

Article

The Role of Research and Innovation in Europe for the Decarbonisation of Waterborne Transport

Monica Grosso ^{*}, Fabio Luis Marques dos Santos , Konstantinos Gkoumas , Marcin Stępniaak and Ferenc Pekár 

Joint Research Centre (JRC), European Commission, 21027 Ispra, Italy; fabio.marques-dos-santos@ec.europa.eu (F.L.M.d.S.); konstantinos.gkoumas@ec.europa.eu (K.G.); marcin.stepniak@ec.europa.eu (M.S.); ferenc.pekar@ec.europa.eu (F.P.)

* Correspondence: monica.grosso@ec.europa.eu; Tel.: +39-0332-785-847

Abstract: Waterborne transport contributes to around 14% of the overall greenhouse gas emissions of transport in the European Union and it is among the most efficient modes of transport. Nonetheless, considering the aim of making the European Union carbon-neutral by 2050 and the fundamental role of waterborne transport within the European economy, effort is needed to reduce its environmental impact. This paper provides an assessment of research and innovation measures aiming at decreasing waterborne transport's CO₂ emissions by assessing European projects based on the European Commission's Transport Research and Innovation Monitoring and Information System (TRIMIS). Additionally, it provides an outlook of the evolution of scientific publications and intellectual property activity in the area. The review of project findings suggests that there is no single measure which can be considered as a problem solver in the area of the reduction of waterborne CO₂ emissions, and only the combination of different innovations should enable reaching this goal. The highlighted potential innovations include further development of lightweight composite materials, innovative hull repair methods, wind assisted propulsion, engine efficiency, waste heat electrification, hydrogen and alternative fuels. The assessment shows prevalence of funding allocated to technological measures; however, non-technological ones, like improved vessel navigation and allocation systems, also show a great potential for the reduction of CO₂ emissions and reduction of negative environmental impacts of waterborne transport.

Keywords: waterborne decarbonisation; research and innovation; technical measures; operational measures; coordination and support measures



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1. Introduction

Waterborne transport includes maritime and inland waterways transport. This transport mode represents more than 80% of global freight volume, as 11 billion tons of freight were transported on water in 2018. Nevertheless, in the same year the annual growth of international maritime transport slowed down, with an increase of 2.7%, which is somewhat below the historical average of 3.0% from 1970–2017 and 4.1% in 2017. This was in line with a global trade slowdown in 2018 [1]. The role of this sector in Europe's economy is significant, as maritime transport represents 70.1% of the European Union's (EU) external freight trade by weight and 29.2% of intra-EU traffic. Additionally, inland waterways accounted for 3.9% of the total goods transport in the 27 EU Member States (EU-27) in 2018 [2]. In terms of employment, the waterborne transport sector employed almost 400,000 people and accounts for more than EUR 35,000 million of GDP [3].

Waterborne transport is among the least carbon intensive modes of transport in terms of CO₂ per ton km transported. Nevertheless, the International Maritime Organisation's (IMO) estimated that international shipping produced around 1 billion tons of CO₂, representing about 2.8% of total man-made emissions in 2018. Moreover, the growth of transport

demand is expected to continue [4]. As a consequence, those emissions could increase by up to 50% until 2050 compared to 2018 levels, despite further efficiency gains.

Waterborne transport represents 14.1% of greenhouse gas (GHG) emissions produced by the European transport sector in 2018 [2], which is slightly more than European aviation (13.2%). Considering its fundamental importance to the European economy and its global nature, effort is needed to reduce its environmental impact [5,6]. To date, EU legislation and international agreements have focused on pollution reductions; however, emphasis on reducing GHG emissions has substantially increased recently, in line with the objectives of the European Green Deal [7].

At the international level, IMO rules are addressed within the International Convention for the Prevention of Pollution from Ships (MARPOL). The Annex VI refers to the following aspects: accidental and operational oil pollution, noxious liquid substances in bulk pollution, pollution by harmful substances carried in packaged forms, sewage, garbage, air pollution and efficiency via the EEDI (Energy Efficiency Design Index) and SEEMP (Ship energy efficiency management plan).

In Europe, the actions defined in the European Green Deal pursue the objective of obtaining a sustainable European economy, where no net GHG emissions will be present, by 2050. This includes a 90% reduction in emissions from European transport. The recent Strategy for a Sustainable and Smart Mobility set the pathway to reach a European transport system which should be sustainable, smart and resilient by 2050 [8]. The EU's strategy towards reducing GHG emissions in the shipping industry [9] foresees a three step approach. Moreover, it includes a list of key measures, such as the implementation of a monitoring, reporting and verification (MRV) system, the definition of GHG reduction targets for maritime transport and the implementation of market-based measures.

Scientific literature and business cases report a wide range of measures, either already applied or in research phases that could enable maritime transport to become less polluting. A list of 22 measures have been identified in [10], which fall within the following categories: hull design, power and propulsion, alternative fuels, alternative energy sources and operations. The detail review of previous research on the topic provides estimations of possible CO₂ reduction for each measure, concluding that significant emission reductions could be achieved by the quick adoption and combination of different measures. Effective regulatory frameworks have been included in the list of CO₂ emissions control measures in [11] which details technological and commercial features of the identified measures and concludes on their interdependent impacts. In [12], four possible estimations of shipping decarbonisation have been presented estimating CO₂ reductions ranging from 82% to 95% by 2035, emphasising the role of alternative fuels and renewable energy together with the support of operational measures.

The actions aiming at reducing waterborne transport emissions vary from promoting technological solutions to operational measures and support and coordination actions [11,12]. A range of technologies for reducing emissions from waterborne transport either has been implemented in vessel fleets or is currently under development. At the vessel level, naval architects have developed and refined design techniques for ships to improve the overall hydrodynamic shape to reduce resistance and hence reduce the power required to cruise at a given speed. A further refinement has been introduced in recent years to tailor ship designs to a lower design speed aiming for efficiency increases, mainly as an impact of the EEDI on the ship speed design, which could range from 1.5% to 10% of speed differences, depending on the vessel types [13,14]. The use of lighter materials in some parts of the ship construction also contribute to reduced resistance [15]. On the engine side, the vast majority of ships use large diesel engines of either the two-stroke or four-stroke mode running on heavy fuel oil (HFO). Their design has also evolved over time, incorporating enhancements such as the Miller cycle [16], two-stage turbocharging and advanced fuel injection systems [15]. These technologies are already widely implemented in new ship engines. More recently, engine manufacturers have begun to produce engines designed to run on both HFO and natural gas (usually stored as Liquefied Natural Gas (LNG)).

However, the appropriate engine technologies to maximise GHG reductions may not be economically profitable, and policies or regulations should account for this fact [17].

More advanced ship propulsion technologies that are under development include wind propulsion devices such as Flettner rotors [18] and other wind-assisted ship propulsion (WASP) systems such as wind turbines and sails. The energy savings deriving from WASP may vary based on the technologies specifications and ships type, nonetheless showing significant potential in fuel reductions based on the different technologies used: rotors: 0.4–50%, kites: 1–50%, rigid sails: 5–60%, soft sails: 4.2–35% and wind turbines: 1–4% [19].

There has been considerable interest in the use of alternative fuels for shipping [20], in particular LNG, hydrogen and ammonia [21]. Nevertheless, maritime transport (and aviation) are not expected to be supplied with a significant amount of biofuels in the near future, and the current set of measures is not perceived as sufficient to support waterborne decarbonisation through biofuels [22].

The fuel consumption of a ship is strongly related to the speed at which the ship cruises. The cruising speed depends on a number of factors, principally the income for the operator and fuel costs. There is effectively (at least) a cubic relationship between the speed of a ship and the power required to propel it, thus a higher speed can increase fuel costs significantly [23]. For example, a 10% reduction in speed leads to a 27% decrease in power demand. Accounting for the lower distance covered, a 10% speed reduction results in a 19% reduction in fuel consumption per unit distance. Such reduction in fuel consumption also leads to similar reduction in CO₂ emissions, which depending on the vessel types could be from 10% to 38% if the ships reduce their speed by 10% to 30% [24,25].

Another factor that influences a ship's fuel consumption and hence emissions is route planning. A route that avoids poor weather, including adverse winds, may lead to lower fuel consumption than one that is theoretically shorter but encounters adverse conditions. Improved route planning technologies, taking advantage of improvements in weather forecasting capabilities, can help the ships' captains to plan optimised routes to follow. Such an operational measure could lead to a possible reduction of CO₂, estimated to be between 0.10% and 3.7% of the total emissions [15]. When berthed in ports, ships generally use their on-board auxiliary engines to provide power to run the ship's system, including heating and air conditioning. The use of cold ironing to replace the use of the auxiliary engines means significant reductions in pollutant emissions.

To ensure that targeted emissions reductions are achieved on a 'net' basis, some sectors have introduced market based measures such as emissions trading or offsetting [26]. For example, in aviation, intra-EU flights have been subject to the EU Emissions Trading System (EU ETS) since 2012, while a new global measure, the International Civil Aviation Organisation (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation-CORSIA [27] will be introduced starting in 2021. To date, no such schemes have been introduced for maritime transport. However, Directive (EU)2018/410 [28] notes that all sectors of the economy should contribute to the reduction of greenhouse gas emissions and the European Commission (EC) announced in the Strategy for a Sustainable and Smart Mobility [8] that it will propose the extension of EU ETS to the maritime transport sector; moreover, the EU Strategy aims to achieve the target of zero emission vessels and to increase the share of inland waterways and short sea shipping by 25% by 2030 and by 50% by 2050. The EU introduced a requirement for all large ships entering EU ports to report their emissions via a MRV scheme [29] known as THETIS-MRV [30]. This scheme was seen as a first step in a staged approach to the inclusion of maritime emissions in the EU's GHG reduction commitment [31].

As previously stated, the EU is taking actions aiming to reduce waterborne transport emissions in many areas. The EU has a key role to play through regulatory actions, but also through financial incentives and the promotion of Research and Innovation (R&I) to develop or enhance innovative technologies. The European Green Deal identifies R&I as a

key aspect for increasing European competitiveness where the transport sector represents one of the most important European industries, both in economic and R&I terms.

R&I can boost technological innovation and help with achieving the emissions targets set at the European level. For this reason, in May 2017 EC adopted the Strategic Transport Research and Innovation Agenda (STRIA), as part of the 'Europe on the Move' package. STRIA highlights main transport R&I areas and priorities for clean, connected and competitive mobility [32]. The EC Joint Research Centre (JRC) has developed the Transport Research and Innovation Monitoring and Information System (TRIMIS) to support the implementation of STRIA and monitor technology trends and transport R&I capacities, as detailed further in the methodological description.

This paper uses the TRIMIS database and capabilities [33], co-developed by the authors, in order to review recent developments, measures and research trends related to waterborne transport, focusing on those related to reduction of CO₂ emissions. The aim of the paper is:

- to provide an overview of waterborne transport projects focusing on decarbonisation, financed through the latest European Framework Programmes (FPs) for research and innovation through a quantitative assessment;
- to qualitatively assess the related project's technologies and measures in the areas of control and reduction of waterborne CO₂ emissions; and,
- to identify research gaps which will help with providing relevant recommendations for future research and policy developments.

The rest of the paper is organised as follows. Section 2 presents the methodological framework of this work. Section 3 presents the quantitative and qualitative assessment of projects in the TRIMIS database. Section 4 provides discussions and conclusive remarks.

2. Material and Methods

The methodological approach used for this analysis combines two complementary parts. First, a quantitative overview of EU projects dealing with waterborne decarbonisation is presented, supplemented by the analysis of evolution of peer reviewed scientific publications and patents associated to those technologies. The second part contains a qualitative assessment of EU projects which aims to identify main R&I directions and technologies. This analysis helped define future indication both at research and policy levels.

This analysis uses the TRIMIS database [34] which contains nearly 9000 publicly available transport research projects and focuses on the most recent FPs, i.e., the 7th Framework Program for Research (FP7) and the Horizon 2020 Framework Program for Research and Innovation (H2020). Projects funded under previous or other R&I programmes like CEF or LIFE, as well as those funded through national research programmes were excluded, as their results are potentially outdated or their description in the database was not complete. The TRIMIS database includes projects' mode categorisation, which permits identifying all waterborne transport projects. Multimodal projects directly linked to waterborne transport were also added to the selection. Finally, the full list contains detailed data on 205 research projects.

The next step of analysis uses a keyword search to identify projects related to decarbonisation of waterborne transport. The selected keywords are decarbonisation, CO₂ and emission and the search covers descriptive text reported in the project objectives, background, methodology and key results. The search was followed by a manual check to verify the accuracy of the selection. The process led to a final selection of 133 projects (for the full list of selected projects, see [35]).

The final step of projects identification and categorisation is based on a literature review [6,10,12,36,37]. It leads to the definition of 5 sub-themes:

1. Hull design which includes projects focusing on lightweight composite materials for structural components, innovative hull repair methods and hull surface protection;

2. Power and propulsion which covers projects focusing on wind assisted propulsion, increases in engine efficiency and recycling of waste heat for use elsewhere in the vessel;
3. Fuels and alternative energy sources which covers projects focusing on the use of electrification (batteries, hybrid systems), use of hydrogen, LNG or compressed natural gas (CNG) or liquefied petroleum gas (LPG) as a fuel;
4. Operational measures which identifies projects focusing on topics such as improved vessel navigation, vessel allocation systems and robotic container handling systems;
5. Coordination and support measures, including research, networking activities: which covers projects focusing on the dissemination and consolidation of research in the waterborne transport sector, as well as planning and investigating future strategy for the sector, including both vessel and port design.

The first three sub-themes (i.e., hull design, power and propulsion and fuels and alternative energy sources) are directly related to a technological advancement, while the other two sub-themes cover other type of measures within the waterborne transport sector. It should be noted that projects may be relevant to multiple sub-themes or can investigate technologies and measures which are not constrained to just one sub-theme. Therefore, projects can be classified under more than one sub-theme.

Then, manual categorisation of the projects was carried out, supported by machine learning and natural language processing methodologies. For this purpose, the Gensim python library [38] was used. Text summaries and keywords were extracted using automated text summarisation and keyword extraction methods [39] on the full project text corpus available from the projects in TRIMIS. Projects were then manually categorised based on the summaries and keywords.

An analysis of the evolution of peer reviewed scientific publications and patents associated with waterborne research complements the quantitative part of the study. The former focuses on the main trends in waterborne research and locates results in the broader, international context, while the latter aims to provide additional insights into private investments and research outputs related to technological topics. The Scopus citation database of data on journal and conference publications [40] is used, limited to the period 2010–2019. A list of regular expressions (REGEX) used for the extraction and categorization of publications is presented in the Appendix A. The patent analysis is based on the European Patent's Office (EPO) Worldwide Patent Statistical Database (PATSTAT). The search was carried out using cooperative patent classification (CPC) codes, patent titles and abstracts. The search was restricted to the CPC code "B63-SHIPS OR OTHER WATERBORNE VESSELS; RELATED EQUIPMENT", and it covers the period of 5 years (2013 to 2017). This time restriction was necessary since the time lap between patent application and granting is generally relatively long; thus, 2017 was the last year on which a meaningful number of granted patents was available in this area.

The final step of the quantitative assessment refers to the maturity of technology researched within specific projects, focusing on technologies developed within the first three technology-oriented subthemes. The assessment aims to understand the extent to which a certain technology is market ready by categorising technology maturity in four phases (research, validation, demonstration and implementation) [41], in a similar way to the original technology readiness levels (TRLs) used by the National Aeronautics and Space Administration (NASA) [42].

For the qualitative analysis, a selection from the 133 identified projects was used, categorised under each sub-theme in order to identify the overall direction of the respective research progress [35]. These projects were selected based on the overall scale of the project (i.e., total funding value), the availability of results and conclusions on the research being performed. Table 1 shows projects examined in detail to illustrate the progress being achieved in particular topics.

Table 1. List of the projects included in the qualitative assessment.

Subtheme	Project Acronym	Key Themes	Funding Programme	Duration
Hull design	ADAM4EVE	Adaptive hull structures; smart materials	FP7-TRANSPORT	2013–2015
	HILDA	Friction stir welding	FP7-TRANSPORT	2012–2015
	LEAF	Hull surface antifouling technology	FP7-TRANSPORT	2012–2015
	MOSAIC	High-strength low-alloy steels	FP7-TRANSPORT	2012–2015
	FIBRESHIP	Fibre reinforce polymers	H2020	2017–2020
	COMPACTGO	Smart repair service	H2020	2018–2020
Power and propulsion	RotorDEMO	Wind assisted propulsion	H2020	2017–2018
	GFF	Fully electric ferry	H2020	2016–2018
	EEECMS-2	Waste heat to energy	H2020	2016–2018
	LeanShips	Increased engine efficiency, emissions abatement technologies	H2020	2015–2019
	HERCULES-2 RotorDEMO	Increased engine efficiency, fuel-flexible engines Wind assisted propulsion	H2020 H2020	2015–2018 2017–2018
Fuels and alternative energy sources	BB Green	Vessel electrification; reduced hull resistance	FP7-TRANSPORT	2011–2014
	PURE	Fuel-cell auxiliary power unit	FP7-JTI	2013–2016
	E-ferry	Fully-electric ferry	H2020	2015–2019
	MARANDA	Hybrid fuel-cell powertrain system	H2020	2017–2021
	HyMethShip	Hydrogen-methanol propulsion system	H2020	2018–2021
Operational measures	RCMS	Robotic container management system	H2020	2015–2017
	CLOUD-VAS	Cloud-based vessel allocation	H2020	2015–2017
	LOGIMATIC	Global Navigation Satellite Systems (GNSS); route planning	H2020	2016–2019
	SHIPLYS	Virtual prototyping, life-cycle assessment	H2020	2016–2019
	H2H	Safe vessel navigation	H2020	2017–2020
	AUTOSHIP	Autonomous vessels	H2020	2019–2022
Coordination and support measures	MESA	Dissemination of research	FP7-TRANSPORT	2013–2016
	VDRConnect	Market assessment of technology	H2020	2016–2016
	Prominent	Assessment of technology development areas	H2020	2015–2018
	DocksTheFuture	Port technology standardisation, dissemination, networking	H2020	2018–2020
	MarTERA	Coordination of technologies	H2020	2016–2021

Source: Adapted from data available in [35].

Figure 1 shows a diagram with the steps taken to perform the analyses in the methodology.

Since full information on the achievements of the projects is not available until the publication of the final report, the majority of projects considered in detail are those that have been already completed. Nonetheless, some projects which have not yet been fully completed are also included in the assessment, motivated by the availability of data and their proposed innovative solutions.

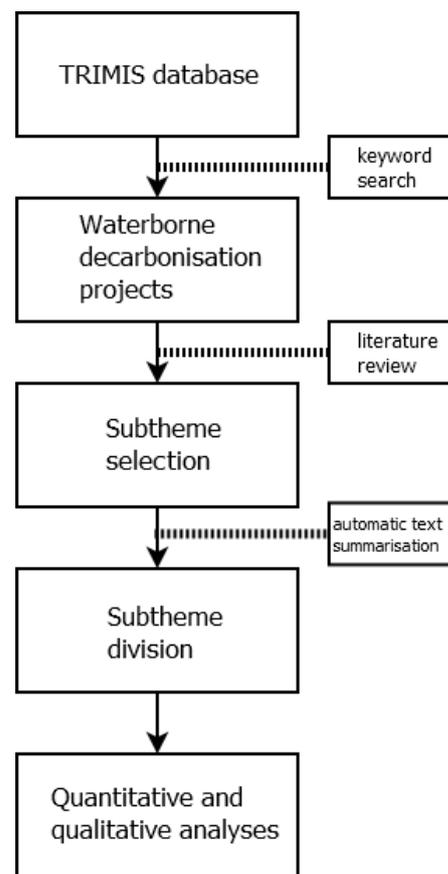


Figure 1. Diagram summarising the methodology.

3. Results

3.1. Quantitative Assessment

Figure 2 shows the total number of projects touching upon the decarbonisation topic and the division in sub-themes. Approximately 65% of the waterborne projects deal with decarbonisation. The majority of decarbonisation-related projects are technical-oriented, while a significantly lower and similar number of them focus on operational issues as well as on coordination and support measures. It is important to note that the total number of projects within all the subcategories is greater than the number of decarbonisation projects, because some projects are double labelled (e.g., technical and coordination and support measures).

In total, under FP7 and H2020, around EUR 995 million has been invested and are currently being spent in waterborne transport decarbonisation research projects. These values include estimates for the years 2021–2023 which are based on the expected project costs.

Figure 3A shows the evolution of the waterborne and decarbonisation transport projects costs from 2008 to 2020, including costs for each decarbonisation subtheme. The project costs are calculated by dividing the total project budget by its duration and assigning them to the respective years. There are two peaks of invested money in the years 2012 and 2018. They are related to peaks of activities within both analysed framework programmes (2012 for FP7 and 2018 for H2020).

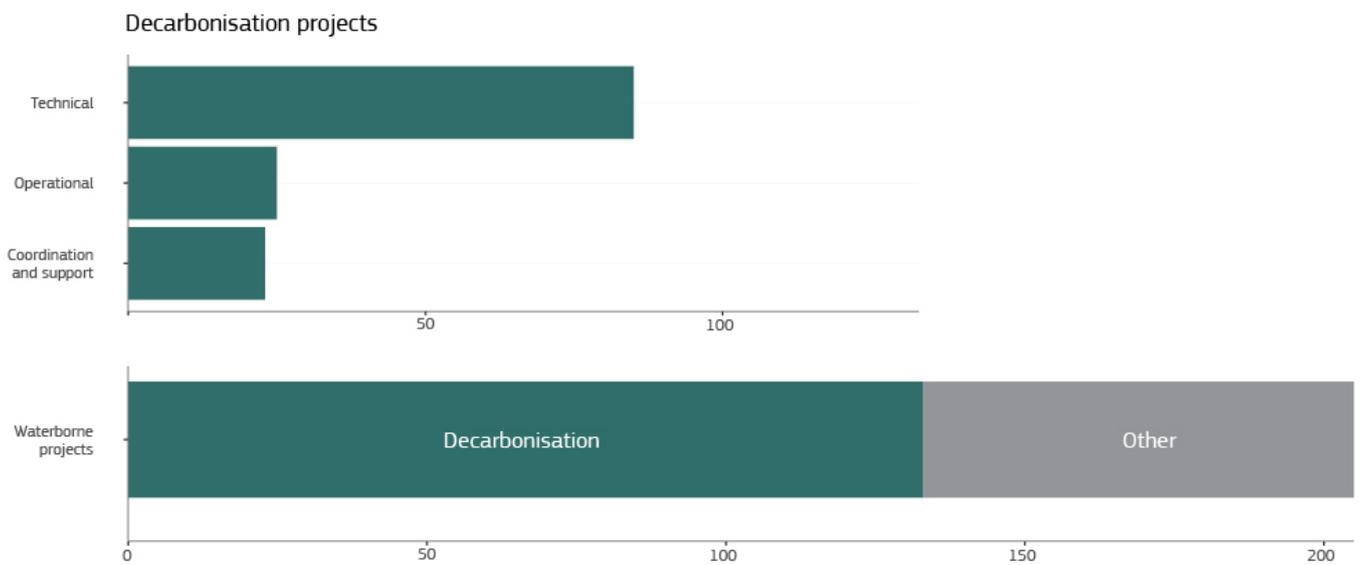


Figure 2. Waterborne projects and theme division. Reprinted from ref. [35].

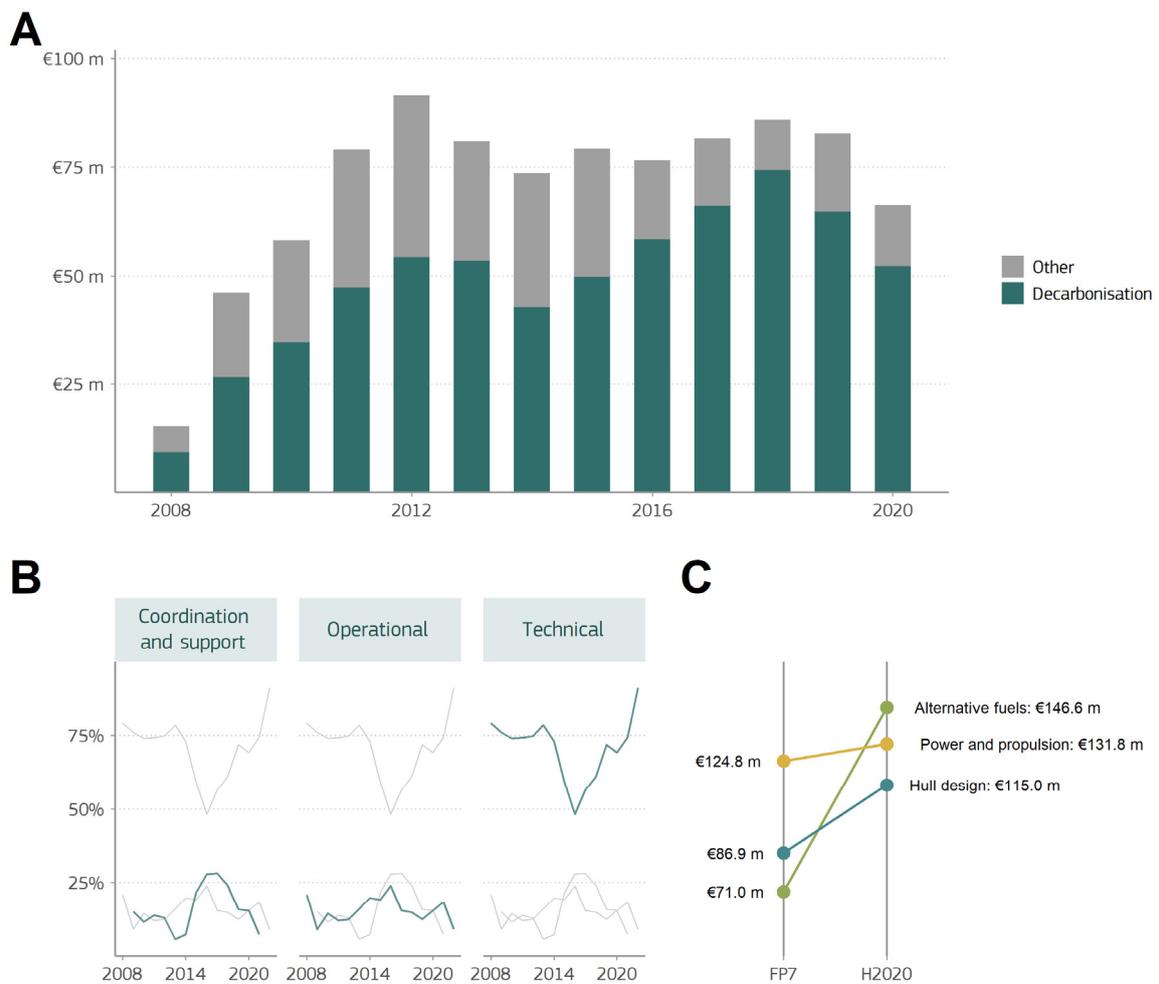


Figure 3. Waterborne project costs in the period 2008 to 2020. (A) Waterborne and decarbonisation waterborne project costs; (B) Yearly decarbonisation project costs by theme; (C) Total technical decarbonisation project costs under FP7 and H2020. Note these costs do not sum to 100% of cost, as they include overlap with other sub-themes. Source: Adapted from data available in [35].

Further, the share of decarbonisation waterborne transport projects increased substantially during the duration of H2020 programme. EUR 71 million out of a total waterborne budget of EUR 464 million has been spent on decarbonisation projects. This is in line with the evolution of the number of decarbonisation projects within waterborne research. The FP7 programme funded 102 waterborne transport projects, of which 53 are under the decarbonisation theme, while in case of H2020, these numbers are 103 and 80, respectively. An increase of share of decarbonisation-related projects in waterborne transport research from 52% in FP7 to nearly 78% in H2020. This clearly shows an increased importance of decarbonisation in research activities.

Figure 3B shows the evolution of funding distribution split into three main categories, namely technical, operational measures and coordination and support measures. In general, the chart reveals a similar pattern to the one presented by the Figure 2, as most of the funding, from 50% up to 80%, supports technical-focused projects. The latter two categories attract a similar share of funding. Moreover, this general pattern is relatively stable over the course of the analysed period of time.

Figure 3C provides further details regarding main trends of investments in waterborne research, limiting the data to the three, technical oriented sub-themes. In the hull design sub-theme, there are similar proportions of participation in both FPs, power and propulsion shows a decrease in budget for H2020, while fuels and alternate energy sources present an increase in project funding in H2020. It could be concluded that there is a budget shift between the two well-linked topics, with fuels and alternate energy sources being the prevalent one in H2020.

Table 2 presents a summary of the total number of projects implemented during both framework programmes, their total funding and EU contribution. The technical projects are more numerous and received higher funding during the last two R&I financial framework. The highest number of projects investigate power and propulsion and these projects have the highest budget among all subthemes. A similar number of projects, with comparable budgets, focus on the remaining two technical sub-themes, namely hull design and fuels and alternate energy sources. The number of projects falling under the operational and coordination and support measures sub-themes is relatively lower, as well as the related funding.

Table 2. Funding level per sub-theme.

Total Funding Action	Number Projects	Total Funding	EU Contribution
Hull design	34	EUR 199,585,618	EUR 147,391,833
Power and propulsion	43	EUR 238,664,870	EUR 163,747,778
Fuels and alternative energy sources	37	EUR 196,232,303	EUR 144,362,260
Operational measures	22	EUR 96,995,701	EUR 80,040,301
Coordination and support measures	23	EUR 118,709,260	EUR 81,659,851

Source: Adapted from data available in [35].

The dominance of the power and propulsion sub-theme in waterborne decarbonisation studies is also reflected in the trends in academic publication records, as scientific articles in this domain range from 42% (2010–2012) to 38% (2018–2019) of the total articles considered. The second most investigated topics are operational subjects representing 32% and 37% over the total articles in 2010–2012 and 2018–2019, respectively. The articles looking at fuels and alternative energy sources issues are around 20% of the total scientific production, not showing any particular change during the 10 years considered. The articles considering coordination and support measures and hull design aspects are relatively lower, accounting for 6% and 2% in 2010–2012 and in 2018–2019, respectively.

All these trends prevail even considering the significantly increased academic publication activities. When looking at the overall scientific production on this specific topic, an increase of 82% in the total number of scientific publications is evident, from around 3000 articles in 2010–2012 to 5600 in 2018–2019. It should be noted though that in the same time span, there has been an increase of publications in the science areas in Scopus

considered in this exercise. As a comparison, and with 2010 as a reference, the total number of scientific publications increased by 20% in 2016 and by 40% in 2019. Considering this, still, the normalised increase of the overall scientific production on this specific topic in 2019, compared to 2010, results in little more than 30%.

The quantitative analysis of a number of patents associated with decarbonisation technologies included in the European Patent Office PATSTAT databases also confirms the dominance of the power and propulsion and hull design sub-themes within waterborne decarbonisation research (Figure 4). Nevertheless, the power and propulsion sub-theme increased in share in the last few years. Moreover, patents within the fuels and alternative energy sources sub-theme show an increase over the total share of patents in the last years, while operational and coordination and support measures are less present overall, also confirming the fact that these sub-topics are not directly technology oriented.

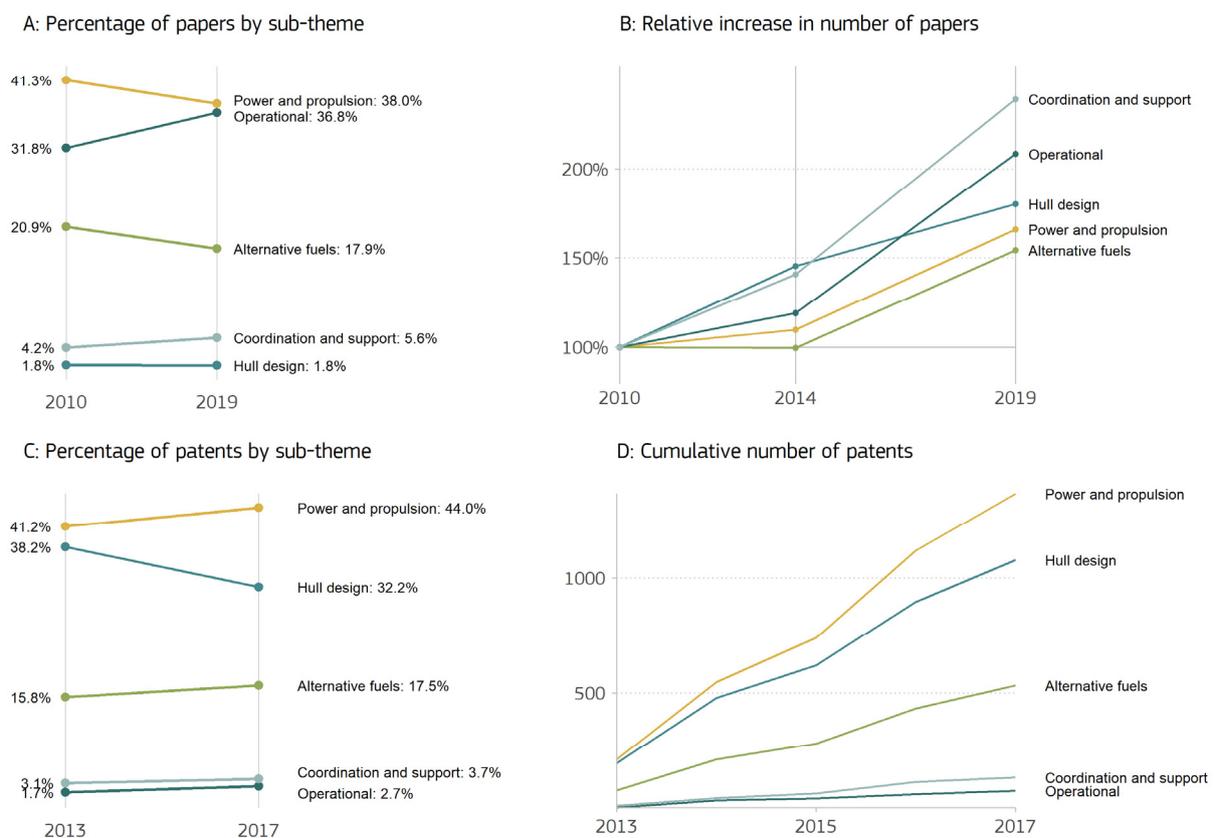


Figure 4. Academic production and patents in waterborne transport decarbonisation. Source: Adapted from data available in [35].

The final part of quantitative assessment summarises the technology maturity breakdown for waterborne projects and the different topics (Figure 5). It is visible that, for all categories, the majority of technologies are under the initial research step, while the number of technologies in the validation, demonstration and implementation stages is quite even, showing that not much difference exists between the various topics.

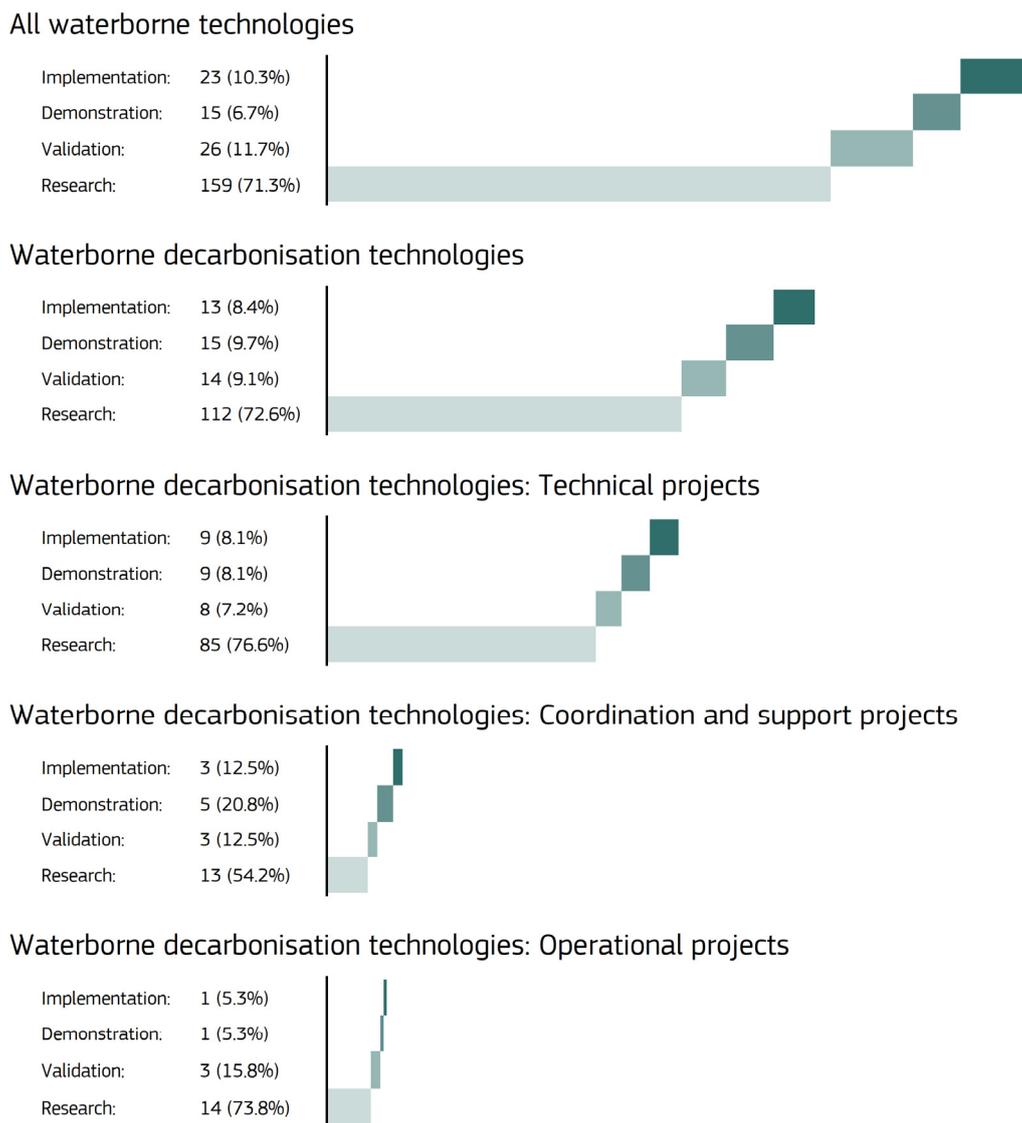


Figure 5. Technology maturity breakdown for waterborne technology and themes division. Reprinted from ref. [35].

3.2. Qualitative Assessment

3.2.1. Sub-Theme 1—Hull Design

The research projects within the hull design sub-theme tend to focus on lightweight composite materials for structural components, innovative hull repair methods and hull surface protection. The use of lightweight materials as replacements for heavier materials has the benefit of reducing the overall fuel consumption of the vessel, which subsequently leads to reduced GHG emissions if fossil fuels are used. Another benefit of reducing the vessel energy consumption is that less energy dense fuels (hydrogen, LNG, batteries) may be able to provide sufficient energy to power the vessel, hence paving the way for alternative fuels use in the maritime sector.

The review of the projects of this sub-theme shows that there is interest in using composite materials for conventionally fuelled ships; friction stir welding technology should allow ships built from conventional steel to be made lighter, with consequent improvements in efficiency. Some of the benefits linked to such technologies have been listed in Table 3 (This and the following tables illustrating European projects results and benefits cannot be considered comprehensive of the overall projects outcome as a selection of information was done for the purpose of this paper and information may not be easily accessible for

all projects) which identifies efficiency improvement associated to fuel savings, weight reduction and possible cost savings. Prototypes were also built into the model or at a large scale, and were assessed in terms of technical properties, safety issues and economic and ecological impacts (e.g., ADAM4EVE, MOSAIC projects).

Table 3. Hull design projects: expected benefits.

Project Acronym	Key Themes	Expected/Proved Benefits	Main Benefits Estimation
ADAM4EVE	Adaptive hull structures; smart materials	Fuel savings due to: retractable stern flap, lightweight panels, adaptive bulbous bow.	Yearly fuel saving of ~5.6% of retractable stern flap
HILDA	Friction stir welding	System and software for using friction stir welding in industrial settings	Potential cost saving per welder per year: -€390 no molten metal injuries; -€160 no UV exposure; -€750 reduced training and certification
LEAF	Hull surface antifouling technology	New antifouling technology without biocide emission and low adhesion	Antifouling efficiency for a wide range of organisms; low biocide release rates; lower environmental impact (global warming, acidification, eutrophication potentials; lower production costs.
MOSAIC	High-strength low-alloy steels	High Strength Low Alloyed Steels and replacement of ship's structural parts with composite materials.	Weight savings of ~30%; reduced material wastage and repair costs due to no corrosion of composite materials
FIBRESHIP	Fibre reinforce polymers	Design and construction of vessels greater than 500 GT in lightweight fibre reinforce polymers	Up to 36% overall weight reduction; bunkering consumption reduction; lower GHG Emissions; increasing payload/passenger capacity
COMPA 2GO	Smart repair service	Composite patch repair for damaged ship pipes	DNV GL certification

Source: Adapted from data available in [35].

Still, some future research should focus on joint implementation of composite materials with alternatively-fuelled vessels and on the wider-scale uptake applied to the whole fleet (e.g., as result of the LEAF project). Tooling issues remain a challenge in using this technology which appeared as a result of the HILDA project; in case of implementation on a large scale, this aspect would need to be investigated and mitigated accordingly. Future research could look for solutions to these problems, enabling the technology to be employed on a large scale. The research on the use of composite materials in ship manufacture is progressing towards implementation. However, due to fire hazards at present, IMO 'Safety of life at sea' rules limit the use of such materials to vessels of less than 500 tonnes gross weight. There may be a need to work at an international level to review and potentially revise the regulations to allow the use of advance materials in larger vessels, considering also the energy return of investment (EROI) linked to such technologies. Technologies to reduce ship resistance due to fouling of the hull by barnacles without harming the environment with toxic substances, were demonstrated to improve ship performance, leading to potential fuel savings ranging from 0.1% to 30%, according to different types of technologies [10,11]. Future research steps in this area should focus on an environmentally friendly coating with extended durability applicable to the full fleet. These technologies allow efficiency improvements, which nonetheless cannot be considered as a standalone solution to meet the challenging ambition of the EU Green Deal. Therefore, additional research should focus on combined solutions, which are capable of delivering significant greater reductions as well as addressing the recyclability of such materials.

3.2.2. Sub-Theme 2—Power and Propulsion

Projects under the power and propulsion sub-theme focus on topic areas such as wind assisted propulsion, increases in engine efficiency and recycling of waste heat for use elsewhere in the vessel. All of the technologies in this sub-theme relate to reducing the

overall energy consumption of the vessel either directly or indirectly. Improving engine efficiency will increase the energy obtained from the fuel used, and therefore will reduce the total volume of fuel required to perform the same operations. Auxiliary systems, e.g., heating and cooling of the cabin, are traditionally powered using the same fossil-fuel source as the engine, which increases the overall vessel's energy consumption. By using the waste heat from the engine to power the auxiliary system, fuel is saved and therefore GHG emissions are reduced. The range of CO₂ reduction estimation is wide, ranging from 1% to 25% and associated to the different technologies in place, as extensively summarised in [10] and [11]. Moreover, multiple European research projects have demonstrated reductions in fuel consumption using different propulsion concepts. A selection of those is shown in Table 4, which includes some of the estimated benefits identified from their implementation.

Table 4. Power and propulsion projects: expected benefits.

Project Acronym	Key Themes	Expected/Proved Benefits	Main Benefits Estimation
RotorDEMO	Wind assisted propulsion	Implementation, validation, update of commercialisation plan of Norsepower Rotor Sail Solution in full scale on a RoPax vessel.	Fuel savings of between 231 to 315 tonnes per year, resulting in ~900 tonnes less of CO ₂ per year (for RoPax)
GFF	Fully electric ferry	Implementation, validation, update of commercialisation plan of the GFF for potential customers	Zero emissions ferry able to sail at a 55 km/h speed, with autonomy of 26 km routes in 30 min and fast recharge at port <20 min. Reduced energy consumption by up to 40%.
EEECMS-2	Waste heat to energy	Reuse waste heat to power heating and cooling systems, optimise on board energy circulation	Fuel savings of ~340 tonnes per year, resulting in ~1200 tonnes less of CO ₂ per year. Cooling operating expenses reduced by up to 94%.
LeanShips	Increased engine efficiency, emissions abatement technologies	Multiple technology demonstrators (e.g., conversion of a diesel engine to a dual-fuel engine with methanol)	Energy savings of 12%, CO ₂ savings of 14%, Reduction of 60% NO _x , 70% SO _x and 77% PM.
HERCULES-2	Increased engine efficiency, fuel-flexible engines	Fuel flexibility, new materials for high temperature component applications, adaptive control methodologies, achieving near-zero emissions, combining an integrated approach after treatment of exhaust gases.	Up to a 25% reduction in GHG emissions using a fuel flexible engine. A 50% longer engine lifetime using new materials. Total of 80% NO _x emissions reduction with the integration of an After Treatment Unit (ATU) into existing engine structure in very large engines.

Source: Adapted from data available in [35].

As separate technologies provide fuel consumption improvements, future research should investigate how the combination of different technologies onto a single ship could enhanced such positive effects within real world conditions. Wind propulsion has been shown to produce savings in fuel consumption, particularly at lower speeds and certain routes. To demonstrate its benefits and to increase market penetration, reliability and performance must be proven at a large scale and within harsh marine environments. Reductions in fuel consumption can be obtained by using waste heat from engines that can then be used to power a ship's heating and cooling systems, which could lead to a 0–4% fuel savings [10], hence future policy could encourage operators to adopt this technology. Applications in the domain of vessel electrification have shown successful results, namely in cases of fully electric high-speed passenger ferries. Future policy could assist in increasing the range and scale of battery electric applications and to expand to other types of vessels (i.e., inland waterway and urban commuter vessels) which may potentially be commercialised more quickly.

3.2.3. Sub-Theme 3—Fuels and Alternative Energy Sources

Current research projects under the fuels and alternative energy sources category relate to the use of electrification (batteries, hybrid systems), hydrogen as a fuel and natural gas/LPG as a fuel. The benefits of alternative fuels in terms of decarbonisation are clear; by

reducing the carbon content of the fuel or eliminating the tailpipe emissions, it is possible to reduce the overall GHG emissions of the vessels. Hydrogen and battery vessel emissions will depend directly on the upstream, carbon content of producing the fuel/energy, emissions in generating the electricity or producing the hydrogen. As such, there are research projects investigating the use of battery vessels, which use 100% renewable electricity. Still uncertainty remains on the implementation of these technologies at a big scale and where the EROI of the overall process needs to be considered too [43].

The assessment of projects under the sub-theme on fuels and alternative energy sources, as illustrated in Table 5, shows that a number of alternative fuels are under consideration for decarbonising the waterborne sector, which can help with achieving the desired European emissions targets.

Table 5. Fuels and alternative energy sources projects: expected benefits.

Project Acronym	Key Themes	Expected/Proved Benefits	Main Benefits Estimation
BB Green	Vessel electrification; reduced hull resistance	New vessel to run entirely on renewable energy, with an on-board battery	40% reduction of hull water resistance
PURE	Fuel-cell auxiliary power unit	Delivery of electrical power sufficient to cover power demand from heating/cooling, etc., of a small yacht	~25% system efficiency, low noise and no smells
E-ferry	Fully-electric ferry	Design concept and demonstrate a 100% electric, emission free, medium sized ferry for passengers and cargo in full-scale operation on longer distances than previously seen (>5 nautical miles)	Annual vessel reduction of CO ₂ emissions by 2000 tonnes, 41,500 kg NO _x , 1350 kg SO ₂ and 2500 kg PM
MARANDA	Hybrid fuel-cell powertrain system	Hydrogen fuelled proton exchange membrane fuel cell hybrid powertrain system for maritime applications with a powertrain power of around 165 kW.	~50% system efficiency, freeze start capabilities from −35 °C, operating temperature from −32° to +50°, fuel cell stack life of 15,000 h
HyMethShip	Hydrogen-methanol propulsion system	Develop a hydrogen-methanol ship propulsion system using on-board pre-combustion carbon capture.	Target: GHG emissions by more than 97%, compared to conventional fuels, eliminating SO _x and PM emissions. Increased energy efficiency of 45% compared to best available technology

Source: Adapted from data available in [35].

However, the ideal mix is not currently clear, as some potential sustainability, infrastructure and distribution drawbacks are associated with these options, as in the case of biofuels, bio-methane, ammonia, hydrogen or methanol [10,11]. There would be benefits in investigating the advantages and disadvantages of the various alternative fuels under different waterborne applications, taking into account their energy return of investments, which may support scaling up of production as well as their use in vessel engines.

For the short-term, alternative lower-carbon fossil fuels, such as LNG, LPG and CNG are being suggested as a means to achieve a rapid reduction in pollutions from shipping. However, their contribution to decarbonisation is limited, as it depends on the engine type and release of unburnt methane. Further consideration is required on how the transition from such fuels should be managed in order to pave the way towards low fossil carbon fuels. It should be investigated whether transitional fuels such as bio LNG, bio-diesel, ammonia, methanol or hydrogen may be a distraction from the development of longer-term low, or zero, carbon fuels, risking infrastructure investment which may become stranded assets.

Multiple projects have explored the use of battery technology for vessels using different battery chemistries. Although this technology seems to be very efficient, the most promising applications are the ones on short distances, due the large amount of energy required. Future research could be conducted into the benefits and disadvantages of different battery chemistries, including the weight ratio, for different ship applications (i.e., ship weight and cargo) to assist vessel designers in choosing the optimum option for a new vessel. The greatest impacts on decarbonisation of the waterborne transport sector

are likely to come from the use of alternative energy sources. For example, electricity from renewable sources or hydrogen from electrolysis can offer a pathway to net zero for the waterborne transport industry.

3.2.4. Sub-Theme 4—Operational Measures

Projects under the operational measures sub theme address topics such as improved vessel navigation, vessel allocation systems and robotic container handling systems. These operational measures can have potential to increase efficiency and therefore reduce overall fuel consumption by up to 83% based on the measure implemented [10,11]. This can have a benefit in reducing GHG emissions from maritime operations.

In this domain, the main findings indicate that the development of robotic container management systems has progressed to the production of design approaches for different sub-systems. Moreover, fully robotic container terminals are already operational worldwide. A selection of such measures is shown in Table 6, illustrating the benefits derived from some European projects.

Table 6. Operational measures projects: expected benefits.

Project Acronym	Key Themes	Expected/Proved Benefits	Main Benefits Estimation
RCMS	Robotic container management system	Efficient terminal design, validated and quantified benefits also related to noise and air pollution	Costs can be reduced by around 20%. RCMS can be the only solution for specific ports.
CLOUD-VAS	Cloud-based vessel allocation	Flexible and affordable optimisation platform to minimise operational costs and fuel consumption	Up to 75% timesaving compared to traditional vessel allocation tools
LOGIMATIC	Global Navigation Satellite Systems (GNSS); route planning	Continuous, reliable and accurate estimation of the position and velocity of platforms, enabling resource and space optimisation.	Use of electric mechanical traction, reducing fuel consumption and CO ₂ by ~50%
SHIPLYS	Virtual prototyping, life-cycle assessment	Increase production efficiency, reduce energy consumption, environmental impacts and production costs both in shipyards and vessels in operation	Benefits reported for different scenarios
H2H	Safe vessel navigation	Increase navigation safety when in the proximity of other vessels or objects.	Benefits not directly quantified
AUTOSHIP	Autonomous vessels	Demonstration of autonomous vessels in real short sea shipping and inland waterway environments.	Benefits not directly quantified

Source: Adapted from data available in [35].

Thus, research should focus on the integration of on shore automated systems with smart scheduling and potentially automated ships, as well as integration of logistic chains and operational measures to reduce GHG emissions (e.g., slower sailing speeds). Interoperability of technologies at different ports around the world is important. Although benefits have been identified for vessel management systems at ports, it is important that the implemented solutions can be used by all ships, particularly by those which apply operation GHG reduction measures. Policy could be developed for all European ports wishing to use these technologies, to create a standard approach to navigation and smart vessel scheduling as well as the seamless integration between port arrivals and GHG efficient hinterland connections. Projects have demonstrated the benefits of Global Navigation Satellite Systems (GNSS) for automated maritime shipping and integrated logistics. This technology could further improve vessels efficiencies, and could reduce fuel consumption and emissions. Further research should investigate how the GNSS technologies would interact with autonomous ship technologies, as well as how to increase safety and ensure the resilience of GNSS based systems against failure or malicious intervention. In the

domain of autonomous ships, research has been recommended on regulations, rules and standards for autonomous ships. In this field, research should include the definition and level of responsibility for the different crew members, the role of human operators on board and the allowed/needed manual operations. Moreover, the management of compulsory systems, devices and procedures that would facilitate crewless vessel operation should be investigated further, as well as the role and responsibilities of remote-control centres. Policy aligned across all Member States could be developed to include safe operation of autonomous vessels, including safe operation within complex mixed traffic, integration within logistic chains and resilience against the consequences of system failure.

3.2.5. Sub-Theme 5—Coordination and Support Measures

Projects under the coordination and support measures sub-theme focus on the research coordination and dissemination within the waterborne transport sector, rather than technological measures, therefore the quantification of possible emission reduction is rather difficult to capture. They include planning and future strategies for the sector, looking both at vessel and port design. As new technologies become more developed, it becomes increasingly important that the results and benefits of these new technologies are relayed to the stakeholders in the waterborne transport sector. This will help to increase the uptake of new and innovative technologies which are focused on decarbonisation.

Results of the industry/market trends to 2030 should be reviewed to consider the socio-economic impacts, such as the Coronavirus disease 2019 (COVID-19) pandemic, and assess whether the impacts on the maritime market are likely to be long lasting.

Further policy development may be needed to ensure that the 2030 decarbonisation targets are met, and that the industry is aware of what needs to be done to reach these targets. Previous projects have investigated trends and expectations of the maritime industry up to the year 2030. Future research should extend this time period towards 2050 to fit in line with the Green Deal targets. It is important to capture the long-term expected market trends such that the long-term decarbonisation targets can be met and adjusted accordingly. Research into the application of telematics solutions to maritime shipping has shown relatively low potential uptake in the markets investigated. Further research in this domain could help with understanding the reasons and how to increase uptake.

4. Discussion and Conclusions

This paper focuses on selected EU funded projects and presents a comprehensive analysis of R&I in the field of waterborne transport decarbonisation in Europe. It identifies relevant technologies related to hull design, power and propulsion and fuels and alternative energy sources, as well as operational, coordination and support measures aimed at decreasing the impact of waterborne transport CO₂ emissions. The analysis is complemented by the findings on the evolution of international scientific publications and patents associated to waterborne transport decarbonisation technologies.

Nearly one billion Euro has been invested in waterborne transport decarbonisation research projects realised under FP7 and H2020. Three quarters of this amount came from EU funds while the rest (EUR 239 million) from contributions by beneficiary organisations. The importance of the decarbonisation theme in waterborne transport, underlined both at the European and international level, is also reflected by share of waterborne R&I projects dedicated to this issue. Approximately 65% of waterborne transport projects in FP7 and H2020 deal with decarbonisation. The majority are technical projects followed by operational and coordination and support measures projects.

All waterborne decarbonisation FP7 and H2020 projects were grouped within one or more of five identified sub-themes. The technical subthemes (i.e., hull design, power and propulsion and fuels and alternate energy sources) dominate EU funded waterborne research. Combined, they were studied in 85% of projects.

Further, within the three technical oriented subthemes, the fuels and alternate energy sources is the one with the highest increased budget, when comparing FP7 and H2020

projects. Hull design has a similar share in both framework programmes, while projects related to the power and propulsion subtheme have lower budgets. Power and propulsion topics are the most intensively investigated in global academic research. The same pattern emerges from the analysis of waterborne-related patents granted by PATSTAT during the years 2013–2017.

As stated, the EU actions aiming at reducing waterborne transport emissions include a wide range of technological solutions, operational measures and support and coordination actions. Depending on vessel and cargo specification, as well as geographical and route characteristics, the applicability of different measures may differ. However, even though there seems to not be a single measure which can be considered as a problem solver, the combination of the following innovations should provide significant improvement in energy efficiency and environmental benefits. The most promising recent European projects dealing with hull design technologies focus on the implementation of lightweight composite materials. Additionally, they cover innovative repair methods and hull surface protection methods, which provide additional cost savings. The innovation in power and propulsion technologies focuses on increased energy efficiency, thereby providing important environmental benefits. The use of wind propulsion and reuse waste heat bring up to 14% of overall CO₂ reduction (e.g., LeanShips project) or up to 40% reduction of energy consumption (e.g., GFF project). Fuels and alternate energy sources represent one of the most promising technological areas in relation to maritime decarbonisation. The previous studies as well as applications developed within European projects have showed that electricity from renewable sources or hydrogen from electrolysis can offer a pathway to net zero for the waterborne transport industry. Moreover, operational measures can substantially help in decreasing maritime emissions, mainly through adjusted vessel navigation speed and allocation and the support of port handling systems. As literature has shown, speed reduction can reduce up to 80% of CO₂ [11] and vessel allocation together with an innovative port system can decrease operational time and costs (e.g., CLOUD-VAS and LOGIMATIC projects). Finally, coordination and support measures prepare and support ground for collaborative R&I environments, leading to increased efficiency and reduced negative environmental impacts of maritime transport.

The analysis conducted in this paper focuses on the achievement of FP7 and H2020 projects on the waterborne decarbonisation theme and the related R&I and policy recommendations naturally emerged from their main findings, hence no indications can be provided on additional or not yet explored research on the topic. It should nonetheless be highlighted that increasing interest is given to this research area, as clearly presented in the draft proposal for the European partnership on Zero-Emission Waterborne Transport under the upcoming Horizon Europe programme [44]. In the proposal, particular emphasis is posed on research themes such as: increasing use of sustainable alternative fuels, electrification, increasing energy-efficiency, design and retrofitting solutions for the new and existing fleet, digital green to improve efficiency and sustainable bunkering and charging solutions for climate neutral ships.

This paper, by providing a comprehensive and up-to-date review of waterborne transport decarbonisation R&I across Europe, may help transport researchers, policy makers, regulators and transport companies in shaping future research, policy measures and business strategies in this domain. This paper is based on a TRIMIS report on R&I in waterborne transport decarbonisation in Europe, which is the first of a series of reports addressing specific transport modes, followed by similar ones on aviation and rail transport. Through the continuous effort in consolidating and expanding the TRIMIS data repository, the TRIMIS analyses aim to better capture R&I efforts beyond the currently included funding means and to provide more accurate details on the technology assessment which will be further refined.

Nevertheless, the analyses presented in the paper face some limitations which should be addressed in future research. First, TRIMIS focuses on publicly funded projects, therefore private initiatives are not fully considered. Moreover, Member States funding information

is fragmented and hence has not been fully included in this paper. Thus, even though the presented results cover the main trends in waterborne R&I at the European level, further analysis is necessary of research financed by private entities or Member State funds. Second, the study identifies decarbonisation as the most important and challenging issue in waterborne research and thus focuses on this topic. As a consequence, waterborne transport projects loosely linked to the decarbonisation topic have not been included. Finally, the technology assessment should be further refined and updated as new research results enter the market. The methodology behind the text analysis on waterborne transport decarbonisation in academic research should also be further developed.

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Glossary

ATU	After Treatment Unit
CNG	Compressed natural gas
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
COVID-19	Coronavirus disease 2019
CPC	Cooperative patent classification
DG MOVE	Directorate-General for Mobility and Transport
DG RTD	Directorate-General for Research and Innovation
EC	European Commission
EEDI	Energy Efficiency Design Index
EPO	European patent office
EROI	Energy Return of Investment
EU	European Union
EU-27	27 EU Member States
EU ETS	EU Emissions Trading System
FP	European Framework Programme for research and innovation

FP7	7th Framework Program for Research
GHG	Greenhouse gas
GNSS	Global Navigation Satellite Systems
H2020	Horizon 2020 Framework Program for Research and Innovation
HFO	Heavy fuel oil
ICAO	International Civil Aviation Organisation
IMO	International Maritime Organisation
JRC	Joint Research Centre
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MRV	Monitoring, reporting and verification
NASA	National Aeronautics and Space Administration
PATSTAT	EPO Worldwide Patent Statistical Database
R&I	Research and Innovation
REGEX	Regular expression
SEEMP	Ship energy efficiency management plan
STRIA	Strategic Transport Research and Innovation Agenda
TRIMIS	Transport Research and Innovation Monitoring and Information System
TRL	Technology readiness level
WASP	Wind-assisted ship propulsion

Appendix A. Regular Expressions (REGEX) Used for Scopus Database Keywords Analysis

Table A1. Waterborne Transport Sub-Themes (left) and corresponding REGEX (right).

Waterborne Transport Sub-Theme	Regular Expressions
Hull design	((DOCTYPE(ar) or DOCTYPE(cp)) and TITLE-ABS (“hull design” or “hull structure” or “Hull weight” or “Bulbous bow” or “Hull shape”) and (boat or ship or ferry or vessel) and not “electric field”) AND PUBYEAR > 2009 AND PUBYEAR < 2020 and not SUBJAREA(MEDI OR NURS OR VETE OR DENT OR HEAL OR MULT))
Power and propulsion	((DOCTYPE(ar) or DOCTYPE(cp)) and TITLE-ABS(engine or power or propulsion and (boat or ship or ferry or vessel)) AND PUBYEAR > 2009 AND PUBYEAR < 2020 and not SUBJAREA(MEDI OR NURS OR VETE OR DENT OR HEAL OR MULT))
Fuels and alternative energy sources	((DOCTYPE(ar) or DOCTYPE(cp)) and TITLE-ABS ((electric or lpg or batter* or hybrid or hydrogen or methanol) and (boat or ship or ferry or vessel) and not “electric field” and not “pressure vessel” and not “spherical vessel”) AND PUBYEAR > 2009 AND PUBYEAR < 2020 and not SUBJAREA(MEDI OR NURS OR VETE OR DENT OR HEAL OR MULT))
Operational measures	((DOCTYPE(ar) or DOCTYPE(cp)) and TITLE-ABS ((electric or lpg or batter* or hybrid or hydrogen or methanol) and (boat or ship or ferry or vessel) and not “electric field” and not “pressure vessel” and not “spherical vessel”) AND PUBYEAR > 2009 AND PUBYEAR < 2020 and not SUBJAREA(MEDI OR NURS OR VETE OR DENT OR HEAL OR MULT))
Coordination and support measures	((DOCTYPE(ar) or DOCTYPE(cp)) and TITLE-ABS(standardization or “Market instrument” or Regulation or “Trading market” or “Emission Trading” and (boat or ship or ferry)) AND PUBYEAR > 2009 AND PUBYEAR < 2020 and not SUBJAREA(MEDI OR NURS OR VETE OR DENT OR HEAL OR MULT))

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