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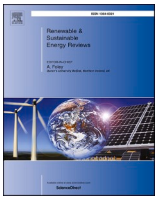

Batteries for sustainable shipping: Current status and potential roles

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ABSTRACT

Due to international commitments to reduce emissions in the shipping sector, new fuels and drivetrains are being explored. However, the potential role of batteries is often overlooked in strategic studies. We fill this gap through a broad literature study of grey and academic literature, complemented with three deep dives into Systems Engineering, Sustainable Business Models, and Transition approaches. Battery electric systems are currently the most frequently applied among alternative fuel-drivetrains, although they account for a low percentage of energy use. They are the preferred technology for zero-emission vessels. However, they mostly find application in small to medium hybrid vessels and support functions. Key drivers are regulation and policies, the increase in energy density, and the decrease in costs. Sectoral barriers include infrastructure, the capital intensity of vessels, cost-driven performance, weak governance, and international operations. Challenges for battery applications include integration in a ship's energy system, battery safety, charging, decision support on feasible applications, and establishing viable renewables-based port energy communities that integrate services to and from battery systems on berthing ships. Due to their diversity, versatility, and current application, batteries are likely to become more broadly applied on small to medium-sized vessels, and as enabling technology in hybrid applications and support functions. They thereby have the potential to influence the transition in the sector. Considering the diversity in batteries, shipping segments, and contexts, this will result in many small steps forward. Fast development requires strong policy support. Inherent uncertainty regarding fuels and drivetrains is best countered by robust decision-making in the sector, and can include battery usage.

1. Introduction

The shipping sector is crucial for global economic trade and societal well-being. It transports 80–90 % of the total international trade volume [1,2] and is competitive with road and air transport, both on a cost and CO_2-emission basis. The sector contributed 2.9 % of anthropogenic greenhouse gas (GHG) emissions in 2018, and a significant increase is foreseen until 2050 under a range of plausible economic and energy scenarios [3]. In addition, it is responsible for around 13 % of the global emissions of sulfur dioxide (SO_2) and 15 % emissions of nitrogen oxides (NO_x) [3,4], which severely impact the environment and human health, causing premature deaths and costs to society [5,6].

As a consequence, in recent years, the sector has started to face increasing pressure to address its impact. The International Maritime Organization (IMO) is responsible for regulating international shipping and its emissions. It adopted emission regulations for SO_x, NO_x, and particulate matter in 2020, with stricter regulations applying to so-called Emission Control Areas [7,8]. Also, in 2023, IMO set a target for the international maritime sector to be climate-neutral close to 2050, with a short-term goal of reaching 5–10 % energy from (near) zero-emission technologies in 2030 [9]. Additionally, maritime emissions have been included in the European Union (EU) Emissions Trading System since January 2024, while the Fuel EU Maritime initiative imposes constraints on the average annual GHG intensity of onboard energy [10–13]. Individual countries with significant shipping sectors, e.g. Norway and the Netherlands, set additional goals supported by policies to reduce their fleet emissions [14–17].

Achieving climate neutrality and emission reduction goals will require a transition, a radical, long-term transformation of the sector. As a result of the increased societal and political pressures, there has been a

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substantial increase in research, development, and demonstration activities and publications on sustainable shipping. Part of this literature is strategically exploring different fuel-drivetrains, showing their (dis)advantages to identify promising candidates that can play a crucial role in the transition [18–28]. What is largely missing in this literature is the (potential) role of batteries, while this seems promising. For instance, the price of battery cells showed a strong decline of 98 % between 1991 and 2021 [29–31], an increase in energy density [32,33], and batteries have found application in several maritime segments [34–36]. This research addresses this gap. Therefore, we pose the research question: What is the current status of batteries, and what are the foreseen battery applications in the shipping sector? Answering this question requires not only studying batteries or their application. It also requires insight into the sectoral structure, including segmentation of vessels and markets and competing solutions. Thereby, insight is given into where batteries might fit in, what structures are beneficial or holding back their application, and with which other technologies and solutions batteries will possibly compete.

To address the research question, we conduct a study of academic and professional literature to study the sector, the current application of batteries, their future potential, and barriers to development. To do so, we take three deep dives, focused literature searches in specific relevant fields that study the application of batteries as an innovation. For this, we identify three complementary approaches: Systems Engineering that addresses the technical feasibility and integration of batteries in ships; Sustainable Business Model Innovation that redefines business practices and value creation; and Transition Studies that study how to push and steer transitions, and the required changes in policy, regulations, and markets. Studying these three approaches will provide a broad, integral view of the status and potential of batteries, potential bottlenecks, and gaps in academic literature. This study serves academia that targets the shipping sector and transitions, as well as frontrunners and strategic decision makers in the sector, such as industry, consultants, and policymakers.

In the next section, the conceptual basis for understanding the status and adoption of batteries is introduced by introducing the three scientific fields. Next, in section 3, the shipping sector is described, including the problems and potential solutions for carbon-neutral shipping and the role of alternative fuels. Subsequently, the current status of battery application in the shipping sector is described in more detail in section 4. This is followed by contributions and research gaps identified through the application of the three academic approaches addressing batteries as innovation in the shipping sector in section 5. Finally, we come to discussions (section 6) and conclusions (section 7).

2. Conceptual foundations

In this section, we will explore different scientific fields that can contribute to insight into the transition in the shipping sector and the role of batteries, as well as their potential overlap or complementarity. We identified three different scientific disciplines that each study and contribute to the development and application of new technologies.

2.1. Systems engineering

Systems Engineering is a transdisciplinary scientific field as well as a pragmatic engineering approach. It is a design discipline, focused on the synthesis or the integration of components in a system that works. As such, it requires understanding the interaction between components. For our case, this might encompass battery cells, packs, and management systems, local grids on ships, integration in drive trains, and embedding in ports and charging infrastructure. A Systems Engineer's goal is to provide good or sufficient solutions that meet the needs of users and other stakeholders, suited for the intended purpose [37–40]. It is about balancing goals and requirements, making them operational, and matching them with a technological possibility space by designing, analyzing, integrating, and testing [38,41]. As such, the discipline bridges between more fundamental research on the one hand, and development, demonstration, and early market application on the other. Systems Engineering provides an understanding of the design process and of design principles for a specific field or problem setting. Initial approaches can provide a conceptual design, while later approaches provide a more detailed and specific engineering design. The scoping of the system ranges from specific products or processes to systems-of-systems, e.g. ships or energy systems.

2.2. Sustainable business model innovation

The successful adoption of batteries as a new technology is not only about integrating batteries in the energy system of a ship. It is also about understanding how companies do business and how this needs to change in support of emerging technology and for future-proofing the business [42–44]. A business model describes *"what a firm does and for who (value proposition), how it does it (value creation and delivery), and why it does it (revenue model)" (*[45] *p873, based on* [46,47]*)*. It answers questions of desirability, technological and organizational feasibility, and economic viability for value capture. Business models describe the rationale of the different activities within a company, as well as the cooperation with value chain and innovation system partners to create and deliver value. Whereas traditional business models have a strong focus on economic value for competitive advantage, sustainable business models also address social and environmental value for customers and society [48–50].

Embracing emerging technologies and creating sustainable value often requires sustainable business model innovation (SBMI) [51]. Existing business models need to be adapted, or new business models need to be created to fully leverage the emerging technology for value creation. This often involves adaptation in multiple areas of the model, such as key resources, key activities, key partnerships and the cost structure, and reconsidering the model's revenue streams and impact. Organizations frequently engage in cycles of development, comparing, experimentation and testing, implementation, and adaptation of potential business models based on feedback until a viable, sustainable model emerges [52–54]. Drivers of successful SBMI implementation include external factors like technology advancement and consumer demand, and internal factors like organizational leadership commitment and orientation toward sustainability, innovation, experimentation, and cooperation with stakeholders across the entire value chain, including employees, suppliers, and customers [48,55–58]. In addition, regulatory frameworks and policies can have a positive effect, through direct regulation, increased taxation, tax breaks, subsidies, procurement, and green financing, including impact investing [59,60].

2.3. Transition studies

Transition Studies comprise a collection of theories and approaches regarding how radical technological innovations – like electrification of transport – occur and become applied to address sustainability challenges [61]. Specifically, these studies build on the notion of a socio-technical system as a configuration of technologies, services, infrastructures, regulations, practices, and actors that together fulfill a societal function [62]. A broad set of actors is involved in developing, implementing, and using the technology. Not only producers and users, but also suppliers, policymakers, non-governmental organizations, regulators, and other actors are involved. Due to the variety of involved stakeholders and the diverse interests, transition theories address political processes that define who gets what, when, and how [63,64]. To overcome tensions and ensure timely, coordinated, and effective action, governance and leadership is required – e.g. by public policies through environmental regulations, standard setting, taxes, subsidies, and innovation policies – and broad support and actions by stakeholders in the sector are necessary [64,65].

Transitions typically require many smaller steps in different market segments, niches, and specific regions that gradually build up and ultimately might result in radical changes that can take decades to unfold, so-called transition pathways [66–68]. Initial innovations entail a balancing effort. On the one hand, they need to fit with current technologies and practices to facilitate acceptance and implementation in the short term, and on the other hand, they need to adapt systems and ways of doing things to contribute to more transformative change [66,67]. Upcoming radical technologies initially do not fully 'fit' in the existing sociotechnical system. They require protection from mainstream regulation and market forces, e.g., by (exemption from) regulation and support through policies or subsidies [69,70]. Also, the focus at the early stage of innovation is not only on the successful realization of a specific project, but also on experimentation, learning, networking, and visioning across different projects.

Finally, there are questions about how and why transitions are similar or different across locations, and how transitions can 'travel' between places and across different scales [64], e.g., from local experimentation in Norway to electrifying inland shipping in Europe or to the global shipping fleet. This can provide insights into how to replicate and upscale.

2.4. *Summarizing insights*

Here we summarize and characterize each of the above approaches by stakeholders involved, their goal and focal points, key concepts, and typical time span (see Table 1).

3. Transition pathways towards climate-neutral shipping

3.1. *Sectoral structure and strategies*

Vessels come with different functionalities, sizes, and are utilized in different contexts. Ship sizes range from tiny vessels (e.g. for recreation, water taxis) and local or regional use (e.g., ferries, service boats, fishing vessels, offshore working vessels), up to very large container vessels and bulk carriers that serve global trade [3,19]. Each vessel has a different functionality, energy use, and emission profile (see Table 2 and Fig. 1). Climate impact is mainly caused by carbon dioxide (CO_2) emissions emitted during the combustion of fuels for propulsion [3]. The main contributors are very large vessels, like container ships, bulk carriers, oil tankers, and liquefied gas tankers. Although limited by number (5 % of the global fleet), they cover 74 % of global capacity and contribute 39 % to CO_2 emissions. The small and medium-sized vessels come in much larger numbers (83 % of the global fleet), are more diverse in shape and functionality, but only emit 21 %. For very large vessels, and for medium to large cruise ships, refrigerated bulk, and fishing vessels, CO_2 emissions due to auxiliary use for electricity production is also significant. Ships that contribute significantly to emissions of particulate matter, NO_x, and SO_x near ports or terminals, and thereby cause local impact, include service, fishing, refrigerated bulk, ferry, cruise, and tanker vessels [3].

Table 2

CO_2 emissions of different vessel sizes and types. Sizes expressed in Dry Weight Tonnage (DWT) (Data: [3]).

	DWT	% global fleet	% DWT	% CO_2	Example vessel type
small	<1000	13 %	0 %	4 %	Ferry, miscellaneous
medium	1-5 *10^3	70 %	2 %	17 %	Highly diverse
large	5-60 * 10^3	11 %	23 %	39 %	Highly diverse
very large	>60 * 10^3	5 %	74 %	39 %	Oil tanker, bulk carrier, container ship, liquified gas tanker

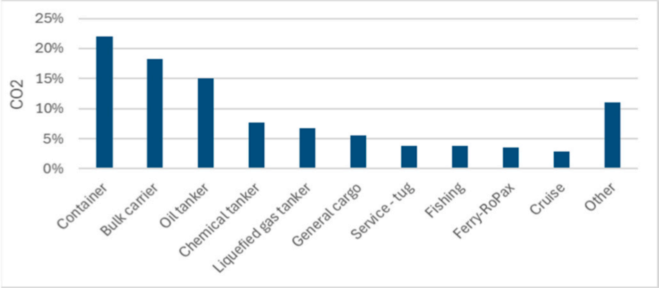

Fig. 1. Percentage of CO_2 emitted per vessel type (Data: [3]).

In addition to seagoing vessels, domestic recreational vessels and inland shipping are relevant for China, the United States, and North-West Europe, especially the Netherlands, Belgium, and Germany [16,71]. For example, the Dutch inland shipping fleet comprises 6500 ships, about half of the European fleet. These are typically small to medium-sized vessels. They do not fall under IMO regulations but under regional regulations (e.g., EU) [13,16], which can offer opportunities for more regional innovation and diffusion of sustainable shipping options.

Addressing CO_2 emissions requires many measures [18,21,72,73]. Typically, this is a combination of management measures (e.g., speed reduction, mission refinement and optimization, operational measures, fleet management), energy efficiency measures (e.g., vessel size, hull shape, resistance reduction by, for example, air lubrication, and propulsion); and alternative fuels and drivetrains (e.g., methanol, ammonia, hydrogen-fuel cell, biodiesel, battery-electric). Several scholars have explored how possible transition pathways in the sector might unfold over time [18,21,28,72,74]. Initially, a substantial contribution is foreseen for energy management and energy efficiency measures,

Table 1

Characterization of complementary scientific fields studying innovation.

	Who	Goal	Focus	Key concept	Time span
Systems engineering	Engineers for engineers	System design and integration, "Making it work", Optimization	Technological systems, e.g. energy & power	Technological attributes, performance, and impact	0–5 years (making it work) 10–30 years (strategic, e.g. exploring fuel-drivetrains)
Sustainable Business Model Innovation	Companies for customers and society	Value creation and capture	Organizational resources and activities, Value chains & markets – within given policy, regulation, and market	Goals and values of company and stakeholders, performance in economic, environment and social domains	0–5 years
Transition Studies	Innovation scientists for policymakers and society	Stimulating and steering transitions	Sociotechnical systems with diverse stakeholders, (Distributed) governance, Challenging policy, regulation, and market	Institutions (standardized social behavior: actions, rules, organizations)	0–10 years (niches, experiments, demos) 0–50 years (full transition)

including speed reduction. In the medium term, there is a role for transition fuels. These are typically low-carbon fuels, like Liquified Natural Gas (LNG), that are relatively easy to implement and contribute to reducing other emissions (SO_x, NO_x, particulate matter). In the long term, towards 2050, a transition to alternative fuels that do not contribute to GHG emissions is required in any climate-neutral scenario. This demands a redesign of ships, adaptation of drivetrains and bunkering infrastructure in ports, and availability of these new fuels.

The dynamics in these transition pathways are influenced by sectoral characteristics [75–80]. For instance, the maritime sector operates internationally, making it hard to regulate, create policies, and coordinate actions across regions and the diversity of stakeholders involved (e.g., changes in ports and fuel infrastructure). An exception to this are policies targeting single ports or green corridors. Another issue is that marine fuels are not taxed, making it harder to tax externalities (pollution) or to provide tax benefits to innovations or alternative fuels. It is also a competitive business-to-business sector that operates on a cost-based business model. Both hold back the pace of the energy transition, even though fast action is needed. As the average lifetime of a ship is 25–40 years for large ships [1,3,19,81] and up to 60 years for smaller ships used in inland shipping [82], all ships built today will still be in service in 2050 when (almost) climate neutrality is targeted. Therefore, these ships should be able to run on alternative fuels to be compliant, or they will require an overhaul during their lifetime.

Several short-term robust strategies for adapting fuel-drivetrains can be followed [14,22,83,84]. First, designing ships and drivetrains for fuel flexibility. This can be multiple-fuel vessels, e.g., that can run on diesel and methanol; alternative-fuel-ready vessels that require limited modification; or the switch to fuel families in which both conventional and alternative fuels can be used interchangeably, e.g., HFO, marine diesel oil, and biodiesel. Second, designing ships' drivetrains for easy modification. For example, by using an electrical drivetrain, different energy converters can be applied (batteries, fuel cell, engine-generator sets). Third, designing hybrid drivetrains that combine combustion engines with batteries. This can reduce energy consumption and emissions and increase functional performance. This is especially relevant for novel drivetrains using alternative fuels that do not yet provide an equal technical performance and are still expensive. And finally, exploring solutions to adapt current vessels to meet new requirements. Engine upgrades can help reduce emissions of SO_x, NO_x, and particulate matter, and blending alternative fuels with conventional fuels can reduce CO_2 emissions.

3.2. Alternative fuel options

Heavy Fuel Oil (HFO) and Marine Fuel Oil (MFO) are still the most applied, respectively 66 % and 30 % of HFO-equivalent fuel consumption in 2018 [3]. However, deep decarbonization of the shipping sector requires transitioning towards other fuels and drivetrains. Many alternative fuel options are being considered, sometimes requiring different drive trains: battery-electric systems, liquefied natural gas or biogas, biodiesel, hydrogen-fuel cell, methanol, ammonia, synthetic fuels, or nuclear [18,19,21–24,26–28]. A useful categorization of fuels is based on their primary energy source: fossil fuels, biofuels, or fuels like hydrogen that are made from renewable electricity, the so-called electrofuels. There is high uncertainty about which fuel will be best or become a standard in the market. Many fuel characteristics play a role in this, and matching depends on context (segment, country). Also, all alternative fuels are currently less mature and therefore come with higher uncertainty of performance, emissions, and costs compared to the standard fossil fuels [19,22,85].

Currently, LNG is the most applied alternative fuel (3.4 % of energy share) [3,86]. It is applied to almost 500 ships in operation globally in all shipping segments and hundreds of ships on order, especially for LNG carriers, container ships, and car carriers (see also [75]). Batteries are most frequently applied across different vessel types. They are mostly applied in hybrid constellations and on smaller vessels, thereby covering a limited share of energy use. However, for low-emission ships, batteries are the most applied option. Around 60 methanol-capable vessels are in use, mostly oil or chemical tankers, and more than 300 further ships are on order, and just under 20 ports offer green methanol [87]. Hydrogen and ammonia have hardly found application yet, although ammonia-ready vessels are on order, and countries like Japan, China, and Korea support their development [14,86,87].

For the near future, until 2030, stakeholders from the shipping sector in EU and globally expect the application of fuel oil, with small shares of LNG, biodiesel, and biogas [26,27,84]. Batteries and full electric operation are considered for short sea shipping (e.g., roll-on/roll-off cargo vessels (RoRo), roll-on/roll-off passenger vessels (RoPax), ferries, feeders, and bulkers). For 2050, most companies expect to be using multiple alternative fuels: ammonia, biodiesel, fuel oil, methanol, and methane, but not hydrogen or nuclear. However, government authorities emphasize social and environmental criteria and thereby prefer green hydrogen or methanol [27].

One crucial characteristic is the potential to reduce greenhouse gas emissions, as that is the key driver of current developments. Fossil fuels (LNG, methanol, ammonia) typically contribute to GHG emissions. Biofuels (biodiesel, biomethane, biomethanol) are made from biological materials. They can contribute to emissions and impact ecosystems and food production, depending on feedstock, growing practice, and conversion process [88,89]. Thereby, biofuels can be part of the solution or part of the problem. Finally, the application of batteries [90,91] and the use of hydrogen [92] rely on the use of renewable electricity to be climate-neutral. Typically, changing to alternative fuel-drivetrains requires adaptations of the ship and of port and fueling infrastructure – possibly with the exception of biodiesel. Changes to infrastructure typically make up a significant share of overall fuel costs when cryogenic storage is required (e.g. for liquid hydrogen, methane gas, or biogas) [93]. Infrastructure changes for charging battery electric ships can also be significant, up to 5–26 % of total transportation costs [35,94].

Most alternative fuels have a lower gravimetric and volumetric energy density and thereby add weight or volume for fuel storage on board. Compared to fossil diesel, with an energy density of 37 MJ/L, only biodiesel and synthetic diesel have similar energy densities [19,22]. Especially batteries have low energy densities, even though their energy densities have increased strongly over the years to 1.3 MJ/l for mass scale produced cells and up to 6 MJ/L for batteries under development [32,94,95]. A further increase is to be expected, but is unlikely to bridge the difference in energy density with diesel fuel.

So, the application of batteries comes with a larger volume and weight to accommodate the same transport distance. This can be problematic in the case of retrofitting a ship, as there is an existing spatial configuration. Furthermore, it might exclude applications in large ships involved in global trade. For all other ships, the energy density is merely a design parameter that results in trade-offs. This can be accounted for by considering the economic value of lost space (volumetric) [93] and/or by the increase in drag and energy use due to an increase in mass (gravimetric) [35]. Also, by not considering the application for the longest trips, the required battery system is significantly reduced and its economic feasibility is increased [94].

Batteries hold the benefit of flexibility in placement and thereby for integration on the ship. Where traditional fuel supply is placed in one compartment relatively close to the engine, batteries can be positioned at different places across the ship as the electricity network extends across the ship. Also, case studies of electric propulsion systems suggest that ballast systems can be partially or fully replaced by battery-electric systems [96].

3.3. Cost considerations

Transportation costs constitute a crucial component of trade costs, and fuel costs traditionally make up the largest part of direct transportation costs – up to 23–55 % depending on the type of vessel, size, and speed [74,97,98]. Especially LNG can be price-competitive with HFO under the right circumstances [34,99]. Direct costs of (near) climate-neutral fuels like biofuels, e-fuels, hydrogen, and full-electric battery energy systems are significantly higher [19,22,93,94,100] than fossil fuels combined with internal combustion engines. However, when also considering the costs of environmental impacts, alternative fuels might become feasible. Incorporating these costs, e.g., by carbon taxes or regulatory requirements, will drive the transition.

Reliable cost and technological data are important for a rigorous economic analysis [93] and learning from modeling and use cases (e.g. Ref. [101]). However, insightful and systemic comparisons of fuel costs are hard. Several of the fuels are not yet produced or applied commercially. It requires evaluation of direct cost (e.g., fuel production) as well as infrastructural costs (e.g., port upgrades for high-power charging), and social costs. The costs can also differ in certainty and variability and may affect multiple stakeholders. This requires careful analysis of costs at multiple levels of analysis and in different domains, see Table 3.

Emergent literature provides a structured analysis of key cost factors of alternative fuels, including battery electric shipping [93,102–104]. When taking environmental costs into account, (near) climate-neutral fuels might become competitive, but this depends very much on policies. Hydrogen and related e-fuels are very costly due to high capital investments in electrolyzers and fuel cells, their round-trip efficiency, and required adaptations in the infrastructure of liquefaction. The latter is also affecting the cost of methane and biogas. The most cost-competitive are biodiesel and biomethanol. For battery electric systems, the cost structure also shifts, as electricity costs are only a small part of overall costs, and total costs are dominated by investment in batteries on board. These systems benefit from high system efficiencies. The current fossil fuel options are widely available and come at the lowest direct costs. However, they operate at a relatively low system efficiency and a high social cost of environmental pollution.

To better understand the economic value and feasibility, and to address fundamentally uncertain conditions, research also highlights the importance of sensitivity analyses considering cost scenarios addressing e.g. assumed life span, different geographical conditions, different ships and operational profiles, different levels of availability of fuels or batteries, volatility in prices of oil, electricity, and critical raw materials, and different policies regarding carbon trading or taxation that influence the level of the social cost of carbon (e.g., Refs. [29,93,94]).

The performance and trade-offs of different alternative fuel-drive trains, as introduced in this and the previous section, are summarized in Table 4.

Table 3

Cost factors involved in the total cost of maritime transportation (based on [93,94,101,102]).

Fuel costs	Cost of HFO, electricity, or other energy carrier. Include costs of mining, production, and transport.
Ship propulsion system & system integration costs	Adaptations to ship, including energy storage, drive trains, control systems, charging systems, system design, building or retrofitting, and testing. Indirect costs can include space/weight penalties for fuels with lower energy density, and extended charging or port downtime.
Operation & maintenance costs	Wages, material costs, repair, and insurance.
Onshore storage & infrastructure costs	Adaptations on shore, e.g., bunkering infrastructure, extension of the grid, charging infrastructure, and adaptations to shipyards.
System efficiency (well-to-wake)	Required to relate fixed costs (€) to output at the shaft, e.g., by Levelized Costs of transportation (€/km)
Contingency costs	Known unknown, possible effects: risk, liability, disruption of supply, volatility of fuel prices, reputational risks.
Externalities and social costs	Costs for society that are not covered by direct costs. Become real costs by taxation (e.g., carbon tax) or regulation (e.g., the requirement to become carbon neutral). E.g.: • Environmental and health costs due to emissions of CO_2, NO_x, SO_2, etc. • Grid congestion in/near harbors (often temporal, depending on grid and energy infrastructure extension) • Trickle-down effects of innovation/ transformation, contributing to larger-scale adoption and transition over time • Port visitability • Creating and distributing knowledge, (re) education, learning, and networking

4. Status of battery applications in the shipping sector

After introducing the broader, sectoral view in the previous section, we now take a deep dive and detail applications and the potential for batteries. As already indicated, batteries are the most frequently applied among all alternative and low-carbon shipping fuels, although their total energy share remains rather small [86]. Batteries have been used for over ten years in the maritime sector. The market mainly took off in 2018 [105]. Several market studies predict further strong growth. The strong increase in interest in and application of batteries over recent years is influenced by a substantial increase in energy density and a

Table 4

Characteristics of fossil fuels versus alternative fuels.

		Fossil fuel HFO/MFO	Biofuel	Electrofuels	Battery electric
GHG & other emissions; environmental costs		–	?	++ (using renewable electricity)	++ (using renewable electricity)
Volumetric energy density (2025)		++ 37–38 MJ/l	+-/+ 16–34 MJ/l	-/++ 9–37 MJ/l	– 1.6–6 MJ/l
Fuel costs forecasts					
(Solakivi, 2022)	2020 [$€_{2020}$/ toe][a]	225–321	826-1274	2224–3884	
	2050 [$€_{2020}$/ toe][a]	373–523	914-1539	756-1419	
(Korberg, 2021)	2030 Fuel costs, $€_{2019}$/ MWh[b]		69–134	102–193	33[c]
	2030 TCO, $M€_{2019}$[b]	1–18	2-59 (ICE) 4-64 (FC)	3-86 (ICE) 5-88 (FC)	2.8–8.3[c]
Efficiency Port-to-Propeller		40–50 %	40–50 % (ICE) (IEC) 55 % (FC)	40–50 % (ICE) 55 % (FC)	76–85 %
Current application		Commonly applied	Limited: biodiesel & methanol	Not yet	Limited: hybrid full electric

[a] Fuel production costs for a RoRo vessel operating in EEC, without the costs of emissions.

[b] ICE = Internal combustion engine; FC = fuel cell. Fuel costs for Europe in 2030 based on different production pathways, including an infrastructure cost for fuel handling, storing, and bunkering in ports, without the costs of emissions. Total Costs of Ownership (TOC) include the cost of fuel utilization, propulsion system, energy storage on board, and costs of reduced cargo space. The data represent the range across different types of ships and voyage lengths.

[c] Only the application in large ferries was considered.

reduction in costs [34–36].

In DNV's Alternative Fuels Insights database [86], 940 battery ships are registered to be in operation, with several hundred more still on order. According to the database, batteries are mainly applied in commercial shipping in Norway (34 %) and in the rest of Europe (35 %), less so in Asia or globally. There might be a geographic bias, or differences in segments considered, or just general uncertainty about the market, as other sources identify, respectively, North America or Asia-Pacific as dominating the global market [106,107]. Batteries are mainly applied in car or passenger ferries, for other activities, and in offshore vessels [86], see Fig. 2. Other applications are being explored. For example, Maersk is piloting battery hybridization on a containership operating between East Asia and West Africa [108]. Small leisure boats are one of the main applications of batteries in ships [109], but are not included in the DNV database. Also, batteries are increasingly applied in defense applications [106,107]. Most battery systems are implemented in newly built vessels [105].

Only 19 % of applications are fully electric; the rest are hybrid [36, 86]. Only a small share is a 'plug-in' hybrid (17 %), which allows for charging by shore power. The rest depends on charging on board, e.g. by engine-generator sets. The relatively low energy density of batteries limits their application for full-electric propulsion to smaller and medium-sized ships and to hybrid propulsion, as energy requirements and costs are too high for ocean-going vessels [34,110,111]. The CO_2 saving potential depends on the configuration (all-electric or hybrid) and the power source (grey or green electricity) and can go up to 100 %. In a hybrid configuration, fuel savings of 0–30 percent are feasible with reasonable payback periods of 1–8 years for a wide variety of applications [34], although the exact conditions for these payback periods were not specified.

Batteries are currently mainly applied in electric cars. Prices of batteries have been dropping fast [29–31] to 101–137$/kWh around 2020 [29,30] and a further decrease is expected [29,112]. Prices of batteries applied in shipping have also dropped fast as they apply the same or similar battery cells, although prices remain significantly higher than for electric vehicles [34,113]: battery packs are not (yet) mass-produced, and the maritime sector poses higher requirements on the battery systems (e.g., a more robust construction to withstand vibration and pounding on board; operation in salty and moist environments; and more stringent fire safety systems).

Recently, several studies assessed the current and future prices of full battery electric systems for large passenger ferries [93], US ships under 1000 gross tonnage (e.g., passenger vessels and tug boats) [94], regional container shipping [35], and specific ships [101]. Across studies, batteries are the dominant cost factor (52–71 %), followed by electricity (16–24 %) and charging infrastructure (5–26 %). Accounting for the value of the second life of batteries can significantly reduce costs [94]. Cost effects of reduced cargo space are small (8 %) [93] or even negative [35]. Current direct costs of battery electric systems are higher compared to internal combustion engines. However, when including social costs of CO_2 emissions and environmental pollution by SO_2 and NO_x, batteries are shown to be competitive or even far cheaper now [35] or in the near future [35,94]. Furthermore, installation on newly designed ships is significantly cheaper compared to retrofitting ships (1100€/kWh compared to 2600€/kWh) [101].

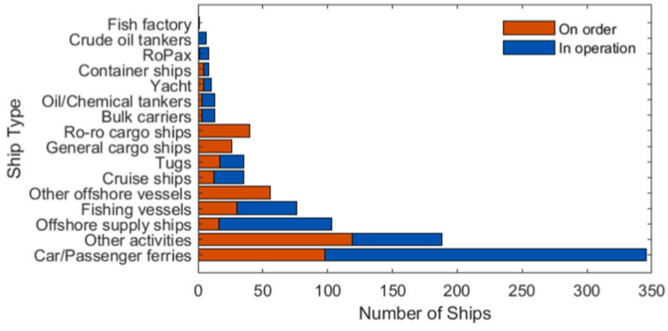

Fig. 2. Segment-wise adoption of batteries (Data: [86]).

Under the best conditions, authors see a large potential for battery electric vessels. By 2030, battery-electric propulsion for large ferries is found at a lower total cost of ownership than all fuels except some biofuels, especially if the battery system costs decrease to levels below 200 €/kWh [93]. For US ships under 1000 gross tonnage, electrifying 85 % of these ships could become cost-effective if they cut off 1 % of the longest trips and charge from a deeply decarbonized grid [94]. While within this decade, global container ships can economically electrify over 40 % of their traffic covering trade routes of 1.500–10.000 km at battery prices of 50–100 U$/kWh [35].

Typically, in maritime applications, power is required for propulsion, hotel functions (e.g., light, kitchen, communication), and auxiliary systems – depending on the ship's function [34,111,113–115]. Batteries can help maximize energy efficiency, increase robustness and operational safety, minimize emissions or run in zero-emission mode, enable fuel cell and biofuel drivetrains by its flexibility and ramp-up behavior, and minimize maintenance as other generators or engines have fewer load hours [34,101,116–119], see Table 5. Additionally, batteries can offer lower levels of noise, vibrations, and local exposure to emissions – thereby providing added value. The downsides of using batteries are the potentially increased system complexity, potential safety issues related to batteries, limited energy density, and battery costs. Specific shipping segments come with different (peak) energy and power requirements and auxiliary functions, which influence the potential role of batteries and their techno-economic feasibility [34,86,107,109,111,113–116, 120–122].

Lithium Nickel Manganese Cobalt oxide (NMC) batteries are currently the most used technology in the shipping market [34,111, 116]. However, various battery chemistries are available and applied, each with a different material composition, manufacturing process, and performance characteristics. Essential characteristics are, amongst others, power, energy, energy density, charge and discharge efficiency, battery life (cycle life and calendar life), cost, criticality and sustainability of materials, and battery safety [34,36,107,111,116,123,124].

Recently, concerns regarding the criticality of materials used in batteries have been growing. These focus on the risk of supply disruption of specific materials, particularly Cobalt, due to the increase in battery applications. However, data from the battery sector show limited battery price increases despite price volatility in materials in the period 2015–2025 [125]. Also, for the future, it is expected that there will be sufficient supply to meet increasing demand [126,127]. An extensive literature review concludes that battery costs are expected to decrease irrespective of raw material price developments [29]. Criticality concerns can be addressed by drastic expansion of supply chains and

Table 5
Functional roles of battery systems onboard ships [34,101,116–119].

Energy regeneration	• Supply energy, charged by onshore power (renewables) • Recover energy used onboard, e.g., from lifting.
Zero-emission	• No running engines: no emissions or noise.
Spinning reserve	• Backup for running generators. Thereby, reduce the number of running engines and increase fuel efficiency
Peak shaving	• Act as a buffer to level power seen by engines and optimize the engine load.
Optimize load	• Optimize the operating point of the generators to increase efficiency and reduce fuel use, emissions, and maintenance.
Increase dynamic performance	• Instant power supply, increase ramp-up behavior, thereby mitigating slow engine response. • Support fuel cells & biofuel engines
Backup power	• Uninterrupted power supply functionality, like spinning reserve.

additional resource discovery, developing new batteries using less critical materials, setting up domestic battery industries, and improving recycling routes, which can play an important role in the long term [126–131]. Also, the current demand for electric vehicles is over 950 GWh [125], while 1.65 GWh of batteries are currently installed in ships [132]. Even in a scenario of a high level of electrification in the maritime sector, only a limited share of total battery production will be applied in the maritime sector [94]. Therefore, battery implementation in shipping will have a limited effect on total demand, the development of supply chains, or market dynamics.

Batteries are either applied as swappable battery containers or as fully integrated energy storage systems in the vessel. The battery containers offer a more flexible and modular alternative, containing customized cooling, inverter modules, racks to hold the battery packs, a communication and management system, and a fire extinguishing system. The integrated application represents a more customizable and case-specific application. Charging can be done onboard for hybrid drivetrains or by plug-in or inductive charging for full-electric drivetrains. With the increased size and number of electric vessels, fast and high-capacity charging by shore power is targeted. Often, this requires specific infrastructure at the harbor and the strengthening or expansion of the grid [34,120,122].

Besides competitive technology, adopting batteries also requires knowledge, institutions, and capabilities. Network and lobbying organizations, like the Maritime Battery Forum [133], are upcoming, and its membership indicates interest by a wide range of stakeholders from the complete innovation ecosystem (battery manufacturers, propulsion system providers, system integrators, infrastructure developers, classification organizations, and recyclers). Applications can also draw on and benefit from the global battery market. This battery market and the related market for electric vehicles show robust growth due to policy support from China, Europe, and North America [124]. This results in knowledge, skills, investments, and infrastructure for production and product integration.

5. Research insights and agenda

Different approaches study and support the application and implementation of batteries in ships. Here we discuss developments in Systems Engineering and Systems Integration to integrate batteries in ships; Sustainable Business Model Innovation that redefines business practices, actor roles, and value creation; and Transition Studies that study how to push and steer transitions, and the required changes in policy, regulations, and markets.

5.1. Systems Engineering and Systems Integration

While electric shipping draws on (new) battery systems, one of the significant challenges is integrating them into the power and energy system on board. Indicative of this are the participating organizations in the Maritime Battery Forum: the most significant group is system integrators [133]. Systems Engineering is a transdisciplinary approach. The current literature that explores different fuels or technological options (see section 3 and [20,134,135]) builds on Systems Engineering on a high-end strategic level. System Integration focuses on the latter phases, the conceptual and engineering design, and testing. Both provide an understanding of the design process and of design principles for a specific field or problem setting.

Several authors focus on the integration of batteries (e.g. Refs. [34,114]) and the integration of the electric propulsion system into the electrical and electronic system of ships (e.g. Refs. [118,136]). Specific integration issues for batteries include battery fire safety, battery aging, and battery charging optimization [34,101,116,120,122,137,138].

Several cases show how stakeholders' goals and the required functionality influence the role of batteries and their integration into systems. For example, the integration of batteries is found in fish farms feeding barges in Norway with no access to shore power. The incorporation of a battery-hybrid system reduced the operational time of their generators to 3 h daily, resulting in 90 % GHG emission reduction, a substantial prolongation of the lifespan of the diesel generator sets, and silent operation - addressing a crucial requirement for onboard crew comfort [139]. In the segment of inland vessels, the short stopping time at ports poses a challenge for charging batteries, and containerized battery-swapping solutions are offered for this market [140,141]. In Offshore Support Vessels, batteries serve multiple functions, such as providing spinning reserve during dynamic positioning, optimizing loading during transit/standby, and enabling emission-free operation at or near ports [101,142]. This versatility enhances power quality, ensures compliance with class regulations, and reduces emissions and fuel consumption.

It is also essential to match the ship's function and operational requirements with the battery characteristics [34,111,138], see Fig. 3. For ferries, endurance, fast charging capabilities, and long cycle life are essential, making Lithium Titanate Oxide (LTO) batteries the preferred chemistry [111,143]. For container vessels, upscaled Lithium Iron Phosphate (LFP) battery systems are considered slightly more promising due to their high energy density and relatively low investment costs compared to NMC and LTO [35,138]. When battery prices reach US$100 per kWh, the total propulsion cost will be lower than diesel on routes shorter than 1000 km. With policy measures to account for environmental and health damage costs and anticipated battery prices of US$50 per kWh, routes exceeding 5000 km could be electrified in a cost-effective manner [35]. Finally, tugboats have high power peaks during assisting periods or for the complete operation of the vessel [137,144,145]. LTO and NMC batteries offer better peak performance (lower euro per kW and higher discharging rates), NMC performs better on endurance (lower euro per kWh and much higher energy densities), and LTO performs better on lifetime costs based on the large number of cycles it can accomplish. LTO batteries were adopted in the tugboat "Sparky" [146]. Overall, the conclusion is that different battery chemistries are only partially in direct competition, as each has different characteristics and can be matched to specific shipping segments.

He et al. [101] evaluated lessons learned from the commercial exploitation of 750 installations by Corvus (a major maritime battery supplier) – accounting for more than 60 % of the total marine battery market in Europe - and operational results from 47 offshore supply vessels and two cruise ships. They developed a decision-making matrix for assessing the risks, expenses, feasibility, and environmental performance, while taking into account the regulatory context, see Fig. 4. Initial efforts to integrate batteries often require considerable time and learning effort, whereas the go/no-go decision matrix can identify

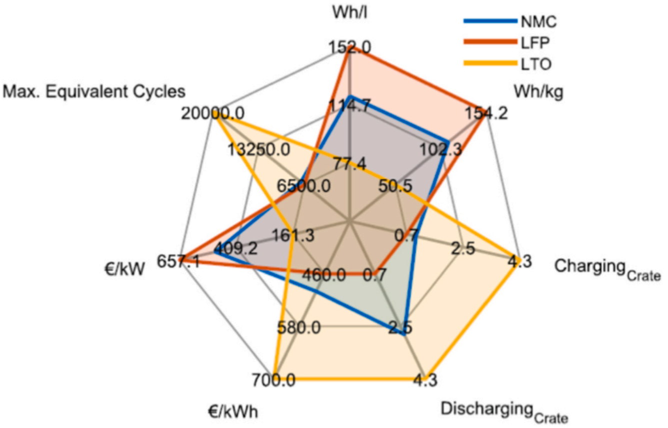

Fig. 3. Characteristics of different types of batteries, including life time, specific costs per capacity (€/kW) and unit energy delivered (€/kWh), specific volumetric (Wh/l) and gravimetric (Wh/kg) energy density, and (dis)charging behavior (Data: [138]).

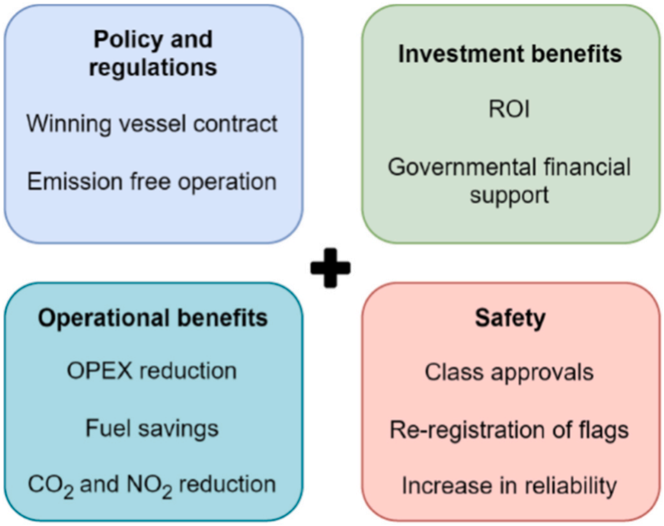

Fig. 4. Go/no-go decision matrix based on experience with 750 vessels across four different categories, including amongst others Return on Investment (ROI) and Operational expenses (OPEX) (Based on [101]).

relevant requirements and streamline the process. Standardized scenarios can be made for similar vessels across sectors and regions that can be updated over time, although some of the major factors, scores, and thresholds should be adjusted for each project.

Finally, integration at the port level has received attention in the literature on port regional energy communities and regional energy system optimization [147–153]. Ports face increasing regulatory pressure to reduce emissions, apply renewables (e.g., wind power and solar cells), and provide services for cold ironing (shore-to-ship power) in order to reach decarbonization and reduce emissions [147,149]. However, both the power supply from renewables as well as the energy demand at the port and by ships at berth are highly variable and uncertain. A good energy management system and energy storage systems (e.g., with batteries), on shore or on board, are crucial to integrate components, match dynamics, apply peak shaving, optimize self-consumption, and make energy trading possible in the (national) energy market. The resulting systems are envisaged to move away from the one-way power supply from the central energy system to the port and the ships, incorporating a two-way system that includes local production, trade, and boat-to-grid or ship-to-shore services. Battery packs on board can reduce peak power and offer energy or provide grid stability services to the local energy system at the port. Establishing a regional energy community can increase self-consumption of locally produced energy, energy flexibility, and energy efficiency, reduce local emissions and costs, and provide economic benefit to all stakeholders. However, high shore investments for port operators and retrofitting costs of ship owners make investors hesitant [147]. Establishing energy communities often encounters competing interests among stakeholders, and fair cost distribution between the port and the ships remains an issue [147]. Existing studies have not yet placed significant focus on the practical implementation of regional energy communities in ports, and not many realized cases exist [149,151], but lessons can be learned potentially from related fields like decentralized energy systems, smart grids, and collective virtual power plants, which have already received more widespread interest [154–156].

5.2. *Sustainable business model innovation*

SBMI is challenging as it involves diverse stakeholders and goals, is targeting a new market, often using emerging technologies (e.g., applications of batteries in ships) – for which technological possibilities and cost implications are still uncertain. As such, it can build on and interface with Systems Engineering and System Integration to explore the technological possibility space and reduce uncertainties. For example, the go/no-go matrix by He et al. [101] introduced above does provide insight into financial feasibility and broad value creation, including fuel savings, emission reduction, and regulatory compliance. In a similar line, Park et al. [25] explored credible business scenarios for 27 short-route ferries in Scotland, considering ammonia, hydrogen, and battery systems. The study supports decision-making between configurations and fuels for policymakers and ship owners, but does not unpack the SBMI process (e.g. how value is captured or what cooperation is required).

Interestingly, battery technology holds potential for new revenue streams like leasing and service contracts for battery-powered energy systems. This can include service level agreements for the provision of power-by-the-hour and the leasing of batteries by shipowners, with pay-per-use with a Battery-as-a-Service business model [157] and second-life applications of batteries [158,159]. The Norwegian maritime shipping sector experimented with new business models in support of battery-electric propulsion [160], aided by external pressures from consumers due to environmental concerns, regulatory bodies, access to renewable energy, international trade agreements, and technological innovation [161,162]. It requires redefining roles in the value chain, e.g. between battery producers, system integrators, grid operators, and vessel owners; as well as the role of infrastructure and storage [163]. For example, Wärtsilä, which introduced the containerized battery-swapping solution, offers this through a new business model in which vessel owners pay per kWh of energy used during operation [140, 141].

SBMI can be a strategic enabler of deep decarbonization by collaboration across industrial alliances, partnerships, supply chains, and port regions, sharing the significant risks tied with transitioning to alternative fuels and ensuring a fair distribution of costs and benefits. For example, this is visible in the organizational structure, management, and contracts underlying port regional energy communities [149,152,153]–as introduced in the previous section. Relevant stakeholders and potential participants in these communities are not only port authorities and ships, but also general companies, passenger sector operators, shipyards, and commercial operators. Different organizational configurations are envisaged. The port energy system could be operated more centrally, typically by the port authority, or more decentralized by an energy community. The latter can help ensure widespread participation, fostering a sense of shared responsibility and environmental stewardship, as well as streamlining design, implementation, and abating management and operational barriers [149]. A mix of long-term and short-term dynamic energy contracts can be applied for optimization. For cold ironing, this can result in mutually beneficial results (win-win) for three key parties involved: the electricity supplier, the port, and the ships [152,153]. Ships with (hybrid) battery systems can engage in these communities, not only by getting electricity supplied, but also by providing electricity (ship-to-shore) or offering grid stability services.

5.3. *Transition studies*

Diverse stakeholder groups, roles, and responsibilities in and around the shipping sector influence sustainability performance and preferences [26,27,80,164–166]. Studies on the transition in the sector emphasize the role of weak governance, lock-ins in infrastructure, by practice, the price gap between conventional and alternative fuels, the lack of innovation capital, the appropriate skill set in the workforce, and ship designs that cannot be adapted in the short term [167,168]. Environmental drivers and slowly emerging social movements drive policymakers and politicians to act. Industry stakeholders aim to comply with legislation. However, relying only on innovation for green growth and non-committal governance action are not likely to result in the sustainable transformation of the sector. More strict regulation and policy support are required [169,170].

Other authors explicitly draw on transition theories and frameworks. Damman and Steen apply a multi-level perspective to analyse the transition of three Norwegian ports [167]. The studied ports use their full spectrum of functions to enable the transition: as landlords, operators, authorities, and community managers. The applied approaches vary by port, depending on context, market situation, and social networks. Harahap et al. study renewable marine fuel production for Sweden, combining techno-economic modelling and socio-technical transition studies [171]. Sweden has a tremendous resource potential for low-carbon fuels. The transition shows resistance towards change from parts of the incumbent industries; niche innovations that are emerging at increasingly competitive prices; and increased pressure from (inter)national energy and climate policies.

Transition studies focusing specifically on the electrification of shipping and the application of batteries are more limited. Studies frequently focus on Norway as the front-runner with a relatively mature innovation system, showing a strong momentum, and a focus on ferries [17,160]. These studies show that public procurement and other policy instruments have been crucial for its development and implementation. It resulted in solid resource mobilization by public institutions and investments by ship owners. Other contributing factors were that it built on existing resources, actors, and structures, and the lack of solid opposition combined with an oil shock [172,173]. An analysis of three segments of Norwegian coastal shipping (coastal ferry, coastal fishing, and offshore supply) suggests that the transition process unfolds along different pathways in different user segments [174]. Transition policy faces several complexities in relation to the variety of technologies and user segments, and interdependencies between technologies, sectors, and user segments [175–177]. For example, grid capacity and congestion hamper the electrification of shipping transport [176].

6. Discussion

The status and potential of batteries in the shipping sector has been presented in this paper by performing a literature study on professional and academic literature, and by adding a deep-dive through a focused literature study on systems engineering to study technological feasibility, sustainable business models to study the role of companies and changes in value creation, and transition studies to better understand radical transformation in the sector and what that would require.

It emerges that batteries are currently the most frequently applied ‘alternative fuel’ in the shipping sector. But this characterization seems somewhat inappropriate. Only 19 % of battery vessels are fully electric. Most batteries are applied in hybrid drivetrains, most of which are not plug-in. Also, batteries are mainly applied in smaller vessels, given their low energy density compared to liquid fuels. As a result, their share in energy use in the sector remains low. Batteries are mainly applied in newly built, smaller vessels in various shipping segments and on different continents. Drivers are emission reduction to comply with regulations and cost reduction. For low-emission ships (typically applied in or near ports, coastal regions, and protected nature areas), battery electric drivetrains are currently the preferred option in the market.

However, most batteries find application in hybrid drivetrains and in support functions, to reduce emissions and energy use, increase performance as auxiliary energy or backup power, and support the implementation of alternative fuels or technologies (e.g., biofuels, fuel cells). Thereby, its relevance seems to be better characterized as an enabling emergent technology, characterized by rapid development and broad application, that can drive radical change.

The literature on Systems Engineering reveals the technical and integration challenges, including the integration of batteries in the ship’s electrical system and drivetrain; battery safety, charging, and aging; battery swapping or charging offshore; the selection of battery types; and the feasibility and suitability of batteries in specific contexts. The diversity in vessel types, functions, sizes, installed capacity, clients, and regulatory context makes it hard to draw generalizable lessons, although initial efforts are made to provide standardized scenarios to assess the feasibility of batteries. Likely, different battery chemistries will be applied in different segments based on their specific characteristics. As such, different batteries are only partially in competition with each other. Business model literature in shipping is rather limited, exploring business scenarios for specific cases, evaluating frontrunners (e.g., in Norway), emphasizing the importance of collaboration as an enabler for deep decarbonization, and the role of policies. Transition Studies literature is also rather limited and mainly focuses on Norway. However, we argue, based on our analysis of the sectoral structure, that the findings from this literature have global sectoral relevance. Niche innovations, like batteries, are emerging at increasingly competitive prices. Their application is stimulated by increased (inter) national policy pressure. Some incumbent industries show resistance to change. Barriers are lock-in in existing infrastructure, current practices, weak governance, and the cost-driven nature of the sector. Our sectoral analysis identified additional barriers: the international scope of the sector, the long lifetime and capital intensity of ships, and the limited appreciation for sustainability excellence in the sector. There is a large diversity in technologies and user segments, resulting in developments along different but interdependent pathways. A variety of alternative, low-emission fuels is considered in the sector, but their current availability, cost competitiveness, and application remain limited, while there is no or limited consensus on which fuels are preferred or most likely applied in the future.

Based on this, we conclude that, currently, batteries in shipping applications are in an early stage of application and market diffusion. Batteries also hold a significant future potential for application in and impact on the sector. Batteries will be increasingly applied for full electrification and hybrid drive trains, especially in smaller ships that make up the majority of vessels. Full battery-electric drivetrains are unlikely to be applied on (very) large vessels that are responsible for the majority of GHG emissions, given limitations in energy density. Thereby, batteries will not provide a full replacement of liquid shipping fuels. At least as important will be the role of batteries as enabling technology in hybrid drive trains and for support functions across shipping segments. Current battery applications seem to be ahead of many other fuels and inventions. These applications are vital to the future development of battery technology, as they contribute to visibility, learning, integration, scaling, and cost reduction. They also contribute to the transition at the sectoral level, not only by reducing emissions, but also by contributing to the legitimacy and momentum of the transition, and by gaining understanding of transition processes - a contribution that is often overlooked.

To support the implementation of batteries, policymakers should strengthen the regulatory framework for the sector. While traditionally this has been weak, cases of frontrunners have shown that regulation and policy support are crucial for making the transition happen. Policies should support the diversity of technologies, segments, and pathways. As the global transition is complex and the performance of alternative fuels is still highly uncertain, it is important to foster bottom-up developments in niches, protected local spaces, or segments that can advance the transition. Transitions in other sectors also did not start with an international consensus on preferred technologies or standardization. Both typically emerge later in the transition process.

Given the large uncertainties regarding the transition in the sector, a recommendation to strategic decision makers in companies and sectoral stakeholders is to follow robust strategies. Regarding choice of fuel and drive train, several robust options exist: end-of-pipe emissions reductions, fuel flexibility, adaptable drivetrains, and hybrid drivetrains – the latter two involving batteries as well. By their diversity and versatility, batteries will find further application in the sector. This makes engaging with batteries a no-regret option. This can go from initial exploration, experimentation, to early application, either with a focus on compliance, on business case development, or strategic learning in anticipation of further developments. Learning from these initiatives will further enrich the economic analysis presented in this paper to assess cost scenarios and supply chain implications. This will help improve the evaluation of batteries, together with other choices, toward decision-making. Not engaging with the transition seems not to be an option. Especially as, given the long lifetime of ships, all new ships built today will need to be compliant with the 2050 emission regulation, or will need a major overhaul.

This study poses several limitations. First, both the field of battery development and greening shipping currently receive a lot of attention, and developments are going fast. This study only provides a snapshot in time. Second, there might be an overrepresentation of developments in Europe due to the authors' proximity and frontrunning countries like Norway and organizations like the Maritime Battery Forum, DNV, and Lloyds that originated in Europe. Some authors argue for the relevance of the American and Chinese markets, which therefore would be interesting to disclose in more detail either by regional deep dives or comparative studies. Third, the deep dive in three specific domains adds to insight, but the choice for these three fields is arbitrary to some extent, and other fields are relevant as well. For example, given the high relevance of policy goals and (lack of) governance structures, it would be interesting to include an analytical lens on policy or governance issues. Fourth, we present an initial economic analysis. However, given its importance for decision-making, more insight is warranted to better understand the complexities. We therefore call for a more systematic examination using field data to more comprehensively understand costs associated with the technology across the supply chain under different conditions, identifying key risks and uncertainties. Finally, existing literature in the scientific fields of business model innovation and transition studies is rather modest. Although this can be explained by the recent emergence of interest, the specific complexities in the sector, and thereby the lack of practical empirical cases to study, this does not have to limit future studies. Both business model and transition studies are broad fields with an established theoretical basis and empirical insight from somewhat related sectors, e.g., the electrification of cars. These can be disclosed and used more proactively to study and guide developments in the shipping sector. Especially, transition-focused action research to explore and design alternative business model constellations in cooperation with sectoral stakeholders might hold benefits for both the sector and academia.

7. Conclusion

The shipping sector is under pressure due to the impact of its emissions. This has resulted in increasing commitment and exploration of alternative fuel-drivetrains. However, the (potential) role of batteries is largely neglected. This is addressed in this study by a combination of a broad and deep literature review.

Batteries are in an early stage of application and market diffusion, but are ahead of many other fuels and inventions. Batteries are frequently applied. They are the preferred choice in all-electric applications in small vessels. However, the majority is applied in hybrid drivetrains or in a variety of support functions. A variety of batteries exist that serve different applications, each following different but interrelated transition pathways. Key drivers are regulation and policies, the increase in energy density of batteries, and the reduction in costs. Barriers include lock-in in infrastructure, practice, weak governance, a cost-driven sector, international operations, long lifetime and capital intensity of ships, and the limited appreciation for sustainability excellence in the sector. Technical challenges include integration in a ship's energy system, battery safety, charging, and assessing the appropriateness and feasibility of specific battery types for specific applications. Due to its relatively low energy density, battery-electric drive trains will not be feasible in (very) large ships that contribute most to GHGs and thereby will not be a full replacement of liquid fuels.

Through their diversity and versatility, batteries already find broad application and a further increase is foreseen, with potential to significantly influence the transition in the sector. This will require strong policy and regulatory support, which can start with local support or for specific promising segments. Strategic decision makers in companies and sectoral stakeholders face high uncertainties. However, engaging with the transition is urgent, as all new ships built today will have to operate under (near) zero emission regulations in 2050. It seems wise to apply robust decision-making strategies regarding the choice of fuels and drive trains, including the application of batteries.

The main limitations of this study are that it is a snapshot in time, a potential bias towards EU developments, and the lack of a deep dive into the policy context. Finally, current literature on business models or transition processes is limited, but there is potential for an increased contribution drawing on theory and insights from other sectors.

We derive two key findings. For understanding the application and potential of batteries in the shipping sector, 1) a distinction should be made between batteries as fuel-drive train (e.g., in all-electric applications) and as enabling technology for hybrid drive trains and in support functions; 2) the diversity in the sector, technologies, and context needs to be taken into account. That is crucial to come to nuanced findings, to be appreciative of the sectoral structure and the nature of transitions, and to identify feasible steps forward.

8. Declaration of interest & funding

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CRediT authorship contribution statement

A.F. Kirkels: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **H. Liu:** Investigation, Writing – original draft. **H.A. Romijn:** Supervision, Writing – review & editing. **S. Durgaprasad:** Investigation, Writing – original draft, Writing – review & editing, Visualization. **H. Polinder:** Writing – Review & Editing, Supervision, Project administration, Funding acquisition. **M. Goudsmit:** Investigation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **N. Hoorani:** Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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