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Rapid battery cost declines accelerate the prospects of all-electric interregional container shipping

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International maritime shipping—powered by heavy fuel oil—is a major contributor to global CO_2, SO_2 and NO_x emissions. The direct electrification of maritime vessels has been underexplored as a low-emission option despite its considerable efficiency advantage over electrofuels. Past studies on ship electrification have relied on outdated assumptions on battery cost, energy density values and available on-board space. We show that at battery prices of US\$100 kWh^{-1} the electrification of intraregional trade routes of less than 1,500 km is economical, with minimal impact to ship carrying capacity. Including the environmental costs increases the economical range to 5,000 km. If batteries achieve a US\$50 kWh^{-1} price point, the economical range nearly doubles. 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 14% for US-based vessels, and mitigates the health impacts of air pollution on coastal communities.

Transporting 11 billion tonnes annually, the maritime shipping industry handles nearly 90% of global trade by mass[1,2]. The industry's meteoric growth 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, produces 2.5% of total anthropogenic carbon dioxide equivalent (CO_2e) emissions in 2018[2,3], and engenders enormous damages from marine eutrophication and ecotoxicity, air pollution, and climate change impacts[4]. By 2050, maritime shipping emissions are projected to contribute as much as 17% of global CO_2e emissions[5,6]. The industry's outsized contribution to criteria air pollutants—12% and 13% of global annual anthropogenic SO_2 and NO_x emissions, respectively—caused an estimated 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 substantially curb the sector's emissions and avert catastrophic climate change. Optimistic outlooks for zero-emissions alternatives for marine applications suggest that electrofuels (e-fuels) would increase the total cost of ownership for bulks carriers by 200–600% relative to HFO[12]. Such analysis prompts additional research into which existing propulsion technologies could achieve parity with HFO in the near-future, particularly battery-electric propulsion. Maersk, the largest shipping company by volume, is already piloting battery hybridization on a containership operating between East Asia and West Africa[13]. 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[14,15]. However, systematic analysis of the adoption potential for battery-electric containerships has yet to be conducted. With the exception of these initial pilot projects, battery-electric propulsion has been underexplored as a potential low-emissions alternative in the marine shipping sector despite: its considerable emissions reduction potential; recent decline in battery costs; improvements in battery energy densities; increasing availability of low-cost, renewably generated electricity; and its substantial efficiency advantage over e-fuels such as green hydrogen and ammonia.

Using the best-available battery costs and energy densities, we examine the technical outlook, economic feasibility and environmental impact of battery-electric containerships. We define two scenarios: first, a baseline scenario using today's best-available battery costs, HFO costs, battery energy densities and renewable energy prices; and, second, a near-future scenario that tests the impacts of projected 2030 improvements in these variables. By contrast to most previous studies, we treat the volume repurposed to house the battery energy storage (BES) system as an opportunity cost instead of a fixed technical constraint. We specify eight containership size classes and model their energy needs, their 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 with almost any containership operating today. We focus on battery-electric containerships and briefly explore the implications of our results for electrifying other ship types. Our results suggest that over 40% of global containership traffic could be electrified cost-effectively with current technology, reducing CO_2 emissions by 14% for US-based vessels, and mitigating the health impacts of air pollution on coastal communities.

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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[16]. However, the 10–15% emissions reductions achievable through these measures are not sufficient to comply with forthcoming IMO efficiency regulations[17,18]. Hybrid battery technology has been explored a viable short-term solution to reduce—but not eliminate—emissions from fossil-fuel energy sources. One study suggests a best-case scenario for hybrid systems is only 14% reduction in emissions for dry bulk carriers (comprising 2% of global fleet emissions)[19], not substantially better than the existing energy efficiency measures. Small modular nuclear reactors, which have been used in military and submarine applications for decades[20], are a viable alternative, but are unlikely to achieve wide-spread deployment in commercial vessels given the regulatory challenges surrounding nuclear proliferation, safety and waste disposal. Marine gas oil, liquefied petroleum gas, liquefied 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 considerably reduce lifecycle GHG emissions[21–23]. Not all transport modes are viable candidates for immediate and direct electrification; commercial jet planes cannot reasonably be electrified until battery pack specific energy increases to three to ten times their current values[24]. It is within this context that propulsion technologies generated with renewable power have received the most attention. For example, blue hydrogen (hydrogen produced from natural gas with carbon capture and storage) is expected to reduce GHG emissions by only 20% compared with burning natural gas[25]. Although renewably produced ammonia and hydrogen provide operational emissions reductions, the inefficiency of the production process relative to HFO makes them unlikely to become sufficiently cost-competitive to displace fossil fuels[26,27]. By 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[27].

By contrast to other modes where battery weight dramatically reduces payload capacity or range, such as light-duty vehicles and planes, the sheer size of containerships means that the additional weight from the battery can potentially be offset with a smaller percentage forfeiture of cargo. Past work has suggested that battery electrification of marine vessels is unfavourable given the low energy density of batteries relative to hydrocarbon fuels[28–31]. 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 of 210 Wh kg^{-1} specific energy[32] and US\$100–134 kWh^{-1} (ref. [33]). 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 of the battery system and electric motor relative to the volume occupied by a vessel's existing engines, fuel storage and mechanical space. The extra weight of the BES system is, however, non-trivial in determining a vessel's power requirements. Operationally, containerships can increase their carrying capacity by increasing draught (that is, the vertical distance between the waterline and the keel) on the basis of the Archimedes principle. A higher draught increases the hull resistance, and thus more power is required to achieve the same speed. On voyages less than 5,000 km, we find that the necessary increase in power is less than 10% of the original power requirements. For example, for a 5,000 km range small neo-Panamax ship, we estimate that a 5 GWh battery with lithium iron phosphate (LFP) chemistry, with a specific energy of 260 Wh kg^{-1} (ref. [34]), will weigh 20,000 t and increase the draught by 1 m—a small fraction of the ship's total height and well within the bounds of the vessel's Scantling (maximum) draught. For voyages longer than 5,000 km, the increase in draught exceeds the vessel's Scantling draught.

The distribution of additional weight also impacts the hydrodynamics, aerodynamics, stability and energy consumption of a vessel[35]. Internal combustion engine (ICE) vessels use a ballast system whereby water tanks charge and discharge depending on the cargo load to distribute weight and counteract buoyancy. Case studies of fully electric or hybrid propulsion systems suggest that ballast systems can be partially or fully replaced by BES systems without substantial impacts to symmetry (trim) and balance by distributing battery components throughout existing void, mechanical and ballast spaces[35]. Furthermore, BES systems do not need to be arranged around a central drive shaft and can be more flexibly configured within the vessel's interior[12,36]. The volume of an onboard BES 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 the Admiralty Law, a version of the propeller law that is widely used in first-order estimations of ship power requirements and fuel consumption[37,38]. Although a bottom-up approach to estimating energy requirements would incorporate additional terms, our objective is to capture the relative changes in energy requirements between the two propulsion methods. Assuming an identical vessel and operational profile, the energy needs of ICE and battery-electric ships differ only by the engine efficiencies and mass, which directly changes the vessel draught.

$$e_{\mathrm{ICE}} = \frac{P_{\mathrm{SMCR}} \times t_{\mathrm{voyage}}}{\eta_{\mathrm{ICE}}} \times \frac{V_{\mathrm{average}}^{3}}{V_{\max}^{3}} \tag{1}$$

Equation (1) describes the energy needs of a ship with a low-speed, two-stroke marine ICE fed by IMO-compliant low-sulfur HFO, where P_{SMCR} is the maximum continuous power rating (where SCMR is the specified maximum continuous rating), V_{average} is the average cruising speed, $V_{\max}$ is the maximum design speed, t_{voyage} is the time to traverse the route and η_{ICE} is the ICE tank-to-wake efficiency.

$$e_{\mathrm{battery}} = \frac{P_{\mathrm{SMCR}} \times t_{\mathrm{voyage}}}{\eta_{\mathrm{inverter}} \times \eta_{\mathrm{motor}}} \times \frac{T_{\mathrm{loaded}}^{\frac{2}{3}}}{T_{\mathrm{reference}}^{\frac{2}{3}}} \times \frac{V_{\mathrm{average}}^{3}}{V_{\max}^{3}} \tag{2}$$

Equation (2) describes the energy needs of an equivalent battery-electric ship, which includes a correction for increased draught due to battery system weight, where T_{loaded} is the draught when loaded with the battery energy system, $T_{\mathrm{reference}}$ is the typical operating draught, and η_{motor} and η_{inverter} are motor and inverter efficiencies, respectively.

Nickel manganese cobalt oxide, LFP, nickel cobalt aluminium and lithium titanate oxide are commercially available lithium-ion chemistries with the requisite cycle life, specific power, charge rates and operating temperatures to support container shipping applications[39,40]. The choice of battery chemistry depends on specific operational characteristics. Vessels with shorter, more frequent voyages, lower power requirements, and charging time constraints would favour the high charge rates and long lifecycles of LFP batteries[41,42]. For ships with longer ranges and less frequent battery cycling, the relatively low cycle life and high energy density of nickel manganese cobalt oxide batteries may be more suitable. Given that electrification will probably be limited to small, short-range vessels until battery costs are further reduced, we model the use of LFP batteries.

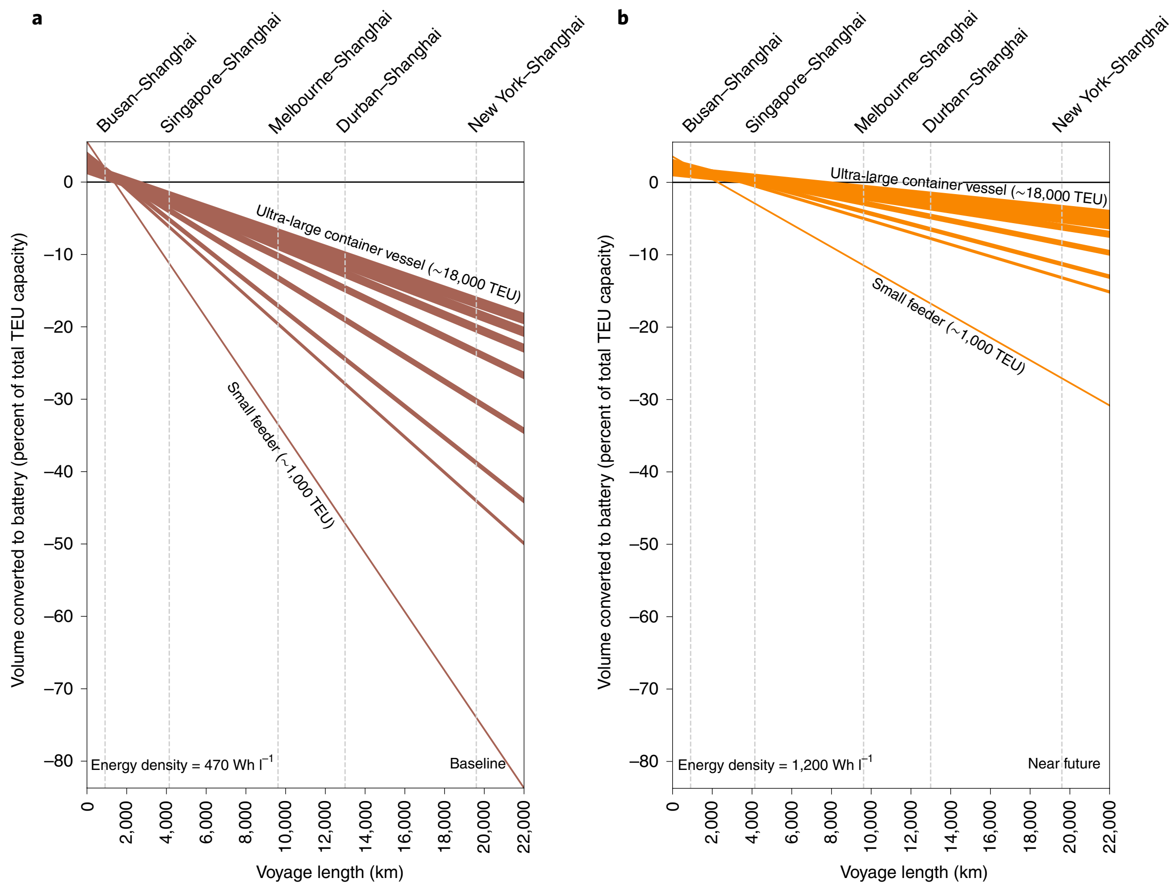

Fig. 1 | Carrying capacity forfeited to onboard battery system as percentage of total TEU by voyage length. We model the volume of the ICE ship's combined engine and mechanical space, assuming a battery packing fraction of 0.76 and an 80% depth of discharge. The line thicknesses denote increasing vessel carrying capacity. A small feeder, with a TEU capacity of around 1,000, is the smallest vessel modelled, whereas the ultra-large container vessel, with a TEU capacity of around 18,000, is the largest. **a**, The baseline scenario results, with a battery energy density of 470 Wh l^{-1}. In this scenario, the battery volume is less than that of the existing ICE mechanical space at voyage lengths less than 1,300–2,000 km. The impacts of the battery system volume on TEU forfeiture decreases as ship capacity increases, reflecting innovations in ultra-large containership design that optimize carrying capacity and energy consumption better than feeder ships. **b**, 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 of up to 2,000–5,000 km, depending on ship type.

We find that minimal carrying capacity must be repurposed to house the battery system for most ship size classes and along short to medium-length routes. 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 3,000 km. For the longest modelled route of 20,000 km for this ship class, the battery would occupy 2,500 twenty-foot equivalent unit (TEU) slots or 32% of the ship's carrying capacity. Supplementary Table 1 provides the baseline values used for each ship class. Figure 1 shows the percentage of ship carrying capacity forfeited to the BES system for the eight modelled ship classes across routes from 0 to 22,000 km, with current and near-future battery energy densities. We find that as carrying capacity increases, the percentage of total carrying capacity volume occupied by batteries decreases because larger ships typically have lower energy requirements per unit of carrying capacity[43,44].

Megawatt-scale charging infrastructure will be required to meet the large energy requirements of battery-electric containerships (for example, 6,500 MWh for a small neo-Panamax containership over a 5,000 km route) without disrupting normal port operation. The average queuing time plus berthing time in a port is 31 h for containerships of 1,000–3,000 TEUs and 97 h for the largest containership size classes of 10,000–20,000 TEUs[45]. The requisite charger capacity to charge within the available port time is less than 300 MW for all ship classes on voyages less than 10,000 km. We estimate that a 220 MW charger could charge a 7,650 TEU small neo-Panamax containership in 24 h. 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[46]. 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[45]. Adapting methods used for trucks[40] and trains[47] we estimate the levelized cost of a 300 MW charging station interconnected at the transmission level to be US\$0.03 kWh^{-1} at 50% utilization, inclusive of hardware, installation, grid interconnection, and annual operations and maintenance costs across the system lifetime[48].

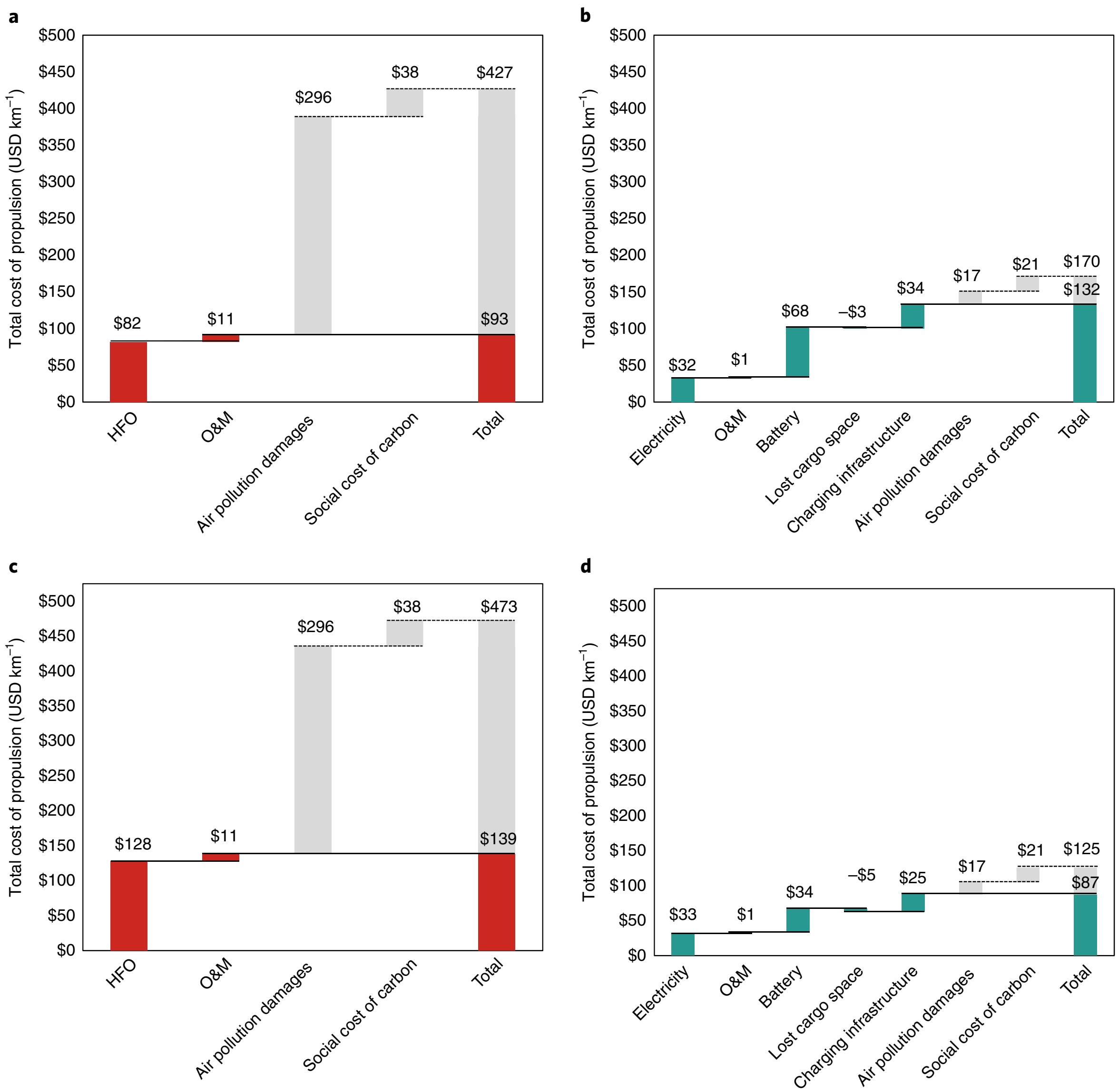

Fig. 2 | TCP including air pollution of a typical small neo-Panamax vessel. A neo-Panamax vessel of 7,650 TEU is modelled over a 1,565 km voyage. **a**, The TCP of an ICE ship in the baseline scenario. **b**, The TCP of the battery-electric equivalent in the baseline scenario. **c**,**d**, The TCP of ICE (**c**) and battery-electric (**d**) vessels in the near-future scenario. Coloured bars (red for ICE, teal for battery-electric) show non-environmental costs. Grey bars and dashed lines capture environmental damages attributed to NO_x, SO_2 and CO_2. 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 that is US$39 km^{-1} higher than the ICE TCP. The baseline scenario assumes a battery cost of US$100 kWh^{-1}, a battery volumetric energy density of 470 Wh l^{-1}, charging station utilization of 50%, wholesale electricity price of US$0.035 kWh^{-1}, and a HFO cost of US$0.048 kWh^{-1} (equivalent to US$538 t^{-1}); in the near-future scenario, HFO costs of US$840 t^{-1} (representing a US$100 per tonne tax on CO_2e), battery costs of US$50 kWh^{-1}, battery energy density of 1,200 Wh l^{-1}, and a charging infrastructure utilization rate of 70% lead to a battery-electric TCP that is US$52 km^{-1} lower than the ICE TCP. Accounting for environmental damages increases the TCP advantage of the battery-electric ship dramatically.

Cost parity with HFO

We test the economic feasibility of a battery-electric containership against that of a slow-speed, two-stroke ICE ship fuelled by very low sulfur fuel oil (VLSFO)—0.5% sulfur content—by calculating its TCP per kilometre by voyage length. For both ship types, we calculate fuel, operations and maintenance costs, as well as the environmental costs of NO_x, SO_2 and CO_2 emissions from direct combustion or grid electricity. For battery-electric vessels, we include the costs of an original and replacement battery set, the opportunity cost of forfeiting TEUs to the battery system and the levelized cost of charging equipment. As we account for the extra cost of the battery energy system separately, we omit the capital cost of the vessel, given that propulsion systems constitute only a small portion of ship newbuild costs and the cost advantage of electric motors relative to marine ICEs.

In the baseline scenario, 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 (refs. [5,40,47,49,50]). Over longer voyages, the additional cost of the battery system, increased power requirements and charging infrastructure outweighs the savings from fuel switching and the efficiency gains of direct electrification. However, if the environmental costs of

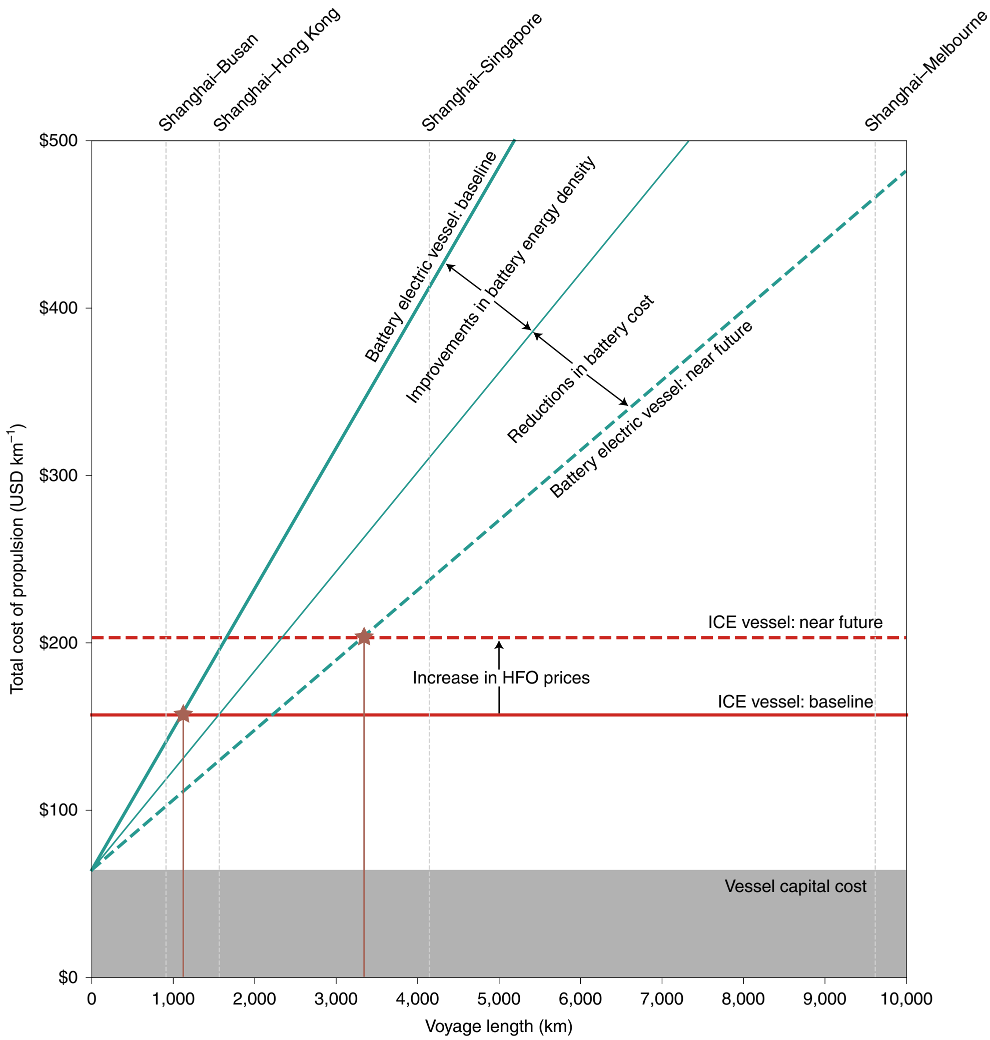

Fig. 3 | TCP of ICE and battery-electric small neo-Panamax containerships in baseline and near-future scenarios excluding environmental costs. Red and teal lines indicate the TCP of an ICE or battery-electric vessel, respectively. Dashed lines represent the near-future scenario. Stars indicate the point at which 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 1,000 km. In the near-future scenario, increases in HFO cost equivalent to US\$0.027 kWh^{-1} enable cost parity across ranges up to 3,300 km. Without increases in HFO prices, the range increases to 2,000 km in the near-future scenario. 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. A capital cost of US\$64 km^{-1} is depicted as a grey band to contextualize the magnitude of the operating expenses[79]. The vertical dashed lines provide example routes and show that vessels traversing shorter, intraregional routes are prime for electrification even in the baseline scenario.

NO_x, SO_2 and CO_2 are considered, the cost-effective range increases to 5,000 km across all size classes given the high emissions rates of HFO relative to the emissions intensity of the US grid.

Under the near-future scenario, the TCP of battery-electric shipping is lower than that of the incumbent ICE ship at ranges around 3,000 km for all ship classes. Including environmental costs, this range expands to 6,500 km for smaller-capacity ships and up to 12,000 km for the largest ship classes. However, although these longer ranges are cost-effective, the weight of the batteries drives vessel draught beyond safe operating parameters and thus they are unlikely to be candidates for full electrification without substantial changes in ship design. The fact that bulk carriers such as iron ore carriers have much higher weight and draught limits than containerships points to the possibility of accommodating the additional weight and draught by changing the ship design.

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 modelled voyage lengths, exclusive of environmental costs.

The primary constraint for cost parity of battery-electric ships with ICE ships over longer ranges is the battery cost. Battery prices need to reach US\$20 kWh^{-1} 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, 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[51]. However, battery technolo-

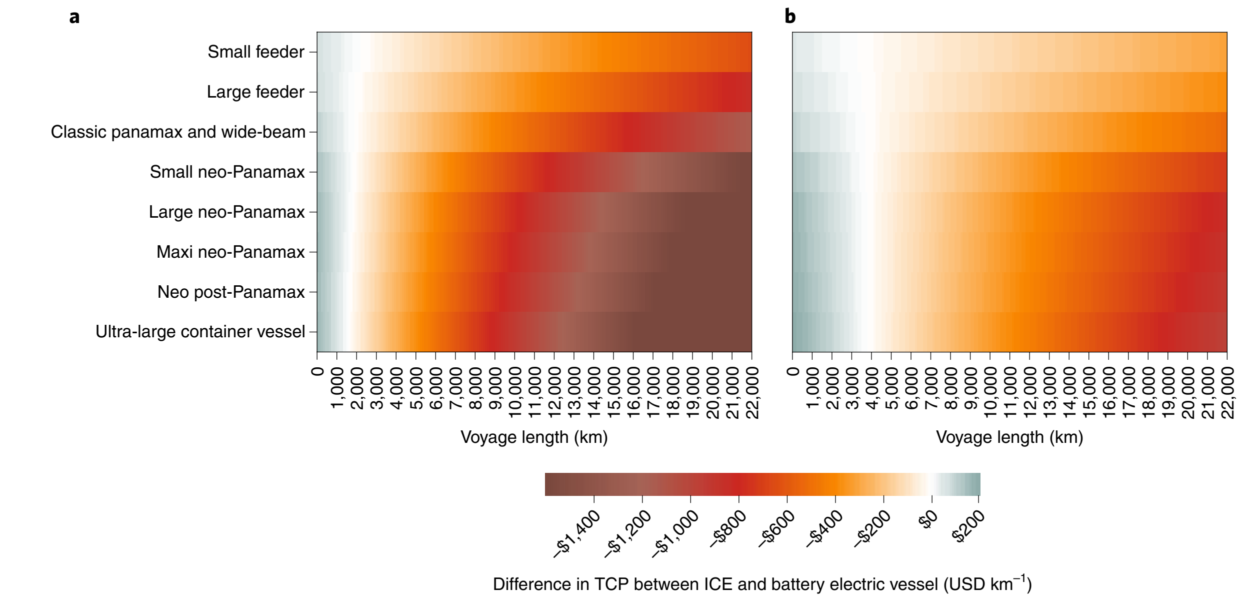

Fig. 4 | Difference in TCP between battery-electric and ICE vessels for all eight size classes for voyages up to 22,000 km. a,b, The baseline (**a**) and near-future (**b**) scenarios. TCP excludes environmental costs. A positive value indicates that the TCP of the battery-electric ship is lower than that of the ICE equivalent, whereas 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.

gies 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[52].

Deployment potential of battery-electric shipping

An estimated 42.3 trillion TEUs (40% of global trade) traversed intraregional routes in 2019[53]. However, this proportion is probably an underestimate owing to recent trends in containership logistics and the regionalization of trade[54], including an 1,100% increase in average containership capacity between 1968 and 2015[55]. The sector's trend towards 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[54]. From the destination hub, a host of smaller feeder ships transport the containers to their final destinations in smaller regional ports. Nearly all of 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 ten best-connected ports in the world, all of which are intraregional routes less than 5,000 km in length[2]. Moreover, feeder ships are older on average than their larger-capacity counterparts, and many are reaching the end of their useful service lives[56]. The 2020 IMO regulation limiting sulfur content will probably lead to the premature scrapping of these fuel-inefficient ships, creating an opportunity for battery-electric models to enter the fleet[57].

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[58]. 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 seem to have the largest emission footprint. Unlike containerships, some of these ship types are primarily constrained by weight rather than volume[41]. Energy density by weight is therefore the critical technical parameter for the batteries that would power these ships. At the same time, some bulk carriers and oil tankers are designed to carry up to 400,000 t—more than twice the weight of the largest containerships[59].

For a 5,000 km range dry bulk carrier, we estimate that the battery system will constitute 5–6% of the ship weight with current battery technology and 3–4% with projected increases in energy density by 2030[28,41,60]. 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 these ship types.

Emissions reduction potential of battery electrification

Battery-electric container shipping would eliminate all direct combustion emissions and considerably ameliorate localized air pollution and related health impacts in communities near ports and global trade lanes[61]. 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 VLSFO to a battery-electric vessel across a range of realistic well-to-wake emissions intensities (Fig. 6). The input tank-to-wake emissions factors (g kWh^{-1}) include downstream losses attributable to transmission, power conversion, shore-side storage and electric motor losses. Battery-electric vessels would also 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[62].

Reductions in carbon emissions and air pollutants are highly dependent on the generation matrix of the grid where the vessel is charged. 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

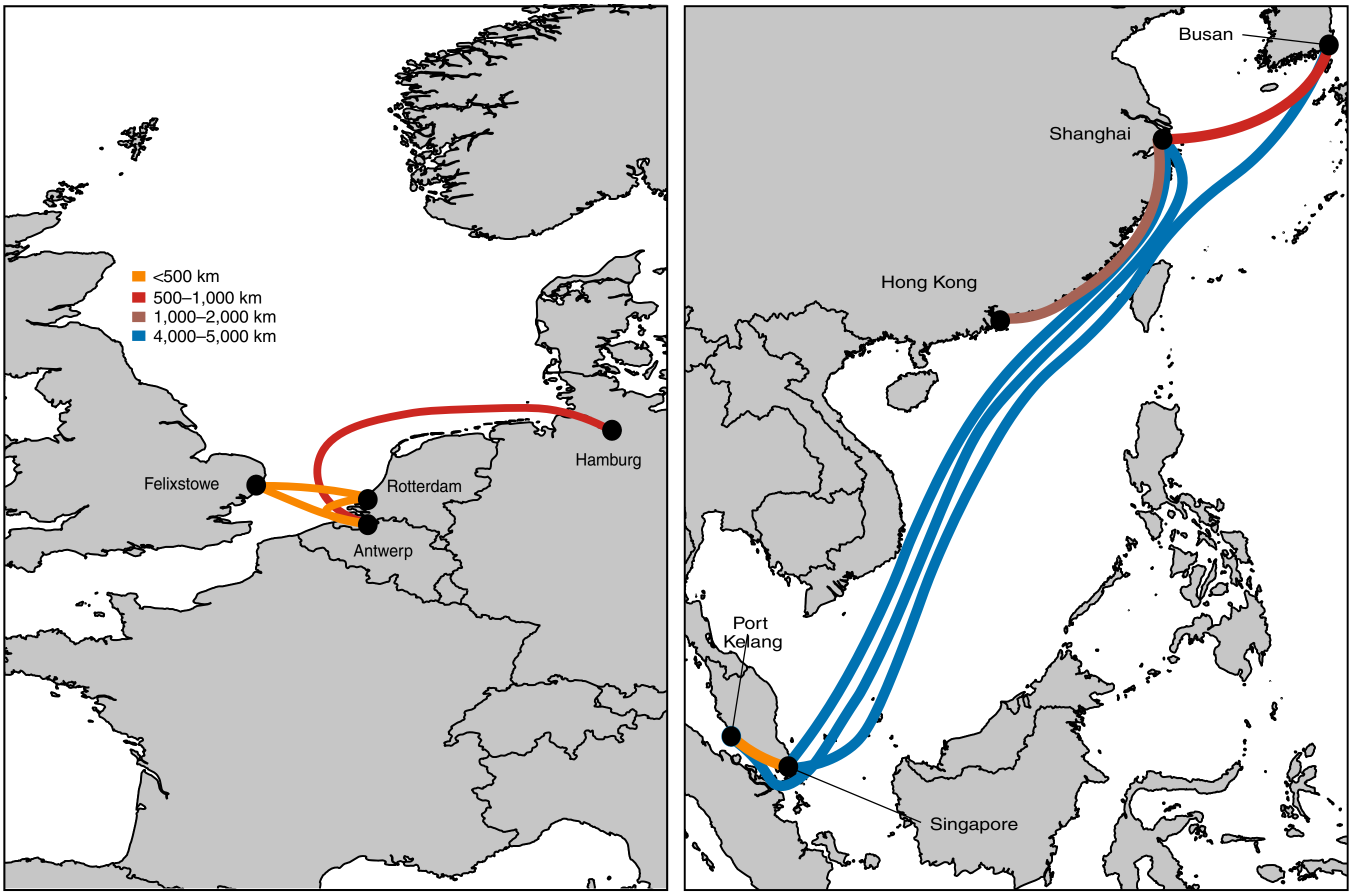

Fig. 5 | Top-ten bilateral maritime trading partners by shipping connectivity in 2019. UNCTAD's liner shipping bilateral connectivity index quantifies the extent to which ports in two countries are connected by maritime trade. The index is based on trade indicators, which include the minimum number of trans-shipments required to get from country A to 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[92]. Connectivity is strongest over short, intraregional routes of less than 5,000 km.

port generates approximately 0.78 g CO_2 km^{-1} (ref. [63]). This is a 16% reduction from HFO and VLSFO, which produce approximately 0.93 and 0.91 CO_2 km^{-1}, respectively. Battery electrification yields an 86% reduction over VLSFO in per-kilometre SO_2 emissions in the US but only a 4% reduction in China[64]. NO_x emissions are reduced approximately 83% and 42% 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[65].

Discussion

We show that battery-electric ships powered by renewable electricity offer a near-term pathway to cut shipping emissions over intra-regional and inland routes. At battery prices of US$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 US$50 kWh^{-1}, routes upwards of 5,000 km can be electrified cost-effectively. Future research should consider how opportunities for intermediate recharging affect the overall economics of battery electrification. If vessels were able to recharge at distinct points en route, the battery cost, forfeited TEUs and additional energy requirements from battery weight will each decrease, potentially making longer-range trips economically feasible.

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[66]. 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 could facilitate electrification of a much larger percentage of global maritime trade. Offshore charging in ports and along shipping trade routes could facilitate collocation of charging stations with renewable generation sources, eliminate direct emissions and alleviate range constraints. Two-thirds of global ship traffic occurs within 370 km of the shore, where wind potential is highest[67,68]. Furthermore, the cost of offshore wind is expected to decline 37–49% by 2050, beating 2015 predictions[69] by 50%.

Electrification provides several 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[29,70]. Hence, retrofitting or hybridizing existing ships with electric drivetrains during propulsion system overhauls is technically and economically viable and could accelerate the electrification of the

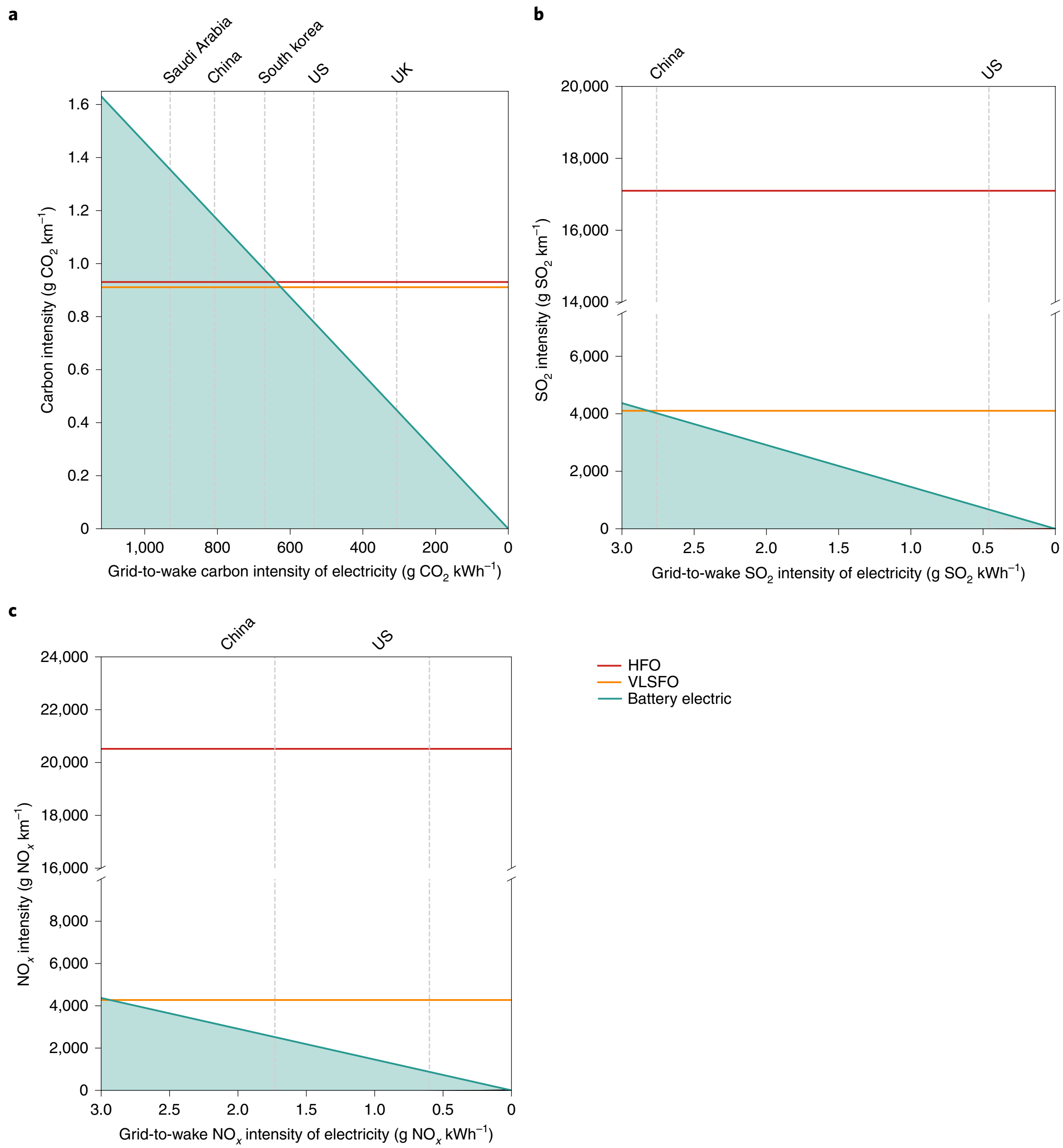

Fig. 6 | Comparison of CO_2, SO_2 and NO_x emissions intensities of a battery-electric, HFO and VLSFO small neo-Panamax containerships charged in different countries. The *x*-axes describe the well-to-wake intensities of the electric grid supplying the battery-electric vessel. The *y*-axes represent emissions intensities of a 7,650 TEU small neo-Panamax ship. The red and orange lines represent HFO- and VLSFO-fuelled containerships, respectively. Blue wedges represent emissions from a battery-electric ship, which vary by grid emissions intensity. **a**, We show that CO_2 emissions reductions depend on grid carbon intensity. A battery-electric vessel charged on Saudi Arabia's carbon-intense grid yields a 46% increase in CO_2 emissions over an HFO-fuelled vessel. The cleaner US and UK grids yield 14–16% and 51–52% reductions in CO_2 emissions, respectively, over HFO and VSLFO. **b**, We demonstrate that a battery-electric vessel charged in the US would yield 86% and 97% SO_2 emissions reductions over VLSFO and HFO, respectively. A battery-electric vessel charged with China's coal-reliant grid would yield a 4% SO_2 reduction over VLSFO and 77% over HFO. **c**, For NO_x, a battery-electric vessel charged in the US yields 83% and 96% reductions over VLSFO and HFO, respectively. A vessel charged in China would yield NO_x emissions reductions of 42% over VLSFO and 88% over HFO. Emissions reductions improve rapidly with penetration of renewable energy. A ship charged with 100% renewable energy would eliminate downstream emissions.

global fleet. One 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 modelled 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[71] than 5 GWh.

Our analysis suggests that rapidly improving battery technology may enable direct electrification to play a key role in decarbonizing the shipping industry. 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 much lower than those of conventional ships, but their upfront costs will be much higher primarily due to the cost of the batteries.

Innovative financing and business models are required to address higher upfront costs. Transmission-connected charging stations with capacities of hundreds of megawats—similar to large scale grid connected storage facilities—will have to be built to support ship charging. Given that environmental damages from conventional ships are an order of magnitude higher than the propulsion costs of these ships, policies such as financial incentives for demonstrations and regulations will play a critical role in supporting the transition to zero-emissions shipping.

Methods

Modelling approach. The energetic requirements of an ICE containership and its battery-electric analogue depend on the ship size and voyage distance. Past studies have approached this analysis by studying specific real-life ships along their usual routes[28–30]. Although this approach has strengths in terms of data availability, an important limitation is the generalizability of the results to similar ships of different route length and carrying capacity. To improve modelling 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 470 Wh l^{-1}, battery cost of US\$100 kWh^{-1}, HFO cost of US\$0.048 kWh^{-1}, charging infrastructure utilization of 50% equivalent to US\$0.029 kWh^{-1}, and electricity price of US\$0.035 kWh^{-1}. The near-future scenario assumes a battery cost of US\$50 kWh^{-1}, volumetric energy density of 1,200 Wh l^{-1} and charging infrastructure utilization of 70%, or a US\$0.021 kWh^{-1} levelized cost of charging infrastructure

Modelling 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 SMCR, which describes its maximum power output during continuous operation. The average power output is lower than the SMCR, as 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[72]. Additional energy requirements during manoeuvreing 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 at 80% of the design speed, which equates to 37 km h^{-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[73]. We use the Admiralty Law load factor to account for resistance created by additional displacement from the weight of the BES system for the battery-electric vessels per equation (2)[38]. Design draught, maximum draught, vessel length and vessel breadth are taken from MAN Diesel Turbo and used to convert from battery weight to change in draught based on the Archimedes principle, which states that the weight of the displaced water is equal to the weight of the ship[72]. We assume an ICE tank-to-wake efficiency of 50% and electric motor and inverter efficiencies of 95% each[28]. 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.

Daily HFO fuel consumption is derived from an empirical study of containership fuel consumption[74]. We assume a containership carries enough fuel for a day's voyage; in reality, this figure is probably higher, because ships often carry fuel for several days after bunkering. The mass and volume of BES and propulsion systems are 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, with a 0.76 battery packing fraction and 80% depth of discharge. We calculate TEU forfeiture by converting BES system volume in excess of the existing mechanical and fuel storage space to standard 2.6 m × 2.4 m × 6.1 m TEUs. The net change in weight used to correct the power estimates for the battery-electric vessels is the weight of the battery system and electric propulsion system (assumed to weigh 50% that of the ICE propulsion system), less the weight of the fuel storage and ICE engine, less the weight of TEUs forfeited to the battery energy system assuming an average loaded TEU weight of 28.2 t (ref. [75]). ICE system weights and volumes are based on correlations developed by[29].

TCP 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 fuelled 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, including periodic repairs, regular maintenance, and operation of a scrubber system to comply with recent IMO sulfur emissions standards (estimated at US\$5 MWh^{-1}), and excluding other shipping operational expenses such as labour, insurance, and port charges[76]. These expenses are developed from industry benchmarks and academic research[77,78].

The battery-electric TCP model accounts for the cost of electricity, TEU forfeiture, additional capital costs of the original and replacement of BES 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 plus replacement costs over the service lifetime of the ship (25 years)[79]. LFP batteries are assumed to need replacement after 5,000 cycles or 20 years, whichever comes first[39,40]. Battery decommissioning costs are neglected based on the assumption that batteries will have a second life application[80]. 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[81]. 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[56,82]. Supplementary Table 2 summarizes the data inputs to the TCP model.

We adapt previous research on electric trains[40] and trucking[47] to estimate the levelized cost of megawatt-scale charging infrastructure and electricity costs. We use an electricity cost of US\$0.035 kWh^{-1} in line with historical real-time prices published by the California Independent System Operator (CAISO) for 2017 through 2019[83]. 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. Supplementary Fig. 1 provides a summary of the components that comprise the total levelized charging infrastructure costs.

Where environmental costs are presented, we assume a marginal cost of NO_x and SO_2 of US\$13,000 t^{-1} and US\$24,000 t^{-1}, respectively[84], and a social cost of carbon of US\$43 t^{-1} in line with the US Environmental Protection Agency's regulatory guidelines[85]. Notably, this value is about one-third that considered sufficient to remain below a 1.5 degree Celsius[86].

Environmental impacts. To quantify the potential environmental impacts of battery-electric container shipping, we use published tank-to-wake CO_2, NO_x and SO_2 emissions factors for a slow-speed, two-stroke ICE ship, as described in Supplementary Table 3. Emissions intensities are converted to per-kilometre intensities by multiplying by the energy consumption in kilowatt hours of a battery-electric small neo-Panamax containership[87,88].

To estimate the emissions of a battery-electric vessel, we calculate a tank-to-wake emissions intensity across a range of real-life grid emission factors sourced from multiple countries[63]. To convert from grid intensities to tank-to-wake emissions intensities, we apply 5% transmission and distribution losses, 10% AC/DC power conversion losses[89], 5% DC/AC conversion losses[28] and 5% electric motor efficiency losses[28]. Calculated tank-to-wake carbon emissions for each country are presented in Supplementary Table 4. We exclude emissions from battery production owing to the wide variation in estimates, which depend on where primary materials are extracted and potential end-of-life recycling opportunities[90]. To ensure a direct comparison with alternative fuels, we use tank-to-wake emissions factors rather than well-to-wake emissions factors[91].

Data availability

All data and assumptions necessary to replicate this study's analysis are included in this published article and its Supplementary information.

Code availability

The source code and data underlying the figures presented in this manuscript is available at https://doi.org/10.5281/zenodo.6594089.

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Author contributions

J.K. developed the model, conducted the analysis, and wrote the draft manuscript. A.P. conceived the project, secured funding and reviewed to the manuscript. N.P. provided input data for charging infrastructure and wrote portions of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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