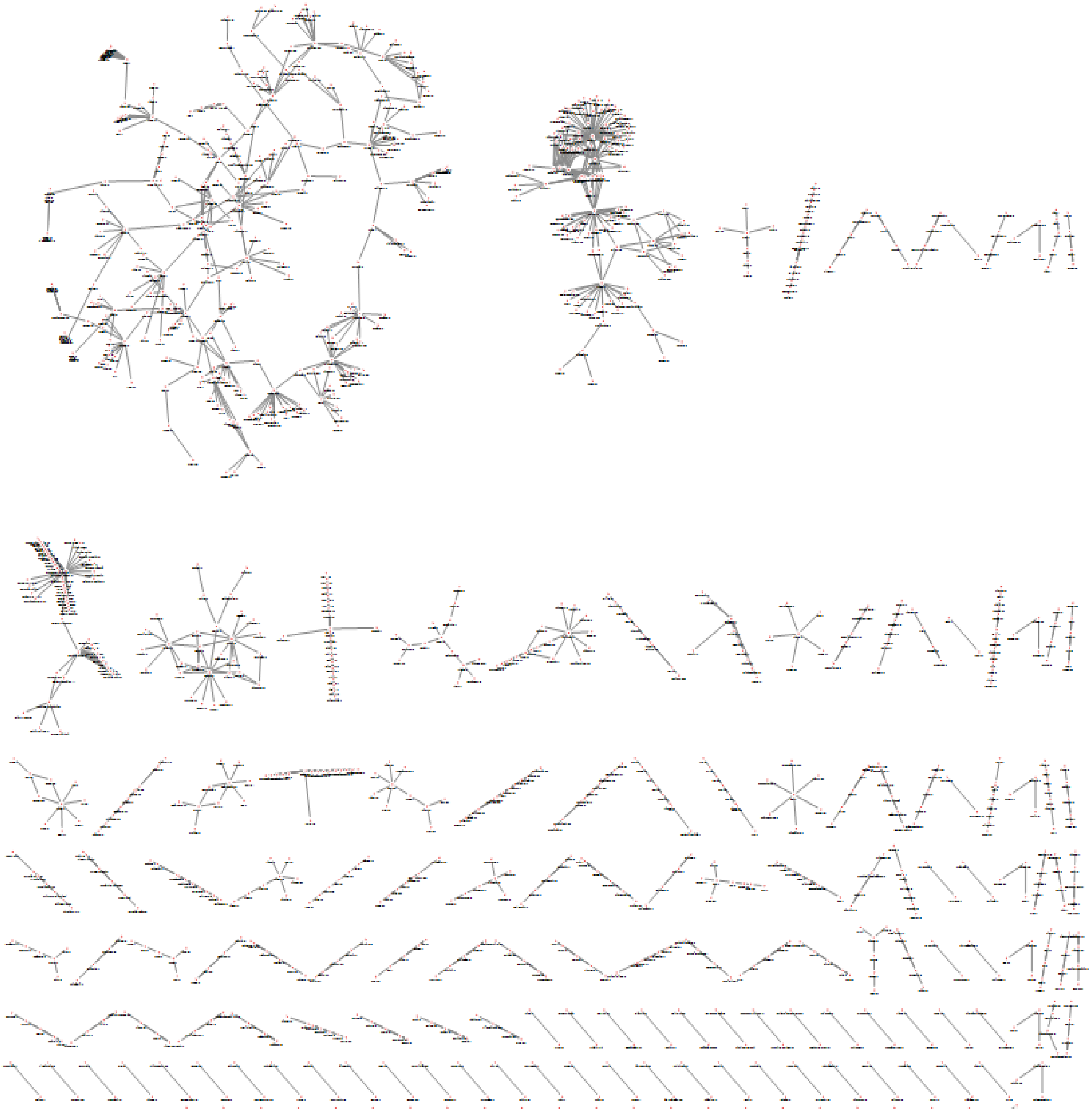

Figure 4 also identifies that there were 2 major branches of collaboration. However, due to several papers having over 20 co-authors this does not adequately identify and demonstrate the largest individual authorship contribution. Considering all articles selected within this paper, there are 1,142 individual authors. These authors were listed and ranked according to the quantity of their contribution for relevant papers within this review. The most prevalent authors are prevalent within the same research group including Jürgen Orashe (University of Rostock, Germany), Benjamin Stengel (University of Rostock, Germany) and most prominently, Ralf Zimmerman (Helmholtz Centre Munich German Research Centre for Environmental Health, Germany,) with 8 different journal articles from 2014-18. The contribution by these authors has been primarily focused on *understanding the content and effects of marine engine emissions* (Mueller et al., 2015; Oeder et al., 2015; Eichler et al., 2017; Corbin et al., 2018a; Corbin et al., 2018b) as well as *how emissions are effected by diesel fuel and heavy fuel oil operations* (Reda et al., 2014; Streibel et al., 2017) in addition to *understanding emissions when a ship is under differing operating conditions* (Sippula et al., 2014). Orashe, Stengel and Zimmerman (when producing these articles) were based in the Bavaria area of Europe, contributing to the large proportion of research from this continent.

### 3.5. Research keywords and topic evolution

To understand how research themes of decarbonisation of the shipping sector have developed and evolved over the last 20 years, keywords from each paper were analysed. Once split into 4-year time periods, keywords were combined and filtered, where the total quantity of unique keywords are demonstrated within Table 4.

**Table 4.** Quantity of unique keywords from 2020-2000.

| Timeblock | Total Keywords | Quantity of Unique Keywords |
|---|---|---|
| 2020-17 | 998 | 680 |
| 2016-13 | 453 | 323 |
| 2012-09 | 143 | 111 |
| 2008-05 | 43 | 38 |
| 2004-00 | 5 | 5 |

Table 4 demonstrates a vast increase in the quantity of unique keywords as a function of time, demonstrating not only an increase in the overall subject areas but also due to the large quantity unique words, the diversity inherently also increases. By comparison, 2017-20 had over 136 times as many unique keywords compared to 2000-04. The increasing trend for quantity of keywords with respect to time is linear and aligns with an increase in journal papers as seen in Figure 1.

To understand how themes across these keywords may vary over these time blocks, the top 10% of words within the total keywords for 2013-20 (due to the large quantity) and 20% of words from 2000-12 were investigated. These keywords are presented in Table 5 and this shows that not only is there an increase in the quantity of papers, but also with research priorities. Keywords that are the same have been highlighted in the same colour to map how they may appear over an extended time span. The most frequently used keyword from 2013-20 was ‘carbon emissions’. The only consistent keyword across all time-blocks was ‘particulate matter’. As the timeline develops towards the present day, the keywords demonstrate less generic language such as ‘climate’ and ‘impact’ and is broken-down into more specific terminology such as ‘black carbon’, ‘carbon emissions’ and ‘green house gas’ (GHG) emissions. Table 5 also succinctly demonstrates how research priorities have evolved with respect to time and how understanding the broader scope of ‘emissions’ has developed into a diverse and complex research field.

**Table 5.** Frequency of most commonly utilised keywords.

| Year | Frequency of keyword | Year | Frequency of keyword | Year | Frequency of keyword | Year | Frequency of keyword | Year | Frequency of keyword |
|---|---|---|---|---|---|---|---|---|---|
| **2000-04** | | **2005-08** | | **2009-12** | | **2013-16** | | **2017-20** | |
| Marine diesel engine | 1 | Particulate matter | 3 | Impact | 6 | Carbon emissions | 8 | Carbon emission | 18 |
| Catalysed particulate filter | 1 | Carbon dioxide | 2 | Climate | 4 | Ship emission | 7 | Carbon dioxide emissions | 13 |
| Pollution source | 1 | Emissions | 2 | Climate change | 4 | Black carbon | 6 | Shipping | 13 |
| Particulate matter | 1 | Shipping | 2 | Shipping | 4 | Particulate matter | 6 | Particulate matter | 12 |
| Gaseous emission | 1 | | | Calibration | 3 | Air Pollution | 5 | Maritime transport | 11 |
| | | | | Emissions | 3 | Climate | 5 | Shipping emissions | 11 |
| | | | | Particles | 3 | Carbon dioxide emissions | 5 | Energy efficiency | 10 |
| | | | | Ship emissions | 3 | Emission reduction | 5 | | |
| | | | | | | Emissions | 5 | | |
| | | | | | | Impact | 5 | | |
| | | | | | | Simulation | 5 | | |

## 4. Research Themes: Diagnosis, evolution and future developments

This section provides a comprehensive review on shipping decarbonisation research themes, their evolution and future developments. In addition to making significant contributions on the diagnosis of the state of the art in the research field but also guides the demands for the future research agenda. After reading and organising the research papers by year of publication, each paper was read and reviewed. Following this, the overall theme was identified and after analysing all papers within each time block, these research items were consolidated in a singular table of themes. As each theme appears in the literature and timeblock, the total quantity is noted as demonstrated in **Table 6**.

**Table 6.** Summary of research themes for shipping decarbonisation from 2000-2020.

| **Themes** | **Subthemes** | **Quantity of Papers** | | | | |
|---|---|---|---|---|---|---|
| | | **2000-04** | **2005-08** | **2009-12** | **2013-16** | **2017-20** |
| Air pollution of areas further than port | | | | | | 2 |
| Air Quality in shipping routes | | | 1 | | 1 | |
| Alternative fuels: | **Total:** | | 1 | 4 | 10 | 12 |
| | *Ammonia* | | | | | 2 |
| | *Biodiesel* | | | | 1 | |
| | *Biofuel* | | | 1 | | |
| | *Biogenic fuel* | | | 1 | | |
| | *Comparison of fuel alternatives to conventional fuels* | | | | | 4 |
| | *Comparison of low sulphur fuels* | | | | 4 | |
| | *Engine performance* | | | | | 1 |
| | *Gas Fuels* | | | | 1 | |
| | *Heavy fuel oil as an alternative to ship diesel* | | | 1 | | |
| | *Hydrogen and Ammonia* | | | | | 2 |
| | *LNG* | | | 1 | 3 | 2 |
| | *Synthetic Fuel* | | | | | 1 |
| Calculation of particle emission | | | | | 1 | |
| Carbon emission analysis at operating conditions: | **Total:** | | | | 8 | 24 |
| | *Plant layout* | | | | 1 | |
| | *Foldable Containers* | | | | | 1 |
| | *Fuel Consumption* | | | | 2 | 1 |
| | *Instruments, fuels and loading* | | | | | 1 |
| | *Loading* | | | | | 1 |
| | *Propulsive power contribution on selected shipping routes* | | | | 1 | |
| | *Refuelling, sailing speed and ship deployment* | | | | | 1 |
| | *Routing* | | | | | 1 |
| | *Routing and Packaging* | | | | | 1 |
| | *Routing and Scheduling* | | | | | 2 |
| | *Routing, Scheduling and Speed* | | | | | 1 |
| | *Scheduling* | | | | | 2 |
| | *Ship manoeuvring* | | | | 1 | 1 |
| | *Ship parameters and power models* | | | | | 1 |
| | *Ship routing and bunker management* | | | | | 1 |
| | *Ship Type* | | | | 1 | 1 |
| | *Shipment Size* | | | | | 1 |
| | *Size, speed and slenderness* | | | | 1 | |
| | *Slow Steaming* | | | | | 1 |
| | *Speed* | | | | 1 | |
| | *Speed and fleet deployment* | | | | | 1 |
| | *Speed and routing* | | | | | 1 |
| | *Speed, scheduling and routing* | | | | | 1 |
| | *Type, engine and navigation process* | | | | | 1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | *Whole route* | | | | | *1* |
| Carbon emission characterisation | | | | | 1 | |
| Characterisation of Overall emissions at operating conditions: | **Total:** | | | 5 | 12 | |
| | *Autonomous Control* | | | | 1 | |
| | *Comparison of conditions* | | | | 1 | |
| | *Decarbonisation of energy systems* | | | 1 | | |
| | *Emission control technologies* | | | 1 | | |
| | *Expert port opinions on emission reduction* | | | 1 | | |
| | *Generator Selection* | | | | 1 | |
| | *Loading and Load Allocation* | | | 1 | 1 | |
| | *Routing and Scheduling* | | | | 2 | |
| | *Ship Type* | | | 1 | | |
| | *Short sea shipping compared to road transport* | | | | 1 | |
| | *Size, fuel consumption, economic activities* | | | | 1 | |
| | *Slow Steaming* | | | | 2 | |
| | *Speed Reduction* | | | | 2 | |
| | *Speed, Fuel Quality and Filtering* | | | 3 | | |
| Characterisation of particle emission | | | 4 | 8 | 12 | |
| Cruise Ship Decarbonisation | | | | | 9 | |
| Decarbonisation of energy systems | | | | 1 | | |
| Economics vs carbon savings | | | | | 7 | |
| Emission reduction strategies | **Total:** | | | 1 | 3 | 13 |
| | *Effectiveness* | | | | | 10 |
| | *At Green Container Terminals* | | | | | 3 |
| | *In Supply Chains* | | | | 1 | |
| | *Evaluation of Control Technologies* | | | 1 | 2 | |
| Emission calculation and characterisation | | | | | | 14 |
| Emission impact | | | | | | 3 |
| Emissions from diesel engines | | | | | | 2 |
| Energy efficiency and performance of ships | | | | | | 3 |
| Evaluation of carbon reducing technologies | | | | | 4 | |
| Exergy analysis of future transport pathways | | | | | 1 | |
| Exhaust emission analysis and reduction | | 1 | | | | 5 |
| Expert port opinions on emission reduction | | | | 1 | | |
| Financial analysis of emission reduction | | | | | | 10 |
| Future analysis of decarbonisation of shipping | | | | | | 3 |
| General Review of low-carbon shipping | | | | | | 6 |
| Green optimisation of supply chain | | | | | | 6 |
| Green and Renewable Technologies | **Total:** | | | | 2 | 25 |
| | *Battery/Generators in hybrid ships for CO2 reduction* | | | | | 1 |
| | *Carbon Capture* | | | | 2 | 2 |
| | *Fuel Cells* | | | | | 2 |
| | *Heat Recovery Systems* | | | | | 5 |
| | *Hydrodynamic optimisation strategy for fuel efficiency* | | | | | 1 |
| | *Large-scale solar energy/diesel generator* | | | | | 1 |
| | *Membrane distillation (MD) for desalination* | | | | | 1 |
| | *Nuclear Power and propulsion systems* | | | | | 2 |
| | *PV output power in moving and rocking hybrid energy ships* | | | | | 1 |
| | *Salvinia air-layer hull coatings* | | | | | 1 |
| | *Ship Propulsion Systems – Use of supercapacitors* | | | | | 1 |
| | *Shore Side Electricity* | | | | | 1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | *Utilisation of waste soot for lithium-ion batteries* | | | | | 2 |
| | *Waste Management Solutions* | | | | | 1 |
| | *Wind propulsion technologies* | | | | | 3 |
| LCA of GHG reduction | | | | | 1 | |
| Location based case study for decarbonisation of shipping | | | | | | 9 |
| Perceptions on sustainable initiatives | | | | | 3 | |
| Shipping emissions in port area | | | | 3 | 7 | 15 |
| Technological solution to energy efficiency | | | 1 | | 3 | |

### *4.1. 2000-04*

Due to there only being one paper produced within this period, there was not a large scope of papers for analysis. The only relevant paper within this review is Lin (2002) where exhaust emissions were reduced using a catalyst particulate filter for marine diesel engines.

This academic contribution does not seem to align with the major environmentalism advances that occurred before and during this time period. Established as ‘The International Convention for the Prevention of Pollution from Ships’ (MARPOL) has paved the way for innovation by the convention of international pollution of ships in 1973 ((IMO), 1997). As a response to a series of accidents involving tankers in 1976-77, the 1978 MARPOL convention was adsorbed by parent convention and combined by coming into force on 2nd October 1983. Following this, a new Annex (VI) and amendment to the convention was made in 1997 but would only come into action on 19th May 2005 (Marine Air Pollution Committee, 19997). Explicitly important to this paper, Annex VI contained 5 chapters with specifically 25 regulations; where it would outline the requirement for ships to conduct surveys to prevent air pollution and comply to the newly endorsed International Energy Efficiency Certificates (IEEC) and Air Pollution Prevention (IOPP) certificate. This annex also outlined quantities and caps on Nitrogen Oxides (NOx) and tiers associated around differing emission control areas. Further to this, Sulphur Oxides (SOx) quantities within fuel oils were controlled whilst both in and out of emission-controlled areas. Volatile Organic Compounds (VOCs) from oil tankers, Energy Efficiency of ships were both attained and required Energy Efficiency Design Index (EEDI), a further Ship Energy Efficiency Management Plan (SEEMP) and exhaust emission requirements were also implemented under this new annex.

As a result of the MARPOL Annex VI coming to fruition, this launched other environmental strategies such as within 2000, such as a European monitoring and evaluation programme. This was launched to understand Sulphur content and SOx emissions (EMEP) ((European Commission, 2002) and to encourage other European countries to update their legislation on shipping emissions. Further to this, in an attempt to curb emissions, in the same year on the

1st January 2000 the European Union (EU) put a ban on the sale of leaded gasoline ((U.N.), 1999). This complimented the ban already put on leaded fuel from other influential nations such as the USA and Germany in 1996 and China in 2000. By banning this type of fuel due to health and environmental concerns, there was a clear need for a sustainable, unleaded fuel– which would inevitably pave the way for alternative fuel design research. In 2001 the National Emissions Ceiling (NEC) Directive would implement emission reducing commitments of the main five air pollutants (2001/81/EC). Further to this, in 2003 the EU would commit to a directive that would limit the sulphur content on marine fuels (2003/33/EC).

Further worldwide environmental legislation to control global climate change was the implementation of the Kyoto Protocol. This protocol demonstrated a commitment of United Nations (UN) countries and economies to reduce and limit the production of GHGs by creating legally binding and country specific emissions targets ((U.N.), 2008). However, despite president of the United States of America (USA), Bill Clinton being part of the formation and signing the Kyoto Protocol in 1997, the incoming presidential office of George Bush and his administration would go on to withdraw from the protocol in 2001. It was cited that the withdrawal was due to 'problematic economic outcomes for energy prices for Americans' and the protocol was also not ratified by the Senate (Phillipson, 2001). Canada was the only other member to have signed and then withdrawn from the treaty in 2011 and the only UN member states to not sign the treaty were Afghanistan and Sudan.

Another important piece of European policy was produced in 2001, where the European Commission White Paper on European Transport Policy was released which highlighted the importance of short sea shipping within Europe and also as a GHG reducing measure (European Commission, 2001). The same principle has been adopted within the US in 2003, where the Department of Transportation Maritime Administration also demonstrated its commitment to developing methods for short sea shipping systems for the overall reduction in emissions and congestion on other multimodal transport networks (Maritime Administration, 2003). Despite having these major pieces of environmental legislation come into force, they are not being reflected in the academic literature that is being produced at the time. This disjointed position between academia and governmental bodies provides little scope for commentary as there is little to configure the established relationships between the two. Nevertheless, one observation was that almost all the regulations and policies were not mandatory in essence. Ship decarbonisation requires the efforts from all the stakeholder groups including shipowners, regulators and researchers.

### *4.2. 2005-08*

Building on the very small quantity of papers from 2000-04 and despite major governmental and legislative influence, 2005-09 only contributed 7 papers. From the papers highlighted in Table 3, all were exclusively published in Europe and North America. Understanding the characterisation of particle emissions seemed to be a key priority within this time period. What can be understood as a reference to the new legislation phasing out leaded petroleum and limitation on sulphur content in marine fuels, a new research avenue of alternative fuels has begun to emerge. Within this time period, liquified natural gas (LNG), marine gas oil, residual oil and marine diesel oil were analysed. As these new alternative fuels emerge, more complimentary studies and literature understanding and developing new techniques to quantify these emissions are also evolving. The characterisation of emissions is two-fold; the first is the quantification of the shipping emissions and what each vessel and/or fuel and/or technology is producing. Secondly, an analysis and characterisation of these emissions and a breakdown of what substances are within these. From Table 6, it suggests that the differentiation between these two categories appears to emerge around 2007.

When comparing this academic literature to major events which occurred around this time, the first was in 2005, when the UK government commissioned Sir Nicholas Stern to conduct (what is now known as) the Stern Review. Published in 2006, the review outlined the economic cost of climate change (Stern, 2007). What is most notable about this landmark report was that it was the first of its kind to present climate change from a new lens of economics (rather than purely environmental). The review was also praised by most world leaders and economists as the “do-nothing” approach must end and immediate action must be taken (Godard, 2008). There is potential that this report could have been a large contributing factor to the increase in decarbonisation literature in Figure 1.

From its previous establishment, MARPOL Annex VI came into force on 18th May 2005. However, in July 2005 at the 53rd session of Marine Environment Protection Committee (MEPC) there was a requirement for the strengthening and tightening of emission limitation on account of the technological advancements from 1997 – 2005. In October 2008, this resulted in MPEC 58 being accepted into the MARPOL Annex VI and the NOx Technical Code 2008 becoming effective on 1st July 2010.

The 21st May 2003 marked the introduction of the Strategic Environmental Assessment (SEA Protocol) on Environmental Impact Assessment in a Transboundary Context for EU members at the Espoo Convention, Kyiv, Ukraine. This would ensure that sustainable environmental assessments are introduced at the earliest stages possible ((E.U.), 2001). The Strategic Environmental Assessment (SEA) directive was confirmed on 21st November 2008 and the protocol for this (2001/42/EC) was transposed into EU legislation.

When comparing these major worldwide events to the academic themes within 2005-08, they do not seem to align. A potential explanation for this could be due to the size of these landmark events and the time required to fully interpret and understand their implications on academia could be lengthy. Further to this, shipowners' perception on decarbonisation was still largely focusing on costs and financial obligations. Their awareness on its urgency was behind other sectors (e.g. manufacturing and even vehicle emission in the road transportation sector).

### *4.2. 2009-12*

The themes for the 28 papers within this time period research into 5 key categories where the most 'popular' topic from this time frame was the characterisation of particle emissions. What is also notable is the emergence of not only the characterisation of particle emissions as a whole concept but particularly towards specific operating conditions or vessel types.

By comparison to the previous time block the exploration of fuel alternatives also continues to diversify by comparison. Biofuels (including algae, biogenic and biodiesel), LNG and heavy fuel oil (as an alternative to ship diesel) are being investigated as a mechanism for the decarbonisation of shipping. What can be noted from this is that as a direct response for the requirement of emissions to be reduced, rather than the deep technological advancement and retrofitting that would be required for a new engine mechanism; a new fuel strategy has been utilised. These research developments align with new policy and global events. During early 2009, OCIMF (Oil Companies International Marine Forum) declared in Energy Efficiency and Fuel Management how $CO_2$ emissions could be reduced by understanding and implementing vessel improvements and voyage efficiencies. Further to this, in 2009 the EU announced its plan to aim for the replacement of 10% transport fuels to renewables (e.g., hydrogen, bioelectricity and biofuels) by 2020. In China, the National Development and Reform Commission, aimed for 15% replacement of transport fuel to biofuel by 2020 (Yang, Zhou and Liu, 2009). From legislation written in 2007, 2009 saw the release of the Energy Independence and Security Act which required the USA to develop the infrastructure required to produce approximately 36 billion gallons of biofuel from both cellulosic and corn sources by 2022 (David et al., 2009).

Literature within Table 6 provided a commentary on maritime and environmental policy for emission reduction. It could be suggested this may have been triggered by an increasing sense of tension between global maritime environmental bodies. As a branch of IMO, the MEPC further discussed in 2009 how emissions could be reduced. A key output of this meeting was how the European Commission (EC) had a perceived 'slow pace' to implement policy. At the MEPC meeting, it was stated that if by the end of 2011, if there was no international agreement on how international shipping emissions could be reduced, MEPC would propose their own policy by 2013 (Faber et al., 2009). The IMO produced its second GHG study which was submitted to the MPEC; utilising six scenarios of $CO_2$ used by IPCC from 2020 - 2050. This study also utilised different emission factors for different ship types and categories (from 1.5-55.2g $CO_2$/tonne km for bulk carriers and RoRo ships (respectively)) (Buhaug et al., 2009). As a further mark of action being taken the ratify and reduce maritime emissions, during December 2009, the United Nations Climate Change Conference in Copenhagen, signatories were made to take action against a global rising temperatures at 2$^o$C (UNFCCC, 2009). Further to the Kyoto Protocol in 1997 (where international bunker fuel emissions were excluded), the Copenhagen Accord crucially negated how to proceed with global international shipping emissions. Due to this, without having formal guidance the IMO was required to regulate their own emissions. What makes this particularly difficult is as the only ratified IMO convention, the United Nations Convention on the Law of the Sea (UNCLOS) would be the only appliable legislation. This underlines the absolute requirement for a globally cohesive protocol and regulation and from the failures at an international governmental level, it further complicates how academic commentary and research can strategically align for shipping emission reduction.

From the previous time block of 2005-08, there was only 1 paper which examined the influence and effect of shipping emissions has on port areas. From 2009-2012, this has increased to 5 papers. A potential understanding for this increase could be from previously developed legislation in 2008, amendments ECAs set out by the IMO to limit SOx and NOx emissions coming into force in July 2010. The IMO also allotted water within 370km from Canadian and US coastlines as ECAs which required SOx, NOx and particulate matter (PM) emissions to be reduced to less than 1% in August 2011 to 0.1% in January 2015 (IMO, 2009). In 2012 was expected that these emission reducing methods avoided approximately 41,000 annual premature deaths (Winebrake, Corbett and Meyer, 2007). Controversially, the World Shipping Council (whom represents ~60% of shipping trade) in response to the IMO emission caps suggested they would be "'inappropriate in the absence of a broader approach to regulation transportation emissions at the national and global level''((WSC), 2010).  This opinion was held due to shipping being such a comparably efficient method of goods transportation.

Significantly, at the end of this time frame during 2011, despite highlighting how the shipping sector suffered from having no formal guidelines to follow for other major environmental emission reducing agreements, the EU also implemented an ambitious new Transport White Paper to reduce GHG via all methods of transportation in EU by 2050(EU, 2011). Within this paper it highlighted how maritime transport GHG emission are to be cut by 40% via a stipulated roadmap to achieve this. However, for the shipping sector clear mechanisms for how these reductions will be completed or realised were not included within the white paper, making the full realization of these targets extremely difficult.

To further complicate the reaching of these environmental targets, in 2012 the World Health Organisation declared that soot particles (found in the diesel PM and containing several severe pathologies) emitted from ships were officially classified as a Class I carcinogenic((IARC), 2012). This had a major effect on future potential research objectives as it highlighted the importance of not only reducing emission quantity but also improving quality for the environmental but also for the health benefits for those who live near ports. 2012 also saw the IMO guidelines for the development in the ships design process via: an energy efficiency management plan (SEEMO) updated from the 2009 standard(IMO, 2012a) and definition of EEDI index (IMO, 2012c; IMO, 2012b; IMO, 2012d). Due to this being such a drastic change, it would take a while to see the true effects of its implementation due to the long-time frame between ship design, build and utilisation in industry. This is highlighted within the research papers in this time block, it is evident that in comparison to the analysis from 2000-08, there is a greater entwinement between research priorities and governmental strategies. This is the first time after nearly 10 years into this review that this is happening and although the quantity of papers is low, the quantity and depth of them start to increase.

### *4.3. 2013-16*

Across 81 papers, within Table 6 that from 2013-16 there was a clear increase in understanding of how carbon emissions of ships are affected by different operating conditions. This also demonstrates how the ‘real world’ implication and quantification of these emissions, rather than just theoretical applications. Whilst the range of conditions has increased, there are still very limited papers so comparable literature for each operating condition is impossible.

Further to this, within the timeblock from 2009-12 not only has the quantity of papers increased but also the diversity of research topics. New branches of research areas such as an overall evaluation of these technologies but also an understanding of how carbon emissions affect economics and financial benefits of the adoption of these technologies. This brings a new dimension to the analysis of carbon emissions within the maritime industry as this seems to be a shift in not only developing the technologies (which has been previously demonstrated) but also the strategic application of technologies for financial and environmental gain. One suggestion for this research branch growing could be as a result of the Stern Review becoming more widely recognised, praised and understood by the academic community.

In 2013 it was announced by National Oceanic and Atmospheric Administration (NOAA) that the $CO_2$ levels had exceeded over 400 parts per million – a clear breach of the protocol level quantities. To improve the environmental performance of shipping, many national governments and industry lead initiatives were developed in 2013. In the UK there was the ‘Logistics Carbon Reduction Scheme’, the US ‘SmartWay programme and on a European basis there was the ‘Green Freight Initiative’. China also had high industrial involvement and in 2013, where it was announced the intent to re-establish the route with a new name ‘One Belt One Road’ (OBOR) (historically known as the ‘Silk Route’). Linking trade routes with Mediterranean Europe, Arabian Peninsula and wider areas of Asia would aspire to increase in both on land and sea connections. With this major infrastructural focus, ports connecting these locations and the emissions released surrounding them will be imperative to monitor. In 2015, China also outlined three Domestic ECAs (DECAs) where implementation would be in April 2016 which would require ships at berth to use a fuel with a sulphur content to be less than or equal to 0.5%.

In 2014, the IMO released the third GHG study which was complimentary to the EU and European Research Innovation Framework Program, launching HORIZON 2020 to encourage and inspire new projects. This saw the launch of energy, efficiency and emission reducing technologies for the shipping industry e.g., ‘LeanShips’ project. In 2015, the IMO developed new air quality regulations by reducing sulphur emissions in SECAs from 1% (as per regulation from 2010) to 0.1%. In a further attempt to curb emissions, in 2015, the EU emissions trading system (EU-ETS) had covered 35 countries to tackle climate change all over the world. But in April 2015, the EU, announced a new regulation (EU 2015/757) for $CO_2$ emissions of maritime transport and their monitoring, reporting and verification (MRV)((EU), 2015). Coming into effect in July 2015 these guidelines fit in accordance with IMO MARPOL Annex VI, EEDI and SEEMP and accurately quantified ship fuel consumption and $CO_2$ emissions. Due to this regulation, this pressured the IMO and in April 2016 a data collection system (DCS) was proposed – notably different from the EUs MRV (IMO, 2016).

2015 was also a landmark year for environmental legislation as the United Nations Framework Convention on Climate Change (UNFCCC) asked members states to commit to reducing their GHG emissions by signing the Paris Agreement. Out of the 197 member states of the UN, the only major emitter to not initially sign was Iran. However, during 2017, USA president Donald Trump officially redacted the signature to the treaty. Whilst the shipping industry is not bound by the terms of this protocol, the introduction of EU 2015/757 and DCS enhanced pressures for the adoption of carbon emission reducing technologies.

On 1st January 2016, the UN officially introduced 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development; these goals build from the 2000-2015 UN Millennium Development Goals. The 17 new goals, promote targeted actions at an international level to support Agenda 2030. Specifically, to the decarbonisation of maritime and shipping industry, this is underpinned by the following SDGs: 7 (affordable and clean energy), 9 (industry, innovation and infrastructure), 11 (sustainable cities and communities), 12 (responsible consumption and production), 13 (climate action), 14 (life below water) and 15 (life on land). 2016 also saw both the USA and China implement major maritime environmental policy. The USAs Environmental Protection Agency (US EPA) and Chinas Ministry of Ecology and Environment of China limits and measurement methods for exhaust pollutants from marine engines (CHINA I, II). GB15097). In October 2016, at the 70th sitting of the MEPC the IMO also released a strategy called 'IMO roadmap' for reducing GHG gases. This road map contains a three-step approach within a list of activities which will be adopted in 2018; to have this strategy full operational by 2023. After the 2011 EEDI and SEEMP IMO initiatives were considered inadequate and the introduction of the EU MRV in 2013, a new National Emissions Ceilings (NEC) Directive (2016/2284/EU) entered into force on 31 December 2016. Replacing earlier legislation (Directive 2001/81/EC), the new NEC Directive sets 2020 and 2030 emission reduction commitments for five main air pollutants. It also ensured that the emission ceilings for 2010 set in the earlier directive remain applicable for member states until the end of 2019.

As demonstrated from these major legislative changes, the maritime and shipping sector has been proactive in recent years in its attempts to curb global warming, decarbonise and reduce carbon emissions in a way that it has never done before. This is reflected in both the quantity and breadth of research items from 2012-16. As these legal frameworks continue to develop and be utilised practically in day-to-day operations there will undoubtably be more critique and analysis of them. This is coupled with scientific and engineering technological advances that the sector will develop over the next time period.

### *4.4. 2017-20*

For the most current research within this review paper, within 2017-20 there are 179 papers which is the largest contribution of papers for any timeblock. With research themed in Table 6, it highlights the further 'phasing out' of analysis and characterisation of ship emissions and focuses more on a development of under what conditions and quantities they are produced. Table 6 also shows that the carbon emission analysis at different operating conditions but also how these emissions affect a surrounding port area. By comparison to 2013-16, 2017-20 papers feature a much broader range of operating conditions and deeper analysis of how these emissions vary during the activities ships are involved in. In other areas of environmental significance, a state of the art international code for ships operating in Polar Waters came into force on 1st January 2017(IMO, 2017). This was the first of its kind to be specifically designed for Arctic and Antarctic areas for both environmental and safety procedures. But most importantly, this code regulated GHG emission to these atmospherically sensitive areas.

Table 6 also shows further diversification of alternative and bio-fuel development, there are also bio-based material fuels (such as lignocellulosic biofuel and waste cooking oil bio-diesel blend) within this time period. An increase in these alternative fuels is coupled with the phasing out of emission analysis of diesel fuelled ships. This is an important observation as in February 2017, at a vote in European Parliament where the inclusion of shipping into the EU Emissions Trading Scheme (EU ETS) (for implementation in 2023) was agreed. If no global agreement is met by 2021, a further vote in November 2017 decided that the EU process will align with that of the IMO. These votes were met with controversy from industry groups such as the European Community Shipowners Associations (ECSA), International Chamber of Shipping (ICS) and nationally based ship owning companies. Due to the incompatibility between the EU ETS and IMO Roadmap there are concerns this may delay, over complicate and negate any actual GHG emission reductions. In addition, the EU MRV system is implemented as of 1st January 2018. In addition to this, a landmark report from International Transport Forum (ITF)suggested a number of different solutions to meet the emission requirements for GHG emissions((ITF), 2018). Suggestions include the use of fuel cells that utilise blue hydrogen or ammonia, electric ships and combustion engines utilising alternative fuels such as biofuels, hydrogen and ammonia.

An IMO road map strategy was also furthered upon in 2018 at MEPC 72. After nearly 3 years of debating, in April 2018 the IMO agreed a strategy for the shipping sector to meet the Paris Agreement goals; via three key sustainably driven targets: 1) reduce GHG emissions by 50% in 2050 compared to levels in 2008, 2) reduce carbon emissions from new ships via the strengthening of EEDI requirements and 3)reduce carbon emissions from shipping by at least 40% by 2030 and a 70% reduction by 2050 (IMO, 2018). This strategy is not expected for a further 5 years with its delivery expected in 2023 and will be reviewed every 5 years after that.

Coming into force in 2019, the Chinese ministry of transport defined the whole countries coastline as a Domestic Emission Controlled Area (DECA). The Chinese government also set the DECA sulphur limit to 0.5% whilst the global limit outside an Emission Controlled Area

(ECA) is 3.5%. There is potential that with having such a strict limit, this could reduce the type of vessel that could be utilised on the new OBOR. In other locations, SOx, NOx and PM reductions outside of ECAs within the revised MARPOL Annex VI demonstrate the new sulphur limit (from 3.5 to 0.5%m/m) (from ship fuel), which comes into force as of 1st January 2020. This requires ships to either use a fuel alternative (to meet 0.5% sulphur content) or use conventional (and cheaper) heavy fuel oil with a suitable exhaust emission cleaning system. Consequentially, imposing this type of restriction to fuel immediately inflates the price of desulphurised fuel. This further exacerbates the requirement of a low sulphur biofuel.

Within 2017-20 timeblock is the first utilisation of green and renewable technologies within shipping, their development and potential implementation into ships have been practically assessed. This is a critically influential theme for this time block as it demonstrated that rather than just analysis or characterisation of emissions in the shipping industry, technological advancements have progressed to a point for these projects could be utilised on board. What is also vital to understand is how within this time block, there is now a defined difference between understanding the effectiveness of the technologies, the law and regulations affects emissions and a financial analysis of them. This holistic approach to ‘green technologies’ considers more than just a ‘if the product works’ mindset but an extensive analysis as to how financially viable they are and which governmental policies they adhere to. A further unique research theme within 2017-20 is the decarbonisation of cruise ships. Some papers feature more decarbonisation technologies and innovations such as Amaya-Vias, Nebot and Lopez-Ramirez (2018) (*Desalination technologies using membrane distillation*), Ancona et al. (2018) (*Load allocation on board*), Trivyza, Rentizelas and Theotokatos (2019) (*Optimal power plant configuration for carbon pricing*), Zheng et al. (2019) (*Using artificial neural network model for adjusting sailing speed optimising fuel consumption*) and Vicente-Cera et al. (2020) (*Using AIS and environmental data to further understanding of cruise ship traffic*). Other cruise ship decarbonisation research investigated energy and exergy analysis (Baldi et al., 2018), ecological efficiency (Ye et al., 2019), disclosure of cruise and container shipping companies sustainable behaviour (Di Vaio et al., 2020) and water and beverage packaging sustainable practices (Paiano, Crovella and Lagioia, 2020). The impact of these techniques and investigations used on these ships would have some transferability to the wider shipping industry which does not yet seem to have been succinctly analysed.

### 4.5. Analysis of shipping decarbonisation methods from 2017-20

When different ‘green technologies’ are utilised to decarbonise the shipping industry, their strengths and weaknesses have been analysed within Table 7. This table demonstrates a summary of both the advantages and disadvantages of each technology in the literature, in addition to the circumstances for which the technology has been utilised. This will aid the understanding, current scope and quantity of literature for each technology. These technologies have also been divided into general technologies, utilisation of renewable energy sources, fuel cells and alternative fuels. More significantly, it provides a solid foundation to develop a decision-making support tool through which different technologies can be prioritised under different circumstances in a quantitative manner.

**Table 7.** Summary of decarbonisation technologies from 2017-2020.

| Decarbonisation technology | Strengths | Weaknesses | Circumstances for use | References |
|---|---|---|---|---|
| Utilisation of waste soot for lithium-ion batteries | - Creates a 'circular economy' for hybrid ships; from waste valourisation where waste soot is increasing as international shipping and trade increases<br>-Using a waste material for creation of renewable energy<br>-Cost effective method of creating graphite compared to other techniques<br>-creation of further versatile products creation and application in other fields | -Lack of industrialisation<br>-Commercial application and feasibility are unknown<br>-Unsure how different soot from different parts of the ship may affect performance | Waste soot was collected from the economizer within a container ship operated by Korea Leading Company of Ship Management Co., Ltd. (KLCSM) | (Choi et al., 2019) |
| | | | Waste soot collected soot from the economizer, on board M/V Sunny Spuce | (Lee et al., 2018) |
| Ship Propulsion Systems – Use of supercapacitors | -Ability to utilise energy from renewable sources<br>-Ensures power continuity for all devices onboard and limited any disturbances to disruptions and continue high power and unlimited power delivery | -When incorporating supercapacitors, needs to be introduced as part of a series and parallel configuration<br>-For high voltage requirements additional and further supercapacitors would be required<br>-High cost and low energy density | All-electric ships (AES) | (Kopka and Tarczynski, 2017) |
| Shore Side Electricity (SSE) | -Reduces GHG emissions and atmospheric pollutants, particularly for port areas<br>-Air quality of local port area is improved<br>-Reduces noise, vibrations and engine wear and tear<br>-Potential to reduce life cycle cost of onboard equipment<br>-Subsidies provided by European Union for SSE installation | -Technology only utilised whilst ships are at berth<br>-High initial investment (and installation costs vary significantly with port size, grid conditions, distance to main powerlines, electricity price etc.)<br>-High sale price of electricity<br>-Potential unwillingness of port authorities to invest<br>-Still no international policies to enforced SSE installation<br>-Many vessels and ports may not be suitable to incorporate technologies for SSE | Port of Shanghai | (Dai et al., 2019) |
| Waste heat recovery systems | -Waste recovery from engine represent 50% overall energy output from engine so wasted energy is valourised from waste-to-power | -Not yet fully integrated onto all types of vessels as part of the ships machinery system<br>-High investment initially | Utilizing scavenge air cooling for a marine diesel engine | (Mito et al., 2018) |
| | | | Waste-heat powered systems in fishing vessels | (Palomba et al., 2019) |

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| | -Cost effective<br>-Auxiliary machinery (such as generators) can be reduced<br>-reduce carbon emissions by up to 20% | -Large space requirements onboard<br>-Specific temperature and power requirements – requiring increased maintenance | On board vessels powered by low-sulphur fuels | (Baldasso et al., 2020) |
| | | | Gas carriers transporting liquefied natural gas (LNG) and liquefied petroleum gas (LPG) and equipped with various types of main engines | (Cherednichenko and Mitienkova, 2020) |
| | | | 8S90ME-C10.2 (with 2×A180-L37) two stroke low-speed diesel engine produced by MAN B&W | (Feng et al., 2020) |
| Carbon Capture Optimisation | -Success at GHG emission reduction on land-based ‘traditional’ fuelled power plants and demonstrated to reduce GHG emissions by up to 65% on maritime vessels<br>-A potential ‘short-term’ solution to reduce CO2 emissions in maritime industry | -Much more complicated integration from on land to maritime application due to limited space, movement/rolling and potential lack of power supply<br>-High investment cost and limited operating conditions onboard<br>-Lack of full industrialisation compared to other products currently available | Solvent-based carbon capture process to capture CO2 from the energy system in a typical cargo ship | (Luo and Wang, 2017) |
| | | | AES | (Fang et al., 2019) |
| | | | LNG-fuelled ships | (Feenstra et al., 2019) |
| | | | Alkali metal carbonates for a Ro-Ro (Roll On/Roll-off) passenger ship equipped with a 4.35MW main engine and 1hour running route | (Erto et al., 2018) |
| Nuclear Power and propulsion systems | -No $CO_2$ emissions<br>-For nuclear powered ships there are no major accidents since their launch in 1955<br>-Compared to ‘traditional’ propulsion system is much more cost effective<br>-Ships can go long intervals before refuelling | -Difficult to achieve adequate shutdown margin whilst core life maintains reactivity control<br>-Lack of harmonisation between national nuclear standards<br>-Safety concerns<br>-Remained largely to only military vessels and not utilised commercially | 333 MWth, SBF and long life civil marine SMR core while utilizing LEU | (Alam et al., 2019) |
| | | | Single batch SMR with LEU (20% 235U enrichment), a soluble-boron-free (SBF) and using mixed D2 O+ H2O coolant for operation period over a 20-year life at 333 MWth | (Alam et al., 2020) |
| *Utilising Renewable Energy Sources*: | | | | |
| Flettner rotor technology | -Potential saving (compared to ‘traditional’ engine power of 24.1% in Fiji<br>-Fuel saving potential for short distance journeys | -Unknown how the technology will combine with others on board such as biofuels, PV storage systems etc.<br>-Lack of industrialisation and “in-field” testing | $CO_2$ emission reduction in Fiji's domestic shipping industry | (Searcy, 2017) |
| Wind propulsion technologies | -Dependant on speed, technology and wind conditions can reduce carbon emission by 10-60%<br>-A rise in cost and environmental impact of ‘traditional’ fuels mean there is a need for alternative technologies<br>-Whilst the technology needs investment and financing, the source of energy is free, so costs are restricted to technology development | -Lack of full industrialisation across all technologies<br>-Lack of incentivisation for technology implementation<br>-Varying fuel savings with different technologies from 5-80%<br>-Technologies are not yet suitable for a long-term future nor larger vessel<br>-Potential for compatibility issues for retrofitting of older vessels | Agent-based model of climate-energy policies | (Karslen, Papachristos and Rehmatulla, 2019) |
| PV output power in moving and | -Considerable noise and sound pollution reductions | -Higher initial costs compared to batteries | Tankers with PV generation | (Liu et al., 2017) |

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| rocking hybrid energy ships | -PV panels are readily available on the market and source is readily available<br>-Continual charging of vessel battery<br>-Versatility to be installed on multiple surfaces and reconfigured to suit the space | -Large installation space required due to the size of panels | | |
| Large-scale solar energy/diesel generator | -Experimental verification<br>-Using the hybrid system fuel consumption is reduced by up t 4.02% and $CO_2$ emissions by 8.55% per year<br>-Lack of hybrid systems available for large scale vessels | -limitations of the conversion of solar efficiency<br>-For ships with a relatively large power requirement, are only functional for 80% of the total operational time | 5000-vehicle space pure car and truck carrier (PCTC) "COSCO Tengfei" | (Yuan et al., 2018) |
| *Fuel Cells:* | | | | |
| Fuel-cell based hybrid power source | -Produces no emissions or noise when generating electricity using several sources of hydrogen<br>-Compared to 'traditional' power generation methods reduces GHGs by 30%<br>-As fuel-cells can be modulised to aide construction and utilisation onboard makes them versatile for many different ships | -High initial investment due to high cost of catalysts<br>-Long term durability unknown<br>-Not fully industrialised and validated worldwide and therefore has infrastructure problems for distribution, storage, availability and production of hydrogen during medium-long term voyages | Hybrid power and a diesel engine generator with a combined capacity of 180 kW; consisting of a molten carbonate fuel cell (MCFC), a battery, and a diesel generator, the capacities of which are 100 kW, 30 Kw, and 50 kW, respectively. | (Roh et al., 2019) |
| Solid oxide fuel cells (SOFC) | -Highly efficient<br>-Could reduce GHG emissions up to 34% and more economical when compared to 'traditional' fuels<br>-High conversion efficiency particularly when at medium-low load<br>-Ability to be modulised so can be utilised in many different set ups depending on the ship<br>-SOFC can use a wide range of fuels | -GHG targets are not yet strict enough to fully benefit from SOFC<br>-Technology not fully industrialised commercially as mainly utilised for military application<br>-Unsuitable for short-medium distance ship applications<br>-Low power density | Two case studies: a cruise ship and a tanker. | (Baldi et al., 2020) |
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| Salvinia air-layer hull coatings | -By introducing a persistent layer of air between the ship hull and water is the most effective for saving fuel due to reduced friction and drag reduction which therefore reduced $CO_2$ emissions<br>-Beneficial antifouling effects | -Potential for plastic waste to become trapped in technology<br>-Lack of industrial development and 'real world' application and testing<br>-Unquantified cost and investment requirements for vessel owners | Five types of maritime: bulk carriers, oil tankers and container ships. Additionally, a cruise ship (*Queen Mary II*) and Ultra Large Container Vessel (ULCV) (*Emma Maersk*) | (Busch et al., 2019) |
| Membrane distillation (MD) for desalination | -Compared to existing technologies such as multi-stage distillation (MSF) there MD has a reduced volume required on board, reducing space requirements. Compared to sea water reverse osmosis MD has a lower fuel consumption<br>-Production of high purity drinking water<br>-Utilises waste and low-grade heat and can be combined with | -Not yet fully commercialised or implemented into cruise industry – only on-board sea going vessels<br>-Potential of pre-treatments being required<br>-Membrane needs replacing and disposing due to fouling and scaling<br>-Consumes a large quantity of both thermal | Cruise Ships | (Amaya-Vias, Nebot and Lopez-Ramirez, 2018) |

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|---|---|---|---|---|
| | renewable/alternative energy to increase energy efficiency | energy for both heating and cooling processes | | |
| *Alternative Fuels:* | | | | |
| Ammonia | -Storage and transportation technologies already exist so implementation is easy<br>-Carbon Capture Systems (CCS) available from ammonia production plants for circular economy benefits<br>-Price compared to conventional fuels is much cheaper | -Acutely toxic with a strong smell<br>-Commonly derived from fossil-fuel hydrogen and renewably sourced ammonia is still in development<br>-Still knowledge gaps safety and development into fuel cells<br>-Corrosive so may have long term implications to the design of marine fuel systems | Energy Systems Modelling and Multi-Criteria Decision Analysis as a marine fuel | (Hansson et al., 2020) |
| | | | Four propulsion systems (different power systems are used: main engine, generators, polymer electrolyte membrane fuel cell (PEMFC), and solid oxide fuel cell (SOFC)) for a 2500 Twenty-foot Equivalent Unit (TEU) container feeder ship | (Kim et al., 2020) |
| Hydrogen and Ammonia | -Can produce fuel cells which have a significantly lower GHG emissions<br>-Compared to 'traditional' fuels, if a spillage occurs, hydrogen and ammonia have much lower environmental effects<br>-Have a potential at port facilities to be utilised for cold ironing to reduce environmental impact | -Due to hydrogen having a lower volumetric energy density so storage systems are required to be larger and therefore distribution can be difficult compared to 'traditional' fuels<br>-Infrastructure for hydrogen fuel is limited as well as cost and financing | Dual fuel operation of vessels are also considered in the study as 50% clean fuel (Hydrogen or ammonia) and 50% heavy fuel oil | (Bicer and Dincer, 2018a) |
| | | | Environmental impact assessment of transoceanic tanker and transoceanic freight ship | (Bicer and Dincer, 2018b) |
| LNG | -Lower quantity of carbon dioxide emissions compared to other carbon-based fuels<br>-In Europe, is considered as a key fuel alternative for energy supply | -Significant environmental impact if spilt into the sea<br>-High financial investment to build LNG facilities<br>-Prices fluctuate unpredictably | LCA Analysis for LNG in the UK | (Tagliaferri et al., 2017) |
| | | | Characterisation of PM from LNG | (Corbin et al., 2020) |
| Synthetic Fuels | -Plentiful raw materials<br>-Flexibility with regards to the location of the sites which will feature convenient ship-based transport to site<br>-Potential to combine with other Blue Economy based activities such as aquaculture | -Life cycle analysis and manufacturing loop is yet to be fully optimised<br>-Long term impacts of fuel are unknown<br>-Cost estimates need to be further refined<br>-Lack of industrial implementation including 'scale up' of the technology | Floating islands with PV panels, converting to electrical energy to produce Hydrogen, extract carbon dioxide from seawater and reacted to form methanol | (Patterson et al., 2019) |

## 4.6. Legal and Policy Developments

With the academic literature developing in terms of decarbonisation methods, there will naturally be a complementary commentary for the legal and policy developments. This section of the literature has been categorised by year within Table 8. Although the timeline of this paper is from 2000-2020, literature of this nature is only published after 2010. Further to just the papers, any legal or policy documentation has also been linked to the journal articles.

**Table 8.** Literature for legal and policy developments from 2010-2020.

| Policy Type | Sub-theme | Where Application, Date of Policy/Law Implementation | Timeblock | | | Reference |
|---|---|---|---|---|---|---|
| | | | 2009-12 | 2013-16 | 2017-20 | |
| Carbon Tax | | | | | 4 | (Ding et al., 2020) |
| | | | | | | (Gaigne, Hovelaque and Mechouar, 2020) |
| | | | | | | (Zhu, Chen and Kristal, 2018) |
| | | | | | | (Falcao, 2019) |
| Climate Change Policy Design | *Total:4* | | | | | |
| | Comparison of EU and IMO emission standards and technology solutions with respect to climate change | | 1 | | | (Kontovas and Psaraftis, 2011) |
| | Local and regional policy actions using market-based measures and technological solutions | | 1 | | | (Miola, Marra and Ciuffo, 2011) |
| | Paris Agreement 1.5ºC temperature goal | Paris Agreement, 2015 | | | 1 | (Halim et al., 2018) |
| | Pathways to avoid 2ºC global temperature rise | | | 1 | | (Bows-Larkin, 2015) |
| Emission Regulation Design | | | | | 1 | (Sheng et al., 2017) |
| Energy Auditing | | | | | 1 | (von Knorring, 2019) |
| IMO | *Total: 5* | | | | | |
| | Energy Efficient Design Index (EEDI) | IMO MARPOL *2012, (EEDI), Annex 10 resolution MEPC.214* | | 1 | | (Niese, Kana and Singer, 2015) |
| | IMO Regulation - Sulphur oxides (SOx) – Regulation 14 | | | | 1 | (Alshammari and Benmerabet, 2017) |
| | IMO Resolution A.963 (23) | | | | 1 | (Wan et al., 2018) |
| | IMO Prevention of Pollution from Ships, 1973/78 | | | | 1 | (Chircop, 2019) |
| | Ship Energy Efficiency Management Plan (SEEMP) | IMO MARPOL Annex VI *2012, Annex 9 resolution MEPC.213* | | | 1 | (Hansen, Rasmussen and Lutzen, 2020) |
| National Law and Policy Development | *Total: 14* | | | | | |
| | *USA* | | | | | |
| | US Laws and International Treaties | | 1 | | | (Hildreth and Torbitt, 2010) |
| | *UK* | | | | | |
| | Scope for complementary sub-global policy to reduce $CO_2$ emissions – UK Case Study | | 1 | | | (Gilbert and Bows, 2012) |

| | | | | | | |
|---|---|---|---|---|---|---|
| | *France* | | | | | |
| | Impact of French policies for reduction of CO$_2$ emission in freight transport | | | | 1 | (Touratier-Muller, Machat and Jaussaud, 2019) |
| | *China* | | | | | |
| | Chinese Coastal transportation system joint taxation-subsidy emission reduction | | | | 1 | (Chen et al., 2020) |
| | Chinese maritime policy implications due to emission trends | | | | 1 | (Yang, Ma and Xing, 2017) |
| | Chinas stance on Ship-Based GHG Reduction Negotiations | | 1 | | | (Wang and Wang, 2010) |
| | Effect of VOC emission increase from ships at berth within Pearl River Delta Emission Control Area | | | | 1 | (Wu et al., 2020) |
| | *European Union* | | | | | |
| | European Law Regulation EC 2015/757 | | | | 1 | (Primorac, 2018) |
| | EU Fuel Regulation 2009/30/EC | | | | 1 | (Blasing et al., 2017) |
| | EU Monitoring, Reporting and Verification (MRV) scheme EU 2015/757 | | | | 1 | (Fedi, 2017) |
| | *Globally* | | | | | |
| | Comparison of all current global regulations | | | 1 | | (Cullinane and Cullinane, 2013) |
| | International Law for Oil Pollution | | | | 1 | (Valiullina and Abdullin, 2018) |
| | International Regulation for Low Carbon Shipping | | | | 1 | (Shi and Gullett, 2018) |
| | Policy development utilising emissions allocation to national inventories | | 1 | | | (Heitmann and Khalilian, 2011) |

When considering the breadth of legal and policy development from 2009-20 it is clear that the volume of papers has significantly increased from 6 in 2009-12 to 20 in 2017-20. Despite this legal commentary from an academic point of view, despite the major environmental legislation being put into force (as demonstrated in Sections 4.1-4.4) there is a lack of international regulatory framework in both the Kyoto Protocol and Copenhagen Accord for the shipping and maritime sector. As a function of time, Table 8 also demonstrates the diversification of policy analysis away from a more global scale. From 2017-20 what can also be shown within the Table is how national case studies are being utilised for how the international policy affects specific nations. However, this is not applicable to all nations and only France, China, USA and UK shipping industries have been studied. Whilst other member states of the EU are considered within several different policies (such as EC 2015/757, EU Fuel Regulation 2009/30/EC and EU 2015/757) there is only a singular reference for each of these documents. This limited scope of academic commentary upon legal frameworks and industrial applications, constrains the further development of policies and legalities. By not adequately exploring these policies and how this may affect vessels on a practical basis would limit the scope for implementation of decarbonising technologies as their effectiveness cannot be effectively demonstrated.

## 5.0 Future Research Developments

The literature explored within this paper provides an insightful scope to be able to use these governmental documents, international protocols and academic literature to examine trends and predict future research developments.

*Biofuels, internal combustion and bunkering systems modification*

Firstly, due to the emphasis on ECAs and the desulphurisation of marine fuels, the use of alternative fuels and 'naturally' derived fuels has become an established research discipline. Moving forward, to particularly align with the 'circular economy' environmental ethos, 2017-20 saw a substantial increase in bio-based fuels. Therefore, low sulphur and carbon emission bio-based fuels (especially fuels utilising abundant waste products) have the potential to come to fruition and have the versatility to work across a broad spectrum of vessels. Further to this, as each nation has their own environmental priorities, there is scope for countries producing certain types of waste in more substantial quantities than others to produce locally sourced marine fuel. The consequential actions of this are that it may drive down the price of fuel as when 'new' ultra low SOx and NOx fuel emission legislation comes into force, nations will be prepared. To enhance this research, a cost to benefit analysis of this fuel could be completed to realise their true benefits.

To compliment the potential implementation of these new bio-based fuels there is also a need for internal combustion and bunkering systems modification. These modifications could be in the form of general optimisation of both volumetric storage space on board and finding further solutions for reducing the volumetric storage space for onboard batteries. Further to this, a gap in the literature seems to exist between the research and development of fuels and consumption of fuels. This gap centres on the decarbonisation of the delivery of fuel to the specific vessel; rather than the decarbonisation of the fuel under different operating conditions.

*Multimodal logistics*

Another aspect of decarbonisation that appears to have been overlooked is a deeper understanding of how decarbonisation plays a bigger role in multimodal logistics. The few examples of how the carbon footprint of supply chains and model shift are demonstrated in Rodrigues et al. (2015), Das and Jharkharia (2018) and Ghosh, Jha and Sharma (2020). Specifically, future research should approach the decarbonisation of transportation of goods with a more holistic approach rather than just specifically shipping logistic segments such as seaports. Further to this, how the different ports incorporate new technologies and decarbonisation techniques would be demonstrated and how their role may change the dynamic of this ‘all compassing’ logistical framework.

When considering the shipping industry, this includes not only the ships but the port infrastructure surrounding them. To decarbonise ports, structures and the buildings in these areas, a key gap in the current literature is a review of these structures’ resistance in such harsh chloride-rich conditions. For example, a relevant further review could be to review any chloride resisting technologies, materials and repair methods specific for a port environment. Innovations in this research area would improve both the durability and resilience of ports and port infrastructure.

*Operating condition types*

From 2017-20, it was demonstrated that there has been a growth in the emission analysis at different operating conditions. However, what this table also highlighted was that whilst there is a larger breadth of research for these operating conditions the depth of research is not sufficient. Therefore, it is likely that in the future there should be a greater quantity of research to verify and ensure these results are accurate, specifically for different ships typologies. Further to a greater depth of comparable literature, more research items will also contribute to a better understanding of which conditions for which ships produce the most emissions. By understanding this data, will provide a better insight as to how to control and reduce these emissions.

*Closing the ‘performance gap’*

When new technologies are designed and utilised on ships, there appears to be a research gap between the modelling, ‘proof of concept’ of the technology and the implementation of the technology onboard. By comparing the theoretical and in-situ performance gap to the construction industry where the energy performance gap has been identified and understood (as demonstrated in van Dronkelaar et al. (2016); Khoury, Alameddine and Hollmuller (2017)) there is a real opportunity for the shipping community to address these issues. Similarly, another research gap opportunity lies within the understanding and comparison of ships with different retrofitting technologies to the performance of new build ships with new decarbonisation technologies.

*Implementation of environmental legislation*

Other substantial world events that may influence these predictions include the 26th UN Climate Change Conference of the Parties (COP26) in Glasgow UK during November 2021. It is predicted that during this conference substantial environmental decisions are set to be made as it is deemed the most important climate summit since 2015 at COP21, where the Paris Agreement was signed. Due to the coronavirus pandemic, this summit was rearranged to 2021 rather than 2020, however this will provide a better comparison and utilisation of environmental data from 2015-20. In addition, this will be the first major global environmental conference where the Biden administration from the USA will attend. This is particularly noteworthy, as the USA re-joined the Paris Agreement in January 2021. As one of the major global contributors to $CO_2$ emissions, and although it is not confirmed, it would seem likely that this would be an opportunity for the USA to implement substantial environmental and emission reducing targets, particularly for decarbonisation through renewable energy technologies. Although it was recognised earlier in this paper that the Paris Agreement did not specifically outline the emission reductions required for the maritime industry. It will be significant if COP26 addresses this and acts to formally provide emission targets for this industry.

## 6.0 Conclusion

To achieve major environmental and climate change goals, the shipping and maritime industry must continue in its efforts to decarbonise. This review paper utilised 294 internationally peer reviewed journal articles to understand how maritime transport has decarbonised between

2000 to 2020. Through this time period, the journal with the most published papers was ‘Atmospheric Chemistry and Physics’, where 50% of all contributing items within this review were from European research establishments. The quantity of research papers and variety of contributing journals has unequivocally grown, particularly from 2017-20. Established research relationships were investigated where the most prevalent authors were Jürgen Orashe, Benjamin Stengel and most prominently, Ralf Zimmerman with 8 different journal articles. By time blocking the 20 years into 4-year spans, analysis of research themes became much clearer to analyse.

What is established is that initially between 2000-04, despite there being a lot of ‘new’ environmental legislation this did not influence the dissemination of research within this sector. As regulations are published, analysed and critiqued there becomes slightly more of an interest in decarbonisation and emission reduction in 2005-08. Within 2009-12, starts a period of change within the industry. Legal, governmental and academic resources began to entwine with growing research branches understanding the characterisation of particle emissions from ships in addition to experimentation of fuel alternatives. 2013-16 saw greater diversity of the operating conditions on ships where emissions are produced, fuel alternatives and most importantly academic commentary on policy amendments and the law surrounding emission mitigation. Finally, 2017-20 highlighted that the analysis of particle emissions from ships in general was not necessary as more sophisticated techniques such as: green and renewable technologies, shipping emissions effects on port areas and a greater range of operating conditions for carbon emission analysis for ships. Within this timeblock, the available decarbonisation technologies are critically analysed in terms of their advantages, disadvantages and application environments under which they are feasible and suitable. Further to this, over twenty years worth of legal and policy developments are summarised from a country, continental and worldwide perspective.

Finally, utilising the selected academic literature theming data, governmental documents and world news has demonstrated the identification of future potential research predictions and inherent research gaps. This review indicates that some of the emerging research trends will focus on sustainable, low-cost biofuel, deeper evaluation of carbon emission analysis at different operating conditions for emission reduction optimisation purposes and a more holistic approach to the decarbonisation of multimodal transport logistics.

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