Application of rapidly improving battery technology for direct electrification of intraregional container shipping

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Abstract

International maritime shipping—powered by heavy fuel oil—contributes 2.5%, 12%, and 13% of global anthropogenic CO_2, SO_2, and NO_x emissions, respectively. The direct electrification of vessels has been underexplored as a low-emission option despite its considerable efficiency advantage over electrofuels such as green hydrogen and ammonia. Previous studies of ship electrification have relied on outdated battery cost and energy density values and have incorrectly assumed mechanical space to be a fixed technical variable. We show that with near-future battery prices of \$100 kWh^{-1} the electrification of intraregional trade routes of less than 1,000 km is economically feasible with minimal impact to ship carrying capacity. Projected declines in battery price to \$50 kWh^{-1} could improve this range to 5,000 km. We describe a pathway for the battery electrification of containerships within this decade that electrifies over 40% of global containership traffic, reduces CO_2 emissions by 40% for US-based vessels, and mitigates the health impacts of air pollution on coastal communities.

Background

The Intergovernmental Panel on Climate Change's sixth assessment outlines the dire consequences of failing to immediately reduce global greenhouse gas (GHG) emissions, including ice-free Arctic summers by 2050, increases in the frequency and intensity of heatwaves, droughts, and tropical cyclones, and a high probability of compound events [1]. The global maritime shipping industry is one key to achieving the necessary carbon emissions reductions. Transporting 11 billion tonnes (t) annually, nearly 90% of global trade by mass [2], the industry's meteoric growth since the mid-1900s has been underpinned by access to cheap, energy-dense heavy fuel oil (HFO). The shipping industry consumes 3.5 million barrels of low-grade HFO annually, producing 2.5% of total anthropogenic carbon dioxide equivalent (CO_2e) emissions in 2018 [2, 3] and engendering enormous damages from marine eutrophication and ecotoxicity, air pollution, and climate change impacts [4]. By 2050, maritime shipping emissions are projected to increase 90%–130% from 2008 levels and to contribute as much as 17% of global CO_2e emissions [5, 6]. The human cost of the industry's outsized contribution to criteria air pollutants—12% and 13% of global annual anthropogenic SO_2 and NO_x emissions, respectively—was estimated to total 403,300 premature deaths from lung cancer and cardiovascular disease in 2020 [3, 7].

Mounting political pressure has prompted the International Maritime Organization (IMO) to take regulatory action to reduce GHG emissions consistent with the Paris Agreement. Actions include resolution MEPC.302(72), which aims to reduce annual CO_2e emissions by 50% by 2050 from 2008 levels [8], and recommended amendments to the International Convention for the Prevention of Pollution from Ships (MARPOL)—whose members cover 99.4% of world shipping tonnage—to prohibit using or carrying HFO in Arctic waters after 2024 [9, 10]. In concert, IMO's 2020 emissions standards reduced the allowable marine fuel sulfur content from 3.5% to 0.5% by mass [11] .

Faced with this tightening regulatory landscape, the marine shipping industry is racing to identify commercially deployable zero-emission alternatives to HFO at a pace sufficient to significantly curb the sector's emissions and avert catastrophic climate change. Until now, battery-electric propulsion has been underexplored as a potential low-emissions alternative in the marine shipping sector despite its considerable emissions reduction potential, recent declines in battery costs, improvements in battery energy densities, increasing availability of low-cost, renewably generated electricity, and significant efficiency advantage over electrofuels (e-fuels) such as green hydrogen and ammonia.

Using best-available battery costs and densities, we examine the technical outlook, economic feasibility, and environmental impact of battery-electric containerships. We define two scenarios: (1) a baseline scenario using today's best available battery costs, HFO costs, battery energy densities, and renewable energy prices, and (2) a near-future scenario that tests the impacts of projected 2030 improvements in these variables. In contrast to previous studies, we treat volume repurposed to house the battery system as an opportunity cost instead of a fixed technical constraint. We specify eight containership size classes and model their energy needs, CO_2, NO_x, and SO_2 emissions, and total cost of propulsion (TCP) across 13 major world trade routes—creating 104 unique scenarios of ship size and route length that can be compared to almost any containership operating today. While we focus on battery-electric containerships, we briefly explore the implications of our results for electrifying other ship types.

We find that with near-future battery prices of \$100 kWh^{-1} the electrification of intraregional trade routes of less than 1,000 km is economically feasible with minimal impact to ship carrying capacity. Projected declines in battery price to \$50 kWh^{-1} could improve this range to 5,000 km, which encompasses a sizeable portion of global containership trade. We describe a pathway for the battery electrification of containerships within this decade that electrifies nearly half of global containership traffic, reduces CO_2 emissions by 40% for US-based vessels, and mitigates the health impacts of air pollution on coastal communities.

The search for low-emissions pathways for maritime shipping

In the short term, most ship operators have turned to energy efficiency measures such as slow steaming (deliberately reducing a ship's cruising speed to reduce fuel consumption), route optimization, and hull fouling management to meet IMO mandates [12]. However, the 10%–15% emissions reductions achievable through these measures are not sufficient to comply with IMO efficiency regulations that take effect in 2025 [13, 14]. Marine gas oil, liquified petroleum gas, liquified natural gas, methanol, and their bio-derivations have received substantial attention as medium- to long-term options, but recent research has questioned the potential of these fuels to reach cost parity and significantly reduce lifecycle GHG emissions [15, 16, 17]. For example, Howarth and Jacobson (2021) estimate that “blue” hydrogen (hydrogen produced from natural gas with carbon capture and storage) could reduce GHG emissions by only 20% compared with burning natural gas [18]. While renewably produced ammonia and hydrogen (or a blend) provide attractive emissions reductions, the inefficiency of the production process relative to HFO makes them unlikely to become sufficiently cost-competitive to displace fossil fuels [19, 20]. In contrast, direct electrification is typically five times more efficient than e-fuels in the transportation sector, exclusive of losses from e-fuel transport and storage [20].

Studies exploring the feasibility of electrifying oceangoing commercial ships found battery-electric propulsion to be unfavorable given the low energy density of batteries relative to hydrocarbon fuels [21, 22, 23, 24] . However, their assumptions about battery energy density and cost are outdated, differing in some cases by one to two orders of magnitude from today’s best available figures. Furthermore, these studies assumed that the maximum battery capacity is limited by the existing onboard space dedicated to mechanical propulsion systems and fuel storage, so their findings suggest that battery-electric ships would require several recharges to traverse even short routes.

Technical feasibility of battery-electric container shipping

The key technical constraint for battery-electric container shipping is the volume, rather than the weight, of the battery system and electric motor relative to the volume occupied by a vessel’s existing engines, fuel storage, and mechanical space. In vessels of a comparable volume, a heavy cargo vessel carries 4–10 times as much weight as a standard containership [25]. Operationally, containerships can increase their maximum carrying capacity by increasing draft (vertical distance between the waterline and the keel) based on the Archimedes principle which states that the weight of the displaced water is equal to the weight of the ship. For a 5,000-km range small neo-Panamax ship, we estimate that a 5-GWh battery weighing 25,000 tons will increase the draft by 1 m, a small fraction of the ship’s total height. Given that large containerships carry some of the lightest cargo and batteries have a volumetric density 3–10 times that of containerized cargo, we treat volume as the primary technical constraint.

The volume of an onboard battery system depends on the ship’s power requirements, cruising speed, voyage length, electrical efficiency, and battery energy density. Containership energy consumption can be approximated with a version of the propeller law, which is widely used in first-order estimations of ship power requirements and fuel consumption [26] . The following equations describe a ship’s total energy needs for a one-way voyage, where is the engine’s maximum continuous power rating, is the average cruising speed, is the maximum design speed, is the time to traverse the route, is the depth of discharge, is the internal combustion engine (ICE) tank-to-wake efficiency, and and are motor and inverter efficiencies, respectively. Equation 1 describes the energy needs of a ship with a low-speed, two-stroke marine ICE fed by IMO-compliant low-sulfur HFO. Equation 2 describes the energy needs of an equivalent battery-electric ship.

$$e_{ICE} = \frac{p_{SMCR} \cdot t_{voyage}}{\eta_{ICE}} \cdot \left(\frac{V_{average}}{V_{max}}\right)^3 \qquad (1)$$

$$e_{battery} = \frac{p_{SMCR} \cdot t_{voyage}}{\eta_{inverter} \cdot \eta_{motor} \cdot DoD} \cdot \left(\frac{V_{average}}{V_{max}}\right)^3 \qquad (2)$$

Assuming an identical operational profile, the energy needs of ICE and battery-electric ships differ only by efficiencies and battery depth of discharge. We assume an ICE tank-to-wake efficiency of 50%, electric motor and inverter efficiencies of 95% each, and battery depth of discharge of 80% [21]. Batteries yield an 80% efficiency improvement compared to their ICE counterparts, which translates to a 30% decrease in total energy needs for the battery-electric ship.

Nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP), nickel cobalt aluminum (NCA), and lithium titanate oxide (LTO) are commercially available lithium-ion chemistries with the requisite cycle life, specific power, charge rates, and operating temperatures to support container shipping applications [27, 28] . The choice of battery chemistry depends on specific operational characteristics. Vessels with shorter, more frequent voyages, lower power requirements, and charging time constraints would favor the high charge rates and long lifecycles of LFP batteries [29, 30]. For ships with longer ranges and less frequent battery cycling, the relatively low cycle life and high energy density of NMC batteries may be more suitable. Given that electric vessels will likely be limited to small, short-range vessels until battery costs are further reduced, we model the use of LFP batteries and discuss the impact of using NMC batteries for longer-range ships [31].

Assuming a battery energy density of 732 Wh L^{-1} for LFP batteries and a packing fraction of 0.8, minimal carrying capacity must be repurposed to house the battery system for most ship size classes and routes [32, 33, 34]. For a small neo-Panamax containership, representing an average containership in the global fleet, the volume required by the battery system is less than the volume currently dedicated to the ICE and fuel tanks for routes under 5,000 km. For the longest modeled route of 20,000 km for this ship size class, the battery would occupy 530 twenty-foot equivalent unit (TEU) slots or 7% of the ship's carrying capacity. **Figure 1** shows the percentage of ship carrying capacity forfeited to the battery system for the eight modeled ship classes across routes from 0 to 22,000 km with current and near-future energy densities of 732 Wh L^{-1} and 1,200 Wh L^{-1}, respectively. We find that with increasing ship capacities, the percentage of total carrying capacity volume occupied by batteries decreases because larger ships typically have lower energy requirements per unit of carrying capacity.

Megawatt-scale charging infrastructure will be required to meet the large energy requirements of battery-electric containerships (e.g., 16,000 MWh for a small neo-Panamax containership over a 5,000-km route) without disrupting normal port operation. The average time in port for containerships (queuing time plus berthing time) is in the tens of hours; averaging 31 hours for containerships between 1,000 and 3,000 TEUs and 97 hours for the largest containership size classes between 10,000 and 20,000 TEUs [35]. The charger capacity required to fully charge within the available port time is less than 300 MW for all ship classes on voyages less than 10,000 km. For longer voyages requiring larger battery capacities, offshore charging infrastructure could be strategically located in global shipping chokepoints such as the Strait of Hormuz, the Panama Canal, and the Strait of Malacca, where ships regularly queue for days awaiting passage.

A number of contact-based options are already commercially available for the shore-to-ship interface, including manual and automated plugs from ABB, Cavotec, Mobimar, Zinus, and Stemmann-Technik, with non-contact inductive charging solutions currently under development [36] . Charging stations can be deployed at port terminals or offshore to allow ships to charge while queuing for berth allocation.

The optimized and high-throughput nature of port operations (average berth utilization rates typically exceed 50%) support high charging infrastructure utilization and associated cost reductions [35]. Using methods from Phadke et. al (2019), we estimate the levelized cost of a 300-MW charging station interconnected at the transmission level to be \$0.03 kWh^{-1} at 50% utilization inclusive of hardware, installation, grid interconnection, and annual operations and maintenance costs across the system lifetime [37].

Cost parity with heavy fuel oil

We test the economic feasibility of a battery-electric containership against that of a slow-speed, two-stroke ICE ship fueled by 0.5%-sulfur HFO by calculating its TCP per km over various voyage lengths. For both ship types, we calculate fuel costs, operations and maintenance costs, and the environmental costs of NO_x, SO_2, and CO_2 emissions from direct combustion or from grid electricity. For battery-electric vessels, we also include the costs of an original battery set and eventual replacement batteries over a 20-year service life or 5,000 battery cycles (whichever comes first), the opportunity cost of forfeiting TEUs to the battery system, and the levelized cost of charging equipment. Because we account for the additional cost of the battery energy system separately, we omit the capital cost of the vessel itself. This assumption is appropriate given that propulsion systems constitute only a small portion of ship newbuild costs, and it is conservative given the cost advantage of electric motors relative to marine ICEs.

In the baseline scenario—which assumes a battery cost of \$100 kWh^{-1}, battery energy density of 732 Wh L^{-1}, charging station utilization of 50%, wholesale electricity price of \$0.035 kWh^{-1}, and HFO cost of \$0.048 kWh^{-1} (equivalent to \$538 t^{-1})—the TCP of a battery-electric ship is lower than that of the incumbent ICE vessel only for ship classes larger than 8,000 TEUs over voyages of less than 1,000 km [38, 32, 28, 5, 37]. Over longer voyages, the additional cost of the battery system and charging infrastructure outweighs the savings from fuel switching and the efficiency gains of direct electrification. However, if the environmental costs of NO_x, SO_2, and CO_2 are considered, the cost-effective range increases to 6,000–7,000 km across all size classes given the high emissions rates of HFO relative to the emissions intensity of the US grid.

The near-future scenario assumes improvements in battery cost and density to \$50 kWh^{-1} and 1,200 Wh L^{-1}, 70% utilization of charging infrastructure, and an increase in HFO costs to \$0.075 kWh^{-1} [32] . Battery pack industry average prices are anticipated to reach \$58 kWh^{-1} by 2030 [38]. Under the near-future scenario, the TCP of battery-electric shipping is lower than that of the incumbent ICE ship at ranges from 5,000 to 6,000 km for all ship classes. Including environmental costs, this range expands to 13,000 km for smaller-capacity ships and up to 17,500 km for the largest ship classes. **Figure 2** presents the TCP analysis in the baseline and near-future scenarios for a 7,650-TEU small neo-Panamax vessel, representing an average vessel in the global fleet across a 1,565-km voyage from Hong Kong to Shanghai. **Figure 3** depicts the relationship between the TCP and voyage length for a small neo-Panamax vessel. The results show improvements in TCP and gains in achievable range by improving charging infrastructure utilization, battery pack cost, and battery energy density from baseline to near-future values. **Figure 4** displays the difference in TCP between ICE and battery-electric vessels for all vessel

size classes across all modeled voyage lengths exclusive of environmental costs.

For battery electric ships to be competitive with ICE ships for much longer ranges, the primary constraint is battery cost. For example, battery prices need to reach \$20/kWh for a 10,000-km range battery-electric ship capable of crossing the Atlantic or Pacific Ocean to be cost-effective without recharging. Current commercial lithium battery technologies, such as LFP and NMC, and emerging technologies such as solid-state batteries are not projected to decline to this extent given the cost of the materials used in these batteries [41]. However, battery technologies designed for long duration storage applications from low-cost materials are under development. Iron-air batteries, for example, offer comparable energy density at a fraction of the cost of current lithium-ion batteries and may offer pathways for cost-competitive long-range shipping [42].

Deployment potential of battery-electric shipping

An estimated 42.3 trillion TEUs traversed intraregional routes (particularly intra-Asian routes) in 2019, representing 40% of total trade on all global routes [43]. However, the proportion of global container trade composed of short intraregional routes is likely far greater than that, owing to recent trends in containership logistics and the regionalization of trade [44], including a 1,100% increase in average containership capacity between 1968 and 2015 [45]. The sector's trend toward containership "gigantism" has promoted a hub-and-spoke model of trade, whereby high-capacity mega-containerships transport goods over long distances from one hub to another [44]. From the destination hub, a host of smaller feeder ships transport the containers to their final destinations in smaller regional ports [46]. Nearly all these feeder ships traverse short routes that could be electrified, which would increase battery-electric containership adoption well beyond the potential suggested by intraregional trade figures. **Figure 5** depicts the 10 best-connected ports in the world as defined by the United Nations Conference on Trade and Development (UNCTAD) connectivity index, all of which are intraregional routes less than 5,000 in length. Moreover, feeder ships are on average older than their larger-capacity counterparts, and many are reaching the end of their useful service lives [47]. The 2020 IMO regulation limiting sulfur content will likely lead to the premature scrapping of these fuel-inefficient ships, creating an opportunity for battery-electric models to enter the fleet [48].

Although containerships, with their standardized cargo and volume dependency, are useful for understanding the technoeconomics of battery-electric shipping, they represent only 23% of total maritime shipping emissions [50]. Achieving larger emissions reductions will require electrifying additional ship types, including oil tankers, bulk carriers, general cargo ships, and cruise liners. Of those, bulk carriers and oil tankers appear to have the largest emission footprint. Unlike containerships, some of these ship types are primarily constrained by weight rather than volume [29] . Thus, energy density by weight is the critical technical parameter for the batteries that would power these ships. At the same time, it appears that bulk carriers and oil tankers are designed to carry significantly higher weight than containerships. For example, some of the largest oil tankers and dry bulk carrier ships can carry up to 400,000 t compared to 100,000-200,000 t for the largest containerships [25].

For a 5,000-km range dry bulk carrier, we estimate that the battery system will constitute about 5%–6% of the ship weight with best available battery technology. With projected improvements to battery energy density by 2030, this will drop to 3%–4% [29, 34, 21] . Factors such as the extent to which ships operate at their weight limit, opportunity cost of foregone weight carrying capacity, and the cost of modest increases to weight carrying capacity of the ships will determine the impact of battery weight on the economics of other types of ships such as bulk carriers and oil tankers. It is plausible that carrying additional weight for ships with ranges up to 5,000 km may not adversely impact their cost effectiveness significantly, as is the case with battery volume for containerships. However, this can only be confirmed with further analysis.

Emissions reduction potential of battery electrification

Battery-electric container shipping would eliminate all direct combustion emissions and significantly ameliorate localized air pollution and related health impacts in communities near ports and global trade lanes [51]. However, lifecycle emissions reductions depend on the pollution intensity of the electricity source as well as transmission, distribution, and charging losses. We compare the CO_2, NO_x, and SO_2 emissions intensities of a small neo-Panamax containership with a slow-speed diesel engine running on HFO or very-low sulfur fuel oil (VLSFO, 0.5% sulfur corresponding to recent IMO emissions standards) to a battery-electric vessel across a range of realistic well-to-wake emissions intensities (**Figure 6**). The input well-to-wake emissions factors (g kWh^{-1}) include upstream emissions related to refining and downstream losses attributable to transmission, power conversion, shore-side storage, and electric motor losses. Though not modeled here, battery-electric vessels would eliminate direct emissions of black carbon, which is a particular concern for the sizeable percentage of vessels operating in Arctic waters given its demonstrated role in reducing snow albedo and accelerating ice melt [52].

Assuming an average grid carbon intensity of 535 g CO_2 kWh^{-1} (inclusive of transmission, conversion, and motor inefficiency losses), a battery-electric containership charged in a US port generates approximately 0.65 g CO_2 km^{-1} [53]. This is a 40% reduction from HFO and VLSFO, which produce approximately 1.1 g CO_2 km^{-1}. Whereas battery-electric vessels

reduce SO_2 and NO_x emissions by an order of magnitude relative to HFO, carbon emission reductions are highly dependent on the carbon intensity of the grid where the vessel is charged. Compared to VLSFO, however, the reduction potential depends on the emissions intensity of the grid where charging occurs. In the US, assuming a well-to-wake emissions factor of 0.46 g SO_2 kWh^{-1}, battery electrification yields an 82% reduction over VLSFO in per-km SO_2 emissions in the US and 22% reduction for vessels charged in China [54]. NO_x emissions are reduced approximately 83% and 25% over VLSFO for vessels charged at US and Chinese ports, respectively. These findings point to the need to couple charging infrastructure with collocated renewable energy generation to fully capitalize on the emissions reduction potential of battery electrification.

Discussion

The international shipping industry is urgently searching for alternatives to HFO to curb its growing share of CO_2e emissions and to comply with tightening IMO regulations. Although ammonia and hydrogen produced from clean electricity have been heavily researched as potential low-emission fuel substitutes, their potential to reduce emissions depends on a global buildout of renewable generation infrastructure three to five times that required for direct electrification [20, 55]. Furthermore, the price declines necessary to achieve cost parity with fossil fuels are unlikely to be achieved in time to meet the IMO's target of reducing shipping sector carbon emissions by 50% by 2050 [56].

We show that battery-electric ships powered by renewable electricity offer a near-term pathway to cut shipping emissions over intraregional and inland routes. At battery prices of \$100 kWh^{-1}, the TCP of a battery-electric containership is lower than that of an ICE equivalent over routes of less than 1,000 km—without considering the costs of environmental and health damages. With policy support to internalize the environmental costs of HFO and near-future battery prices of \$50 kWh^{-1}, routes upwards of 5,000 km can be electrified cost-effectively.

A direct electrification pathway can leverage higher efficiency compared with e-fuels as well as future cost reductions and improvements in battery technology driven by wide-scale battery deployment in road transport and stationary storage [57]. Battery costs are projected to decline by 50% in 2030, with battery manufacturers such as Tesla claiming these reductions can be achieved much earlier [58, 59]. Responding to these trends, ship operators have shown increasing interest in battery-electric options. Maersk, the largest shipping company by volume, is already piloting battery hybridization on a containership operating between East Asia and West Africa [60]. A fully electric 80-m containership, the Yara Birkeland, is expected to begin autonomous operation in Norway in the early 2020s. Similar battery-electric vessel projects are underway in Japan, Sweden, and Denmark [61].

Strategic adjustments to container shipping logistics could provide a partial solution to the range challenges facing battery-electric vessels and facilitate the electrification of long-distance transoceanic routes. Major maritime chokepoints—such as the Suez Canal, Strait of Gibraltar, Strait of Malacca, and Cape of Good Hope—present an opportunity for long-range vessels to recharge offshore while queuing for passage. Breaking the longest voyages into segments that are economically and technically feasible for near-future battery technology could facilitate electrification of a much larger percentage of global maritime trade. Offshore charging in ports and along shipping trade routes is attractive given the potential to collocate charging stations with renewable generation sources, eliminate direct CO_2 and air pollutant emissions, and alleviate range constraints. Several trends point to offshore wind playing a key role in containership electrification. Two-thirds of global ship traffic occurs within 370 km of the shore, where wind potential is highest [62, 63]. Furthermore, the cost of offshore wind is expected to decline 37%–49% by 2050, beating 2015 predictions by 50% [64].

Electrification provides several additional benefits over e-fuel alternatives in addition to global availability and cost-competitiveness. For the same power rating, the capital cost and volume of electric motors are typically smaller than the capital cost and volume of ICEs [22, 65]. Hence, retrofitting or hybridizing existing ships with electric drivetrains during propulsion system overhauls is likely to be technically and economically viable and could accelerate the electrification of the global fleet. One additional advantage of having dual-fuel capabilities is that these battery electric ships could serve as large emergency back-up power plants during increasingly common extreme events leading to power supply disruptions. For example, battery electric ships modeled in this paper will have 5–10 GWh of storage capacity. In comparison, the generation deficit that caused the 2020 California blackouts, leaving more than 800,000 customers without power during an extreme heatwave, was less than 5 GWh [66].

Although direct electrification has become a technically feasible and cost-effective pathway for zero-emission shipping, several challenges need to be addressed for commercial deployment. The operating costs of battery electric ships are significantly lower than those of conventional ships, but their upfront costs will be significantly higher primarily due to the cost of the batteries. Innovative financing and business models are likely to be required to address higher upfront costs. Transmission-connected charging stations with capacities of hundreds of MWs—similar to large scale grid connected storage facilities—will have to be built to support charging of these ships. These challenges highlight the critical role of government policy including support for demonstrations and financial incentives and regulations for deployment given that environmental damages from conventional ships are an order of magnitude higher than the propulsion costs of these ships.

Projected to contribute as much as 17% of anthropogenic CO_2e emissions by 2050, the maritime shipping sector is a critical target for global decarbonization efforts [5] . However, the unique requirements of oceangoing ships have heretofore hindered the identification of viable low-carbon solutions. Our analysis suggests that rapidly improving battery technology may enable direct electrification to play a key role in decarbonizing the shipping industry. Policymakers and other stakeholders should consider battery-electric technology as a potential near-term option for reducing the industry's outsized environmental and health impacts .

Methods

Modeling approach

The energetic requirements of an ICE containership and its battery-electric analog depend on the ship size and voyage distance. Previous studies have approached this analysis by studying specific real-life ships along their usual routes [23, 21, 22]. While this approach has strengths in terms of data availability, a significant limitation is the generalizability of the results to similar ships of different route length and carrying capacity. To improve modeling sensitivity to ship size class and route length, we specify eight containership size classes and model their energy needs, emissions, and economics across 13 major world trade routes ranging from a 911-km voyage from Shanghai, China, to Busan, South Korea to a 20,476-km inter-Atlantic voyage from Shanghai, China, to Santos, Brazil.

We define two technoeconomic scenarios. The baseline scenario considers the state of technology in the near future with a volumetric battery energy density of 732 Wh L^{-1}, battery cost of \$100 kWh^{-1}, HFO cost of \$0.048 kWh^{-1}, charging infrastructure utilization of 50% equivalent to \$0.029 kWh^{-1}, and electricity price of \$0.035 kWh^{-1}. The optimistic future scenario assumes a battery cost of \$50 kWh^{-1}, volumetric energy density of 1,200 Wh L^{-1}, and charging infrastructure utilization of 70% or \$0.021 kWh^{-1}.

Modeling containership technical parameters

The rated energy of the battery must be large enough to supply power for the entirety of each one-way voyage, assuming the ship can be charged at both its port of origin and its destination. Each marine engine is designed with a specified maximum continuous rating (SMCR), which describes its maximum power output during continuous operation. The average power output is lower than the SMCR, because the engine seldom runs at its maximum power output even while cruising. The engine load factor describes the ratio of the ship's average power output during normal operations to its SMCR and can be estimated as the cubed ratio of the ship's average speed to its maximum design speed. The marine engine manufacturer MAN Diesel Turbo publishes SMCR and maximum design speed values for containerships based on Holtrop and Mennen's power prediction calculation method [67]. Additional energy requirements during maneuvering and hoteling, as well as energy savings through slow steaming practices, are neglected. The voyage time varies depending on the route length and the average speed. The average speed is fixed as 80% of the design speed, which equates to 37 km hr^{-1} (20 knots) for any ship 7,650 TEUs or larger. Auxiliary engine power needs are assumed to be 22% of propulsion engine power per port emission inventory best practices [68].

The daily HFO fuel consumption is derived from an empirical study of containership fuel consumption [69]. The conservative assumption is made that, at any given point, a containership is carrying enough fuel for a day's voyage; in reality, this figure is likely higher, because ships often carry fuel for several days after bunkering. The mass and volume of battery energy storage and propulsion systems are simply the total energetic needs of the battery system (including efficiency gains from electric propulsion) multiplied by the assumed volumetric or specific energy of the battery depending on the scenario and including a 0.8 battery packing fraction and 80% depth of discharge. We calculate TEU forfeiture by converting battery energy storage system volume in excess of the existing mechanical and fuel storage space to standard 2.6 m x 2.4 m x 6.1 m TEUs.

Total cost of propulsion analysis

We quantify economic feasibility through a TCP framework, whereby a battery-electric containership is compared to a reference ship with a two-stroke ICE fueled by HFO with an onboard scrubber system for compliance with IMO sulfur emissions regulations. Cost drivers for the traditional ship include HFO costs, which vary by scenario as described above, and operations and maintenance costs. The operations and maintenance costs include periodic repairs, regular maintenance, and operation of a scrubber system to comply with recent IMO sulfur emissions standards (estimated at \$5 MWh^{-1}), and they are exclusive of other shipping operational expenses such as labor, insurance, and port charges [70]. These expenses are developed from industry benchmarks published by Drewry Shipping Consultants as well as the work of Agememnon et al. [71, 72].

The battery-electric TCP model accounts for the cost of electricity, TEU forfeiture, additional capital costs of the original and replacement battery energy storage systems, operations and maintenance, and the levelized cost of charging infrastructure. Battery costs are defined as the uniform annual payment for upfront battery capital costs in addition to replacement costs over the service lifetime of the ship, which is assumed to be 25 years [40]. LFP batteries are assumed to need replacement after 5,000 cycles or 20 years, whichever comes first. Battery capital costs are assumed to be additional to ship newbuild capital costs, allowing us to neglect the inclusion of newbuild costs for both battery-electric and ICE ship types. Given the relatively low cost of marine engines compared to the total ship newbuild capital cost, this assumption is reasonable and conservative. This study assumes the case of a newbuild only and does not consider retrofit costs, although the economics of battery electrification through vessel retrofits are an important area of future research.

We assume the operations and maintenance cost of the battery-electric vessel is 50% of the ICE equivalent, commensurate with savings on electric vehicles and exclusive of the operating expenses of an onboard scrubber [73]. An economic penalty or credit, characterized as TEU forfeiture, is included in the TCP analysis to account for carrying capacity gained or lost based on the volume requirements of the battery system relative to the ICE ship baseline. The volume differential quantified in TEUs is multiplied by the freight rate for the trade lane, divided by half to account for the inequality in global trade flows that results in underutilization in carrying capacity for at least one leg of a roundtrip voyage [47, 74].

We adapt previous research on electric trains and trucking to estimate the levelized cost of MW-scale charging infrastructure and electricity costs [28]. We use an electricity cost of \$0.035 kWh^{-1} in line with historical real-time prices published by the California Independent System Operator (CAISO) for 2017 through 2019 [31, 37]. This price is inclusive of the cost of generation, compliance with California's renewable portfolio standards, applicable CAISO fees for a direct-access customer, demand charges, and applicable delivery charges. The charging infrastructure cost includes hardware costs, grid connection fees, operations and maintenance expenses, and the cost of installation.

Where environmental costs are presented, we assume a marginal cost of NO_x and SO_2 of \$13,000 and \$24,000 t^{-1}, respectively, and a social cost of carbon of \$43 t^{-1} in line with the US Environmental Protection Agency's regulatory guidelines for the early 2020s [75, 76].

Environmental impact

To quantify the potential environmental impacts of battery-electric container shipping, we use published well-to-wake CO_2, NO_x, and SO_2 emissions factors for a slow-speed, two-stroke ICE ship. Carbon emissions intensities for HFO and VLSFO are 656 and 661 g CO_2 kWh^{-1}, respectively [7, 77]. We assume emissions intensities of 10 g SO_2 kWh^{-1} for HFO, 2.4 g SO_2 kWh^{-1} for VLSFO, 12 g NO_x kWh^{-1} for HFO, and 2.5 g NO_x kWh^{-1} for VLSFO [78]. Emissions intensities are converted to per-km intensities by multiplying by the energy consumption per kilometer of a battery-electric small neo-Panamax containership.

To estimate the emissions of a battery-electric vessel, we calculate a well-to-wake emissions intensity across a range of real-life grid emission factors sourced from multiple countries [53]. To convert from grid intensities to well-to-wake emissions intensities, we apply 5% transmission and distribution losses, 10% AC/DC power conversion losses, 5% DC/AC conversion losses, and 5% electric motor efficiency losses [22, 21, 79]. Calculated well-to-wake carbon emissions intensities are 930 g CO_2 kWh^{-1} for Saudi Arabia, 670 g CO_2 kWh^{-1} for South Korea, 808 g CO_2 kWh^{-1} for China, 535 g CO_2 kWh^{-1} for the US, and 307 g CO_2 kWh^{-1} for the UK. Well-to-wake emission intensities are 0.60 g NO_x kWh^{-1} and 0.46 g SO_2 kWh^{-1} in the US and 1.7 g NO_X kWh^{-1} and 2.76 g SO_2 kWh^{-1} in China [80, 54, 81]. Emissions from battery production are neglected.

Declarations

Data Availability

The data supporting this paper are available from the corresponding author upon reasonable request.

Competing Interests

The authors have no competing interests to declare.

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Figures

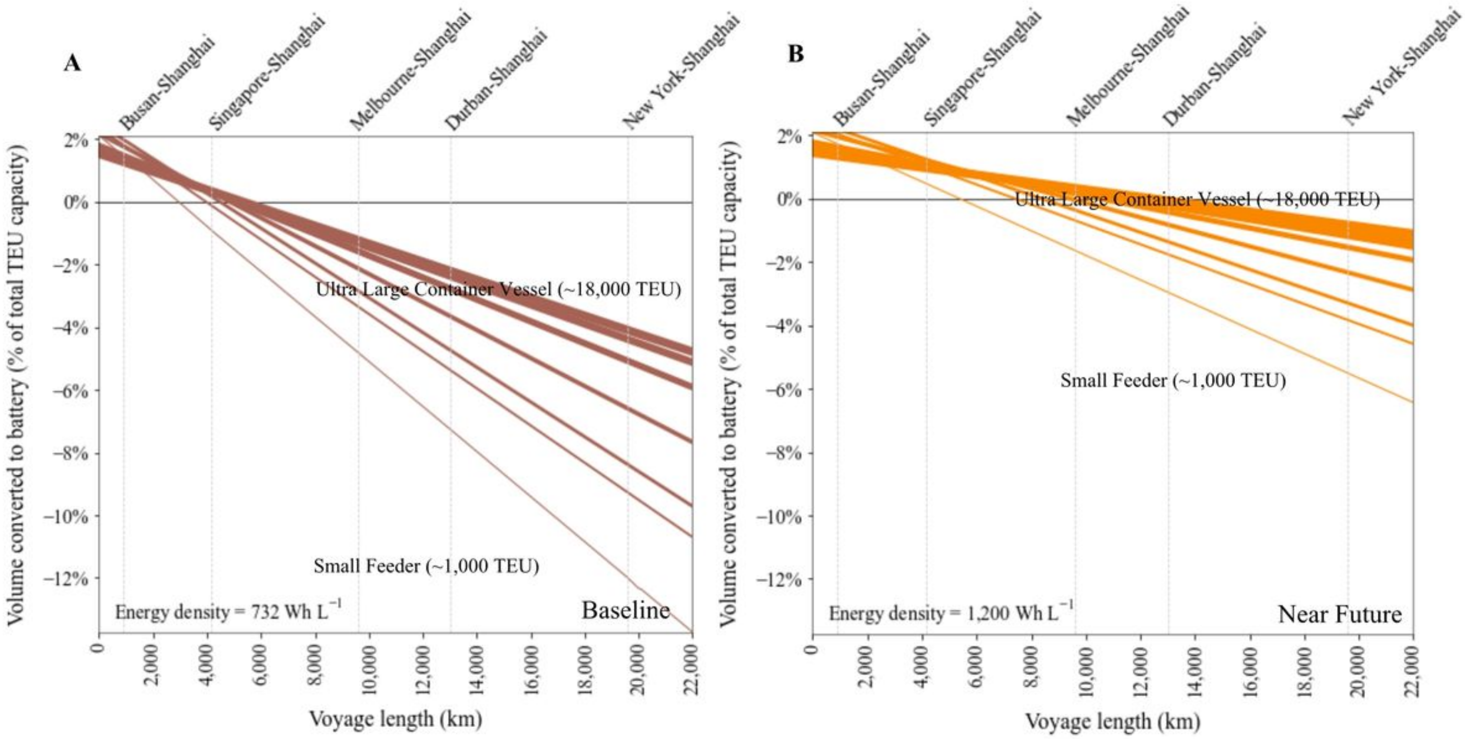

Figure 1

Carrying capacity forfeited to onboard battery system as percentage of total TEU by voyage length. We model the volume of the ICE ship’s combined engine and mechanical space assuming a battery packing fraction of 0.8 and an 80% depth of discharge. The line thickness denotes increasing vessel carrying capacity. A Small Feeder of around 1,000 TEU capacity is the smallest vessel modeled, while the Ultra Large Container Vessel with around 18,000 TEU capacity is the largest. Panel A depicts the baseline scenario results with a battery energy density of 732 Wh L-1. In this scenario, the battery volume is less than that of the existing ICE mechanical space at voyage lengths less than 4,000–6,000 km. Less than 5% of carrying capacity is forfeited to the battery system for the largest ship types over all voyage lengths, reflecting innovations in ultra-large containership design that optimize carrying capacity and energy consumption better than feeder ships. Panel B depicts the results with a battery energy density of 1,200 Wh L-1. In this near-future scenario, the net change in carrying capacity is positive for voyages up to 6,000–13,000 km, depending on ship type

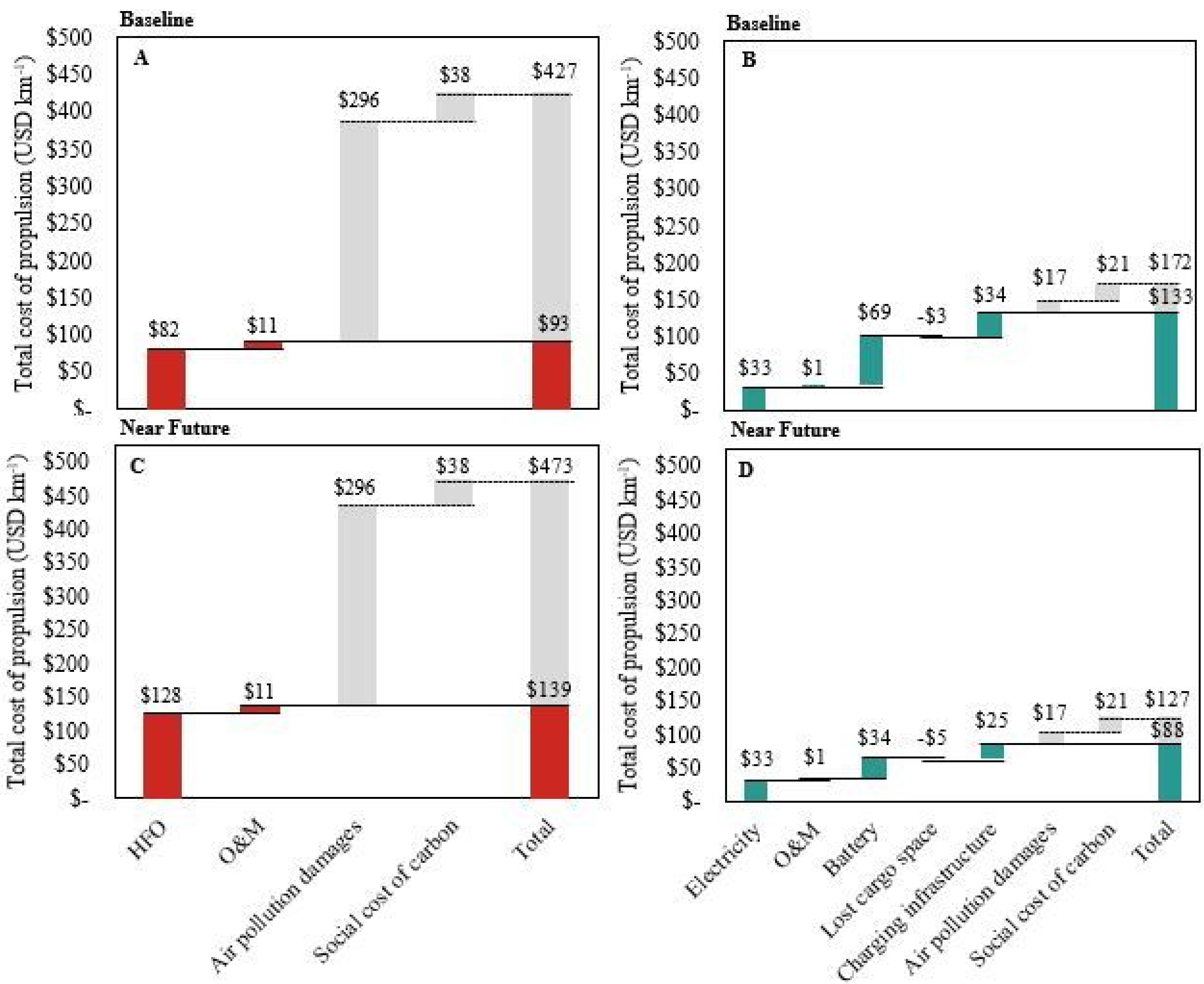

Figure 2

Total cost of propulsion including air pollution of a typical small neo-Panamax vessel. The neo-Panamax vessel is modeled as 7,650 TEU over a 1,565-km voyage. A depicts the TCP of an ICE ship in the baseline scenario. B shows the TCP of the battery-electric equivalent in the baseline scenario. C and D present the TCP of an ICE and battery-electric vessel, respectively, in the near-future scenario. Colored bars (red for ICE, teal for battery-electric) show non-environmental costs. Gray bars and dashed lines capture environmental damages attributed to NOx, SO2, and CO2. Not accounting for environmental damages, in the baseline scenario, the cost of the battery system and charging infrastructure outweigh the economic benefits of fuel switching, leading to a battery-electric TCP $41 km-1 higher than the ICE TCP. In the near-future scenario, an increase in HFO costs to $840 t-1 (representing a $100/t tax on CO2e), a decrease in battery costs to $50 kWh-1, improvements in battery energy density to 1,200 Wh L-1, and a charging infrastructure utilization rate of 70% make the battery-electric TCP $51 km-1 lower than the ICE TCP. Accounting for environmental damages increases the TCP advantage of the battery-electric ship dramatically.

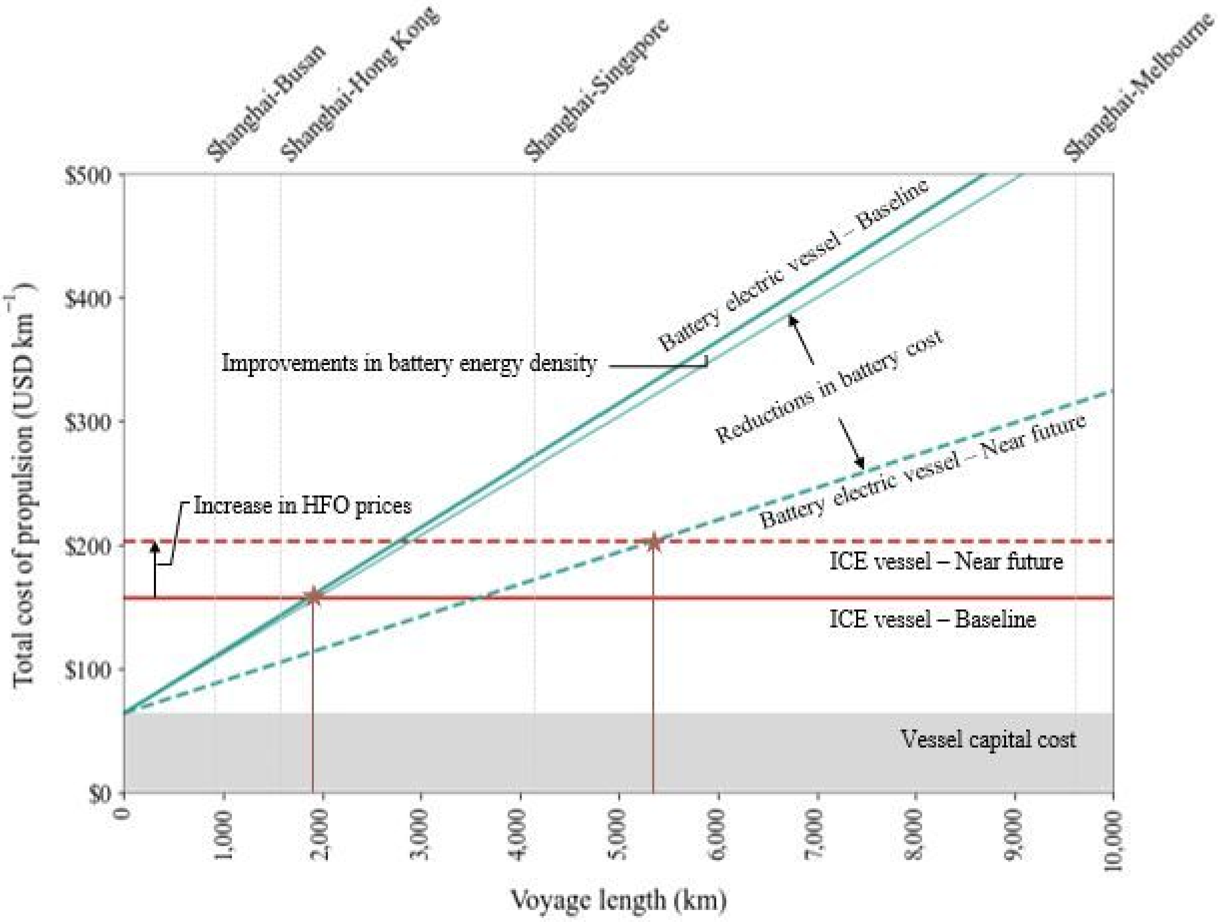

Figure 3

TCP of ICE and battery-electric small neo-Panamax containership in baseline and near-future scenarios excluding environmental costs. Red and teal lines indicate the TCP of an ICE or battery electric vessel, respectively. Dashed lines represent the near future scenario. Stars indicate the point where battery electric vessels achieve parity with ICE vessels for both baseline and near future scenarios. In the baseline scenario, the TCP of the battery-electric vessel is less than that of the ICE vessel at distances less than 1,800 km. In the near-future scenario, increases in HFO cost equivalent to $0.027 kWh-1 enable cost parity across ranges up to 5,300 km. Without increases in HFO prices, the range increases to 3,600 km in the near-future scenario. The TCP of the battery-electric vessel is most sensitive to changes in battery cost. Improvements in battery energy density produce small improvements in battery-electric vessel TCP by decreasing the volume forfeited from the vessel's carrying capacity to house the battery system. Improvements in charging infrastructure utilization (not shown) produce a negligible improvement in battery-electric vessel TCP owing to the low levelized cost of electricity and marginal decrease in cost of charging infrastructure with increasing utilization. A capital cost of $64 km-1 is depicted as a gray band to contextualize the magnitude of the operating expenses [39, 40]. The vertical dashed lines provide example routes and show that vessels traversing shorter, intraregional routes are prime for electrification even in the baseline scenario.

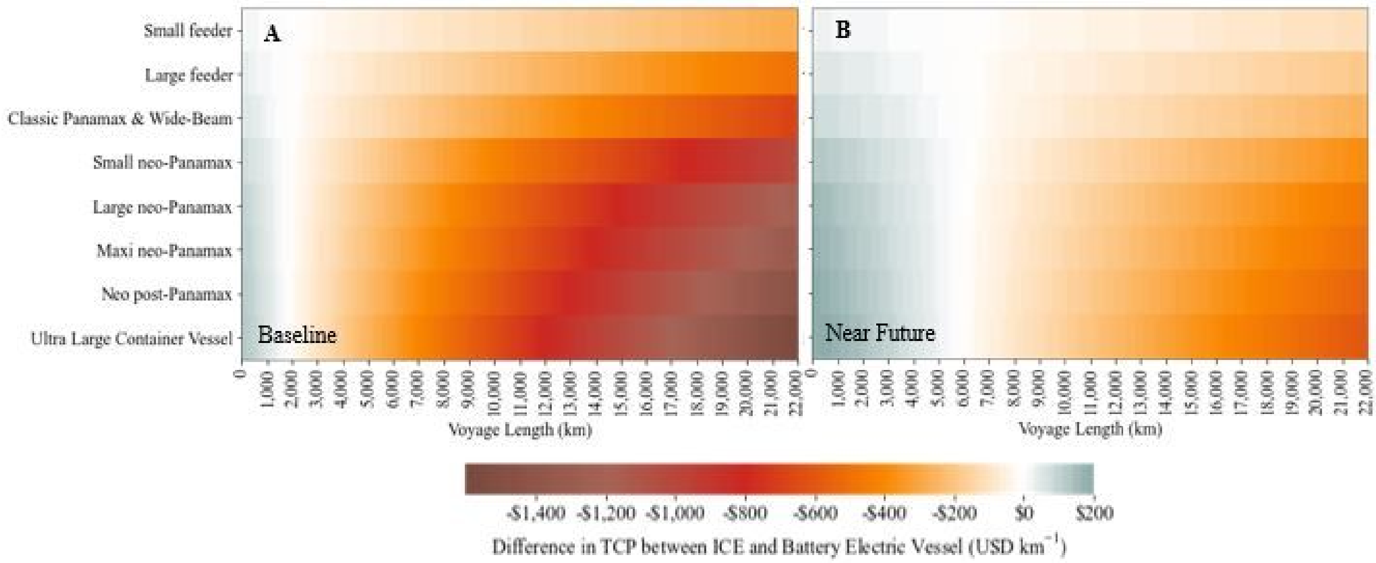

Figure 4

Difference in TCP between battery-electric and ICE vessels for all eight size classes for voyages up to 22,000 km. Panel A depicts the baseline scenario, while Panel B shows the near-future scenario. The TCP presented here excludes environmental costs. A positive value indicates that the TCP of the battery-electric ship is lower than that of the ICE equivalent. A negative value represents a lower ICE TCP. The TCP difference is larger in magnitude for larger ship classes, indicating the difficulty of cost-effectively electrifying large containerships over intercontinental routes, but also the potential economic benefit of phasing in battery-electric vessels over short to medium intraregional routes.

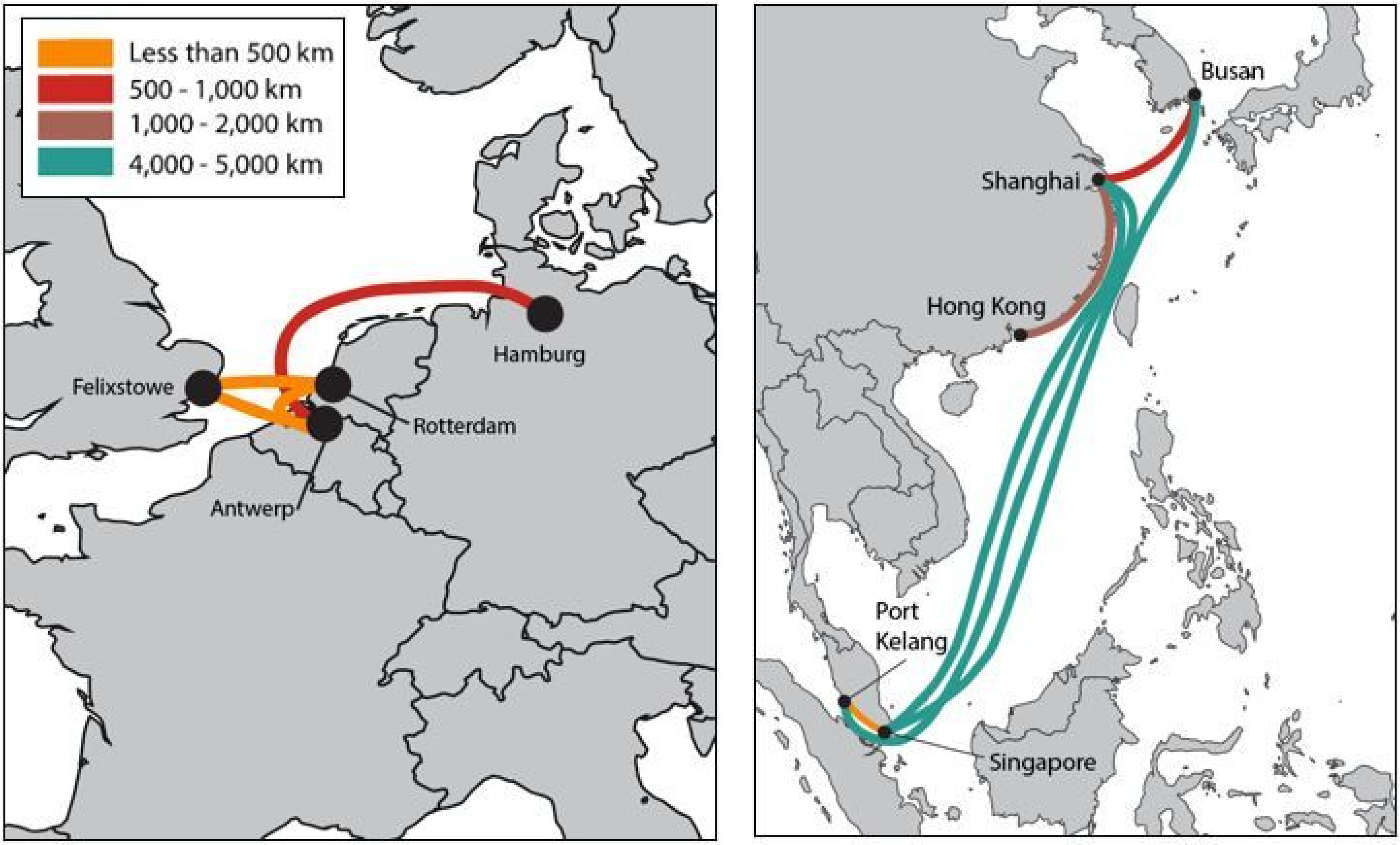

Figure 5

Top 10 bilateral maritime trading partners by shipping connectivity in 2019. UNCTAD's liner shipping bilateral connectivity index quantifies the extent to which ports in two countries are connected by maritime trade. The index is based on trade indicators which include the minimum number of transshipments required to get from country A to country B, the number of common direct third country connections between the country pair, the number of direct connections, the level of competition of shipping services connecting the country pair, and the size of the largest ship connecting the country pair [49]. As depicted in the figure, connectivity is strongest on short, intraregional routes of less than 5,000 km.

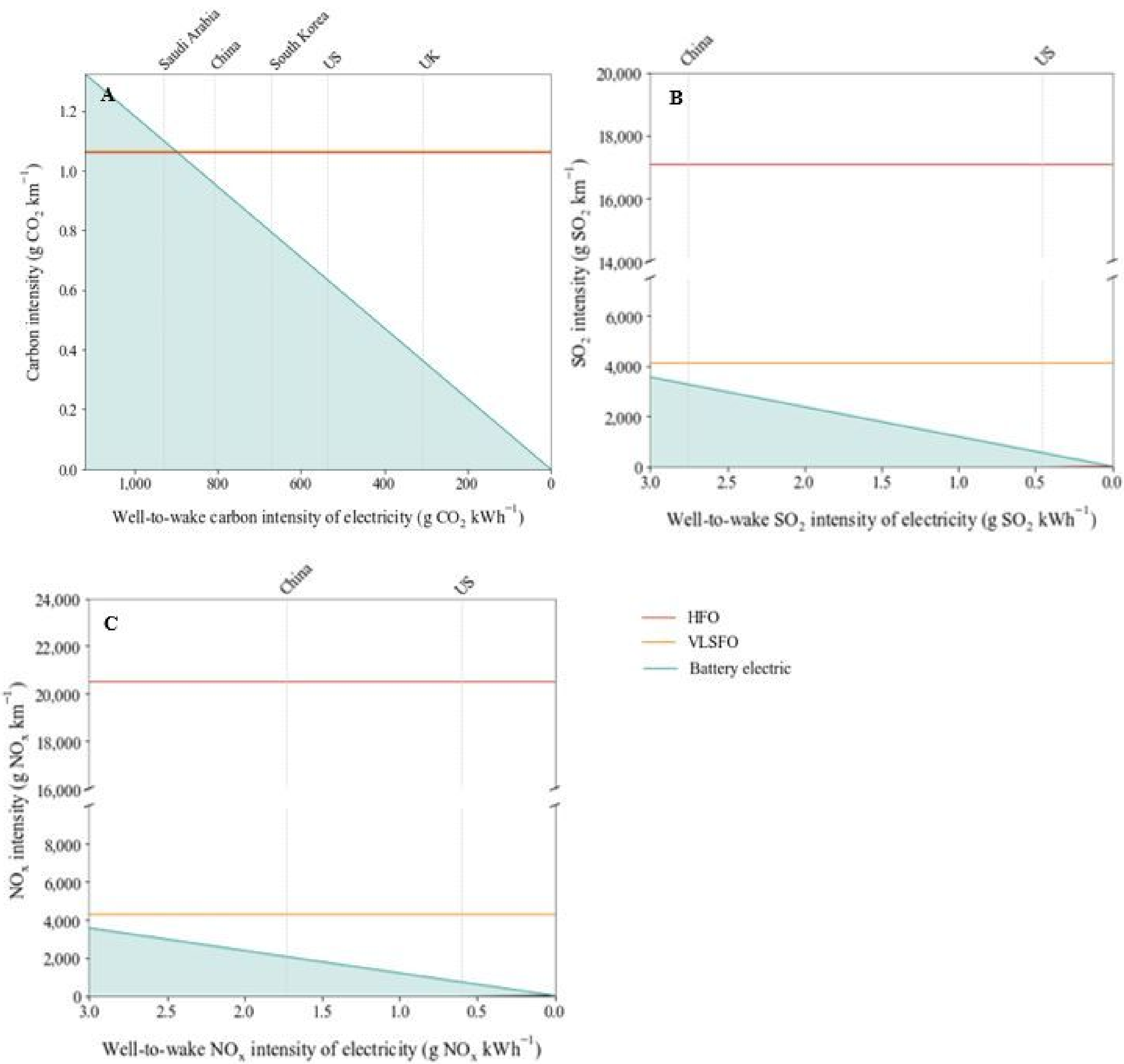

Figure 6

Comparison of the CO2, SO2, and NOx emissions intensities of a battery-electric, HFO, and VLSFO small neo-Panamax containership in different countries. The x-axes describe the well-to-wake intensity of the electric grid supplying the battery-electric vessel. The y-axes represent the emissions intensity of a small neo-Panamax ship. The black and red lines represent HFO- and VLSFO-fueled containerships, respectively. The blue wedge represents emissions from a battery-electric ship, which vary based on the grid emissions intensity. Panel A shows that CO2 emissions reductions depend on grid carbon intensity. A battery-electric vessel charged on Saudi Arabia's carbon-intense grid yields a 4% increase in CO2 emissions over an HFO-fueled vessel. The cleaner US and UK grids yield 40%−41% and 65%−66%

reductions in CO_2 emissions, respectively, over HFO and VSLFO. Panel B demonstrates that a battery-electric vessel charged in the US would yield 82% and 96% SO_2 emissions reductions over VLSFO and HFO, respectively. A battery-electric vessel charged with China's coal-reliant grid would yield a 22% SO_2 reduction over VLSFO and 81% over HFO. For NOx, depicted in panel C, a battery-electric vessel charged in the US yields 83% and 97% reductions over VLSFO and HFO, respectively. A vessel charged in China would yield NOx emissions reductions of 25% over VLSFO and 84% over HFO. Emissions reductions improve rapidly with penetration of renewable energy. A ship charged with 100% renewable energy would eliminate downstream emissions.