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Exploring the cost and emissions impacts, feasibility and scalability of battery electric ships

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The United States' greenhouse gas (GHG) emissions reduction goals, along with targets set by the International Maritime Organization, create an opportunity for battery electric shipping. In this study, we model life-cycle costs and GHG emissions from shipping electrification, leveraging ship activity datasets from across the United States in 2021. We estimate that retrofitting 6,323 domestic ships under 1,000 gross tonnage to battery electric vessels would reduce US domestic shipping GHG emissions by up to 73% by 2035 from 2022 levels. By 2035, electrifying up to 85% of these ships could become cost effective versus internal combustion engine ships if they cover 99% of annual trips and charge from a deeply decarbonized grid. We find that charging demands from electrifying these ships could be concentrated at just 20 of 150 major ports nationwide. This study demonstrates that retrofitting to battery electric vessels has economic potential and could significantly accelerate GHG emission reductions.

The United States aims to cut greenhouse gas (GHG) emissions 52% by 2030 and 100% by 2050[1]. The International Maritime Organization (IMO) is targeting GHG emissions reductions from international shipping, starting with 20–30% reductions by 2030 and 70–80% reductions by 2040 (both from 2008 levels) before realizing net-zero GHG emissions near mid-century[2]. US domestic marine vessels with internal combustion engines (ICEs) emitted 21.9 million metric tonnes (MMT) of carbon dioxide equivalent (CO_2e) in 2021[3,4]. Whereas maritime vessels represent 3% of total transportation emissions in the United States, identifying decarbonization pathways for these vessels is critical to achieving net-zero transportation emissions[4].

Although battery electric ships (BESs) have received considerable attention, questions remain about their feasibility due to challenges related to scaling up battery sizes[5], the difficulty of bringing electricity to vessels for charging[6] and ship weight constraints. In light of these challenges, other zero-emission fuels such as hydrogen and sustainable liquids are being considered as alternatives for maritime transportation[4]. However, plummeting battery costs coupled with increasing battery energy densities create an opportunity for battery-powered shipping as a potential zero-emission freight solution. Whereas battery pack prices increased for the first time during the COVID-19 pandemic, to US$161 per kilowatt hour (kWh), by late 2023 they had resumed decreasing, to US$139 kWh^{-1} (refs. 7,8).

Recent advancements in battery technology have been spearheaded by the US Department of Energy's Battery500 and PROPEL-1K programmes, which aim to considerably increase energy density in batteries[9,10]. Battery500 targets achieving a cell energy density of 500 watt-hours per kilogram ($Wh\ kg^{-1}$), which represents a substantial leap from current capabilities. Notably, recent experiments have demonstrated promising results, with lithium nickel manganese cobalt oxides (Li-NMC) pouch cells attaining energy densities up to 450 $Wh\ kg^{-1}$. These and related developments can be expected to enable substantial advancements in battery electric transportation systems.

Several studies have estimated emissions from ship activities, including two comprehensive global assessments[11,12]. Gutiérrez compared various methods for estimating GHG and air pollutant emissions

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from maritime transportation[13]. Chen et al. delved into emissions estimates for tugboats by distinguishing different operational modes (for example, berthing and un-berthing) and analysing the positions of tugboats in relation to containers[14]. Other studies conducted region-specific analyses, including a spatial-temporal estimation of ship emissions along the Yangtze River in China[15], emissions from ships operating within the Great Lakes–St. Lawrence Seaway[16] and emissions from non-oceangoing vessels in the United States[17]. These studies all focused on estimating emissions and did not compare the economics of BESs to ICEs.

Advancements in battery technology have enabled recent deployments of battery electric ferries in Norway[18], Japan[19] and Denmark[20]. Whereas ferries' predictable service routes make them ideal electrification candidates, other ship types, such as tugboats, are also being considered; the first battery electric tugboat, the 6-MWh eWolf, was unveiled in 2021[21].

Previous studies have explored the decarbonization potential of BESs. Comparison of grid emissions data from 33 countries identified power system emissions as the key parameter affecting BES emissions[22]. A study comparing BESs with alternative fuels across three ship types through life-cycle assessment (LCA) and techno-economic analysis (TEA) demonstrated that BESs emit the lowest GHG emissions and have the lowest cost for passenger ships compared with alternatives, suggesting those ships may present a unique electrification opportunity[23]. From an LCA perspective, lithium-ion batteries are the most environmentally friendly option, relative to lead-acid or nickel-metal hydride chemistries, primarily due to their extended lifespan and greater energy density[24]. The potential for battery electric interregional container shipping, enabled by a rapid decline in battery costs, has also been identified[25]. Furthermore, analysis utilizing an emissions–energy–economic impact model has demonstrated that increasing the share of BESs can reduce GHG emissions from shipping[26].

Whereas these studies provide a helpful foundation for estimating maritime GHG emissions and the electrification potential of specific applications, none addresses the broader regional or national implications of replacing ICEs with BESs. Here we assess the costs, equipment needs and environmental benefits of converting US domestic shipping to battery electric. In so doing, we address a specific assumption—namely, that BESs would always serve 100% of historical trips—that may have led observers to underestimate BES economic feasibility. By evaluating the economic feasibility of battery electric ships at different percentages of historical trips served, we present a valuable framework for assessing the reasonable pool of ships that could be electrified.

We consider fuel production, electricity generation and battery manufacturing and operation through both a TEA and LCA, looking closely at a specific pathway for maritime decarbonization, namely the retrofitting of ICE ships. In our TEA, we assess the routes and ship types that can feasibly be electrified at current and near-future battery costs and energy densities given ships' energy requirements, the distribution and length of shipping routes and vessel engineering considerations. Then we estimate the grid and port infrastructure requirements to enable such a nationwide transition. In our LCA, we quantify the full life-cycle environmental impacts of transitioning to battery electric shipping, including potential reductions of criteria air pollutants and GHG emissions.

To complete our analysis, we developed a modelling tool, the Maritime Battery Electrification Simulator (MariBES), to explore electrification options in different maritime contexts using both TEA and LCA and provide insights for electrification planning. Our model is unique in its high spatial and temporal resolution, which enables a granular understanding of the opportunities and constraints facing different ship types and port systems. Whereas we use US-flagged vessels under 1,000 gross tonnage (GT) as a test case, the model is flexible to other input data and could be used to examine fleets in other countries using the same global activity database. Finally, we identify priority US ports and regions for electrification based on projected electricity requirements. This analysis of zero-emission domestic shipping lays important groundwork for a global zero-emission shipping sector.

Our results indicate that electrifying 6,323 domestic vessels with a gross tonnage of less than 1,000 would reduce US domestic maritime GHG emissions up to 73% below 2022 levels by 2035; and that up to 85% of battery electric ships become cost effective, compared to internal combustion engine ships, when they cover 99% of historical trips and charge from a deeply decarbonized grid.

Ship battery potential and feasibility

From three US vessel databases[27–29], we assess the battery electrification potential of 6,323 US domestic ships, which we refer to as the 'Domestic Fleet' (Supplementary Table 3). From these, we identify 2,722 ships with sufficient data from the Automatic Identification System (AIS)[30] that travelled more than 1,500 km in 2021, which we then group into the 'AIS Analysed Subset'. By analysing high-resolution temporal and spatial AIS data on ship operations, along with ship engineering specifications, we evaluate the technical feasibility of electrifying different ship types.

AIS data include ICE ships' historical trip activity. Some trips involve one-way distances that exceed feasible battery sizes or costs with current technology. To address this issue, we create four capacity tiers—BESp100, BESp99, BESp95 and BESp90—to denote the percentage of ICE vessels' historical trips that a BES can serve (Supplementary Note 3).

By excluding a small percentage of long trips, we can significantly reduce BES required battery sizes while still allowing it to perform most usual tasks. Figure 1a shows that excluding just 1% of the longest trips allows for a two-thirds reduction in battery size (Supplementary Fig. 19). This trend is particularly pronounced for passenger ships, whose battery size can be reduced by 85% (Supplementary Fig. 21). Availability of battery components is essential for ship electrification. Figure 1b shows that the batteries required to electrify the US domestic maritime sector would not exceed 14% of North America's projected battery manufacturing capacity in 2030[31].

The weight of batteries largely determines the physical feasibility of vessel electrification. Weight increases can be mitigated by excluding a small percentage of long trips. Figure 1c demonstrates that with a battery system weighing 21 kg kWh^{-1} (ref. 32), electrification at BESp100 leads to a 137% increase in the median weight of BESs compared to ICEs. However, excluding the top 1% of energy-demanding trips (that is, BESp99) limits the median weight increase to only 30%. Advancements in battery materials and packaging that yield 25% lighter battery systems could limit BESp99 median weight increases even further, to 21% (Supplementary Fig. 28)[33].

Emissions reductions

We estimate total operational emissions of ICEs in the AIS Analysed Subset to be approximately 2.1 million metric tonnes of CO_2e (MMT-CO_2e) or 9.5% of the 21.9 MMTCO_2e emitted by the entire domestic fleet in 2021[3,4]. A fair comparison of CO_2e emissions from BESs and ICEs involves looking not only at BES charging and the emissions of associated electricity generation but also battery manufacturing. Because the study's scope is confined to the period when retrofitting begins, prior vessel manufacturing and operational phases (and associated emissions and energy consumption) are excluded from the analysis. Thus, we develop and employ a post-retrofit LCA model of BESp100 ships that includes full life-cycle CO_2e emissions for electricity generation and battery production and compare this with life-cycle emissions of ICE fuel consumption[34]. We allocate these emissions across the expected lifetime and distance travelled of vessels post-retrofit, which may vary from other LCAs that select a different allocation method and functional unit (for example, per t-km travelled). Notably, battery manufacturing emissions can be significantly mitigated (by up to 72%) if batteries, after initial deployment, are utilized in stationary second-life applications[35].

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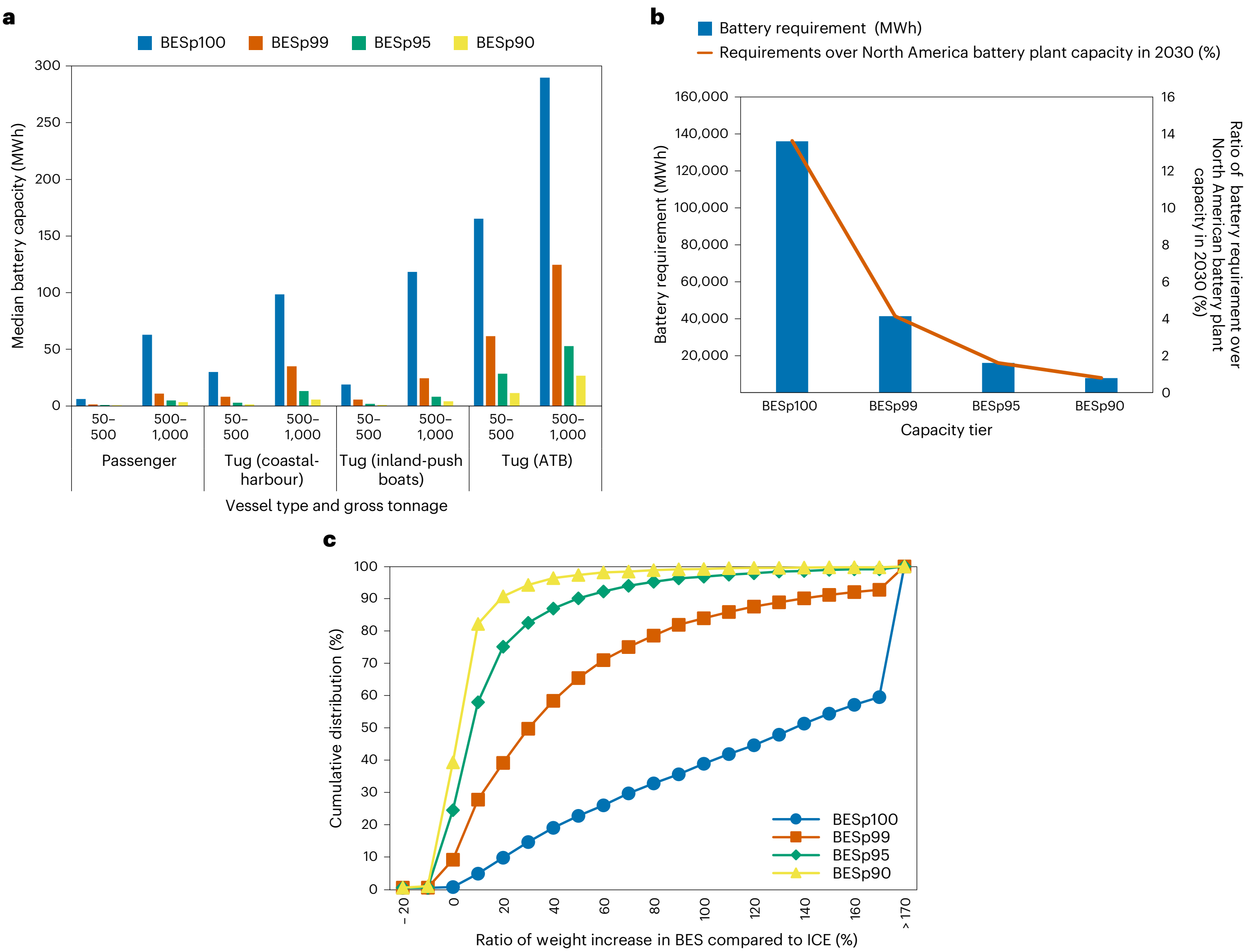

Fig. 1 | Battery requirements and technical feasibility by vessel type and capacity tier. a, Median battery requirements by ship size, ship type and capacity tier. The capacity tiers—BESp100, BESp99, BESp95 and BESp90—represent the percentage of historical trips by ICE vessels that BESs can serve. As the BES capacity tier decreases, battery size decreases by an average of 67%, 86% and 92%, respectively. Within the BESp99 cohort, the most significant reduction in battery size is observed for passenger ships of 500–1,000 gross tonnage (GT), followed by inland and push tugs of 500–1,000 GT. Articulated tug barges (ATBs) of 500–1,000 GT exhibit the smallest reduction due to their unique trip characteristics and large share of energy-demanding trips. **b**, BES battery requirements by capacity tier compared to North American battery manufacturing capacity in 2030 for vessels of 50–100 GT. Battery demand ranges from 7,898 megawatt hours (MWh) for BESp90 to 135,973 MWh for BESp100. **c**, The ratio of BES weight to ICE weight by BES capacity tier. The weight differential varies by capacity tier, with smaller weight increases seen in lower-capacity tiers. For BESp100, 41% of vessels had a weight increase of over 100%. By contrast, BESp99 weight increases were more modest, with 65% of vessels showing an increase of 50% or less. For BESp95, 69% of vessels had a weight increase of 20% or less, whereas a striking 91% of BESp90 had weight increases of 20% or less.

Table 1 presents the scenarios assumed in this study for emission and economic analyses.

Figure 2a shows that retrofitting ICEs to BESs can reduce maritime CO_2e emissions by 34–73% in 2035, depending on the carbon intensity of the electric grid[36]. Under the DEC50 scenario, this reduction reaches 75% in 2050. But in DEC35, which broadly aligns with Biden–Harris administration goals[37], the 75% CO_2e emissions reduction seen in 2050 under the DEC50 scenario could be nearly achieved by 2035, with a 73% reduction[36]. Whereas retrofitting ICEs to BESs can significantly reduce maritime CO_2e emissions, achieving complete decarbonization faces two main challenges. First, the focus of power system decarbonization is primarily on the combustion stage, not accounting for emissions in the pre-combustion stage, which still amount to 107–122 CO_2e g kWh^{-1} inclusive of infrastructure, material and any energy consumption for production of renewable energies. Second, our assumptions indicate that during the battery manufacturing process, 41% of energy is sourced from electricity, whereas the remaining 59% is derived directly from fossil fuels (that is, coal, natural gas and petroleum). From an LCA perspective, reducing CO_2e emissions in the pre-combustion stage of electricity generation and achieving carbon-free battery manufacturing are both essential to achieving 100% decarbonization with BESs.

Figure 2b shows cumulative US domestic maritime sector emissions between 2022 and 2050 could fall by 58% under DEC35 compared to BAU[38]. Accelerating power sector decarbonization thus enables significantly larger and faster CO_2e emission reductions from shipping electrification.

Figure 2c shows that per-km CO_2e emissions from BESs decrease by up to 12% as capacity tier decreases. Because BESs with lower-capacity tiers do not serve all ICE trips, we estimate per-km CO_2e emissions by excluding the emissions and travel distances of unserved trips. The most cost-effective emissions reduction is achieved by retrofitting ICEs to BESp90 under a DEC35 scenario, which reduces per-km CO_2e

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Table 1 | Description of emission and economic scenarios

Type of scenario	Description	Scenario name	Note	Key parameters			
					2022	2035	2050
Emission scenarios	For BESs, GHG emissions from electricity generation were assessed based on three projected generation scenarios for the United States.	Business as usual (BAU)	Grid emission factors: 'Mid-case' in NREL's Cambium model[36]	Grid-side emission ($gCO_2e\,kWh^{-1}$)	424	293	218
		95% electricity decarbonization by 2050 (DEC50)	Grid emission factors: 'mid-case with 95% decarbonization by 2050' in NREL's Cambium model[36]		424	251	70
		95% electricity decarbonization by 2035 (DEC35)	Grid emission factors: 'Mid-case with 95% decarbonization by 2035' in NREL's Cambium model[36]		424	82	68
Economic scenarios	For BESs, three price scenarios are considered for charging cost and battery system cost.	Optimistic (OPT)	Charging cost: 'low zero-carbon technology' scenario for transportation sector in Annual Energy Outlook 2023[52] Battery system projection: 'conservative' scenario in NREL's ATB 2022[42]	Battery system cost (US$ kWh^{-1})	378	174	139
		Intermediate (INT)	Charging cost: 'reference' scenario for transportation sector in Annual Energy Outlook 2023[52] Battery system projection: 'moderate' scenario in NREL's ATB 2022[42]		378	254	203
		Challenging (CHA)	Charging cost: 'high zero-carbon technology' case for transportation sector in Annual Energy Outlook 2023[52] Battery system projection: 'advanced' scenario in NREL's ATB 2022[42]		378	320	320

To assess decarbonization potential through vessel electrification under varied power system decarbonization scenarios, we assume three emission scenarios: business as usual (BAU), 95% electricity decarbonization by 2050 (DEC50) and 95% electricity decarbonization by 2035 (DEC35) based on scenarios in the National Renewable Energy Laboratory (NREL)'s Cambium model[36]. BAU assumes no new carbon policies after 2021. DEC50 is the base scenario used in economic analyses. DEC35 broadly aligns with the Biden–Harris administration goal to decarbonize the US power system by 2035[37]. Three additional economic scenarios—optimistic, intermediate and challenging—evaluate how electricity prices and battery costs affect BES economic feasibility.

emissions by 81% compared to ICEs in 2022. Whereas well-to-tank emissions show minimal differences among scenarios, decreasing carbon intensity across upstream inputs will lower well-to-tank emissions, leading to greater CO_2e reductions.

Economic feasibility of battery electric ships

To compare vessels retrofitted with battery electric systems to their ICE counterparts, we estimate a levelized cost of transportation (LCOT) in US$ km^{-1} that divides the annualized capital and operating costs of ICE and BES technologies by the annual distance travelled[25]. For ICE ships, the total cost includes ultra-low sulfur diesel fuel[39], the social cost of CO_2e emissions[40] and air pollution (NO_x and SO_x)[41]. For BESs, the total cost includes battery capital costs[42], operations and maintenance, charging infrastructure[43], CO_2e[40], air pollution[41] and the battery's net salvage value at end of life[44,45].

Regarding BES CO_2e emissions, no direct emissions occur during BES operation. BES CO_2e emissions arise from the processes involved in producing batteries for BESs, generating electricity used by BESs and producing fuel for electricity generation. Additionally, for determining BESs' air pollution, we included emissions of NO_x and SO_x from the direct combustion for generation of electricity that BESs consumed.

We estimate costs in 2022, 2035 and 2050 for each of the four BES capacity tiers under three grid emissions scenarios (BAU, DEC50 and DEC35) and three cost scenarios (optimistic, intermediate and challenging). Comprehensive explanations of cost calculations and individual scenarios are available in Methods and Supplementary Notes 5 and 6.

Figure 3a shows that most BESp99 are cost effective compared to ICEs in 2035, depending on cost and emission scenarios. 'Cost effective' means the cost of retrofitting an ICE vessel to BES is at or below parity with the LCOT of operating an equivalent ICE vessel. The ratio of cost-effective BESs to ICEs increases significantly when the capacity tier shifts from BESp100 to BESp99 due to smaller battery requirements. More BESs are cost effective in 2035 than in 2022 due to lower battery costs and higher CO_2e social costs, with 85% of BESp99 systems becoming cost effective under the DEC35 intermediate scenario. Figure 3b shows that despite projected BES cost reductions of up to 63%[42], BESs always show higher direct costs compared to ICEs when environmental costs are not considered.

It is important to note that BESs may not be financially attractive to vessel owners when only considering direct costs. But if external costs associated with GHG emissions are included, such as under a policy mandating carbon trading or a carbon tax, investing in BESs becomes beneficial. The pricing of GHG allowances varies by jurisdiction. For example, in the European Union's Emission Trading System, the cost was US$93 t^{-1} CO_2e in 2023 and projected to reach US$157 t^{-1} CO_2e in 2030[46]. In the United States, Washington state had a cost of US$55 t^{-1} CO_2e in 2023, the highest in the nation[47–49]. Recognizing the inherent uncertainty of future carbon prices, we adopted the US Environmental Protection Agency's projection of US$250 t^{-1} CO_2e for 2035. Supplementary Fig. 42 shows that in 2035, carbon costs of US$250^{-1} t CO_2e and a more conservative US$157 t^{-1} CO_2e would enable 80% and 60%, respectively, of BESp99 vessels to achieve cost parity.

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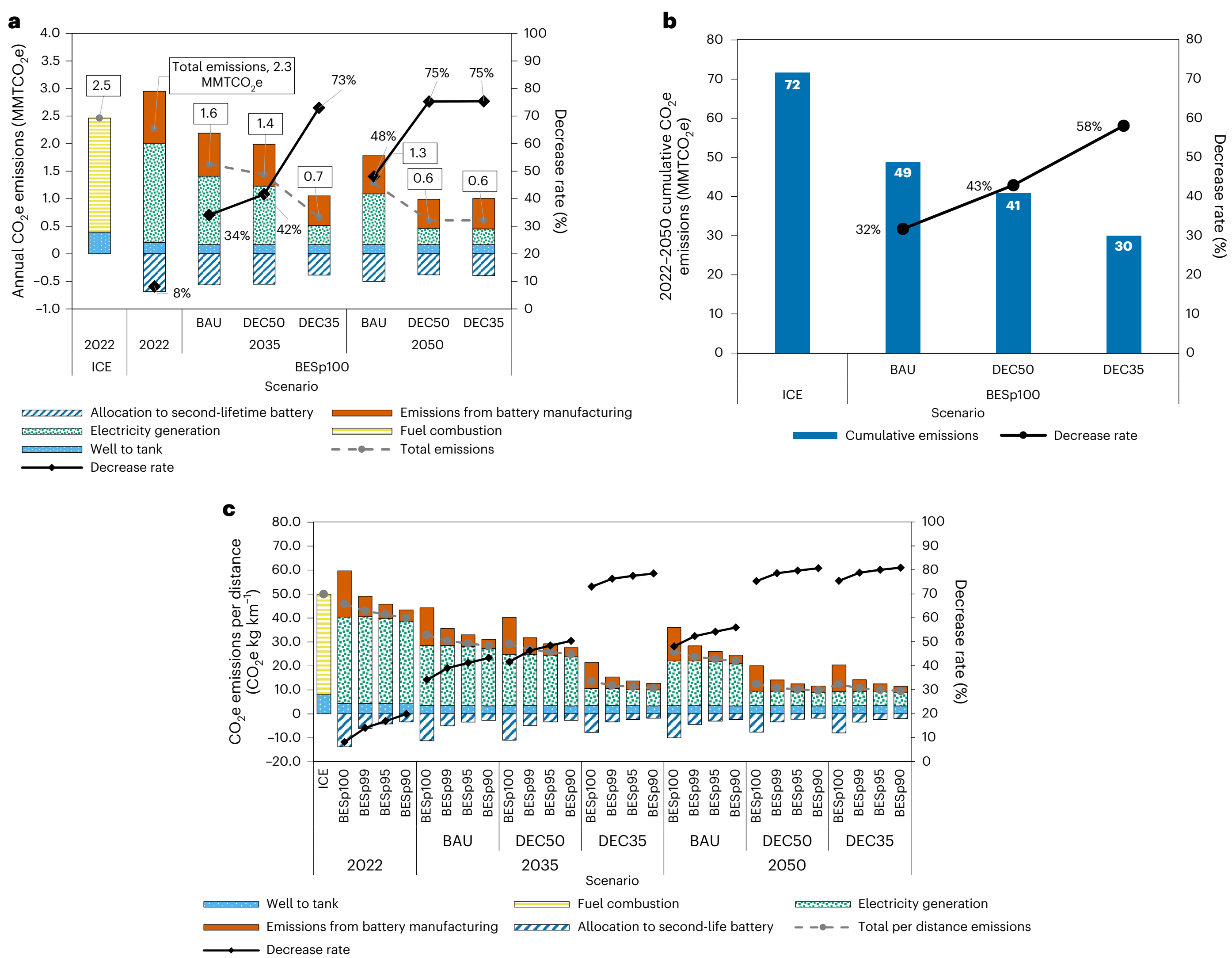

Fig. 2 | CO_2e emissions from ICEs and BESs. Each of BESp100, BESp99, BESp95 and BESp90 represents a group of BESs, indicating that the BESs cover only the respective percentage of ICEs' historical trips. **a**, Annual CO_2e emissions from ICEs and BESs. Under the BAU scenario, BES emissions in 2022 are only 8% lower than those of ICE ships. However, BES emissions decrease significantly over time, falling to 1.6 MMTCO$_2$e in 2035 and 1.3 MMTCO$_2$e in 2050 under BAU. Under the DEC50 scenario, BES emissions fall to 1.4 MMTCO$_2$e in 2035 and 0.6 MMTCO$_2$e in 2050, corresponding to reductions of 42% and 75%, respectively, below 2022 levels. Under the DEC35 scenario, CO_2e emissions are projected to decrease significantly, indicating a 73% reduction by 2035 and a 75% reduction by 2050. **b**, Cumulative emissions reductions by emissions scenario between 2022 and 2050. Retrofitting to BES yields a minimum cumulative CO_2e reduction of 32% under the BAU scenario and a maximum reduction of up to 58% under the DEC35 scenario. **c**, Per-km CO_2e emissions from ICEs and BESs by capacity tier. As capacity tier decreases, per-km CO_2e emissions from BESs also decrease due to smaller batteries in lower-capacity-tier ships. Battery manufacturing emissions as a share of total BES CO_2e emissions decrease for lower-capacity tiers, with values of about 53%, 26%, 19% and 15% for capacity tiers BESp100, BESp99, BESp95 and BESp90, respectively, in 2035 under the DEC50 scenario.

Figure 4 illustrates the average LCOT breakdown under various scenarios. Figure 4a shows that LCOT parity of BESp99 with ICEs will occur in 2035. Average LCOT of ICEs shows an annual increase of 1%, whereas that of BESp99 decreases by 1.5%. For ICE vessels, most of the cost increase is driven by the social cost of CO_2e emissions. In contrast, for BESp99, cost decreases result from falling battery costs and reducing CO_2e social costs.

Figure 4b shows that BESp99 in passenger and tug (inland-push boats) categories have a lower average LCOT compared to ICEs in 2035. On the basis of ship-to-ship comparisons, roughly 90% of these BESp99 ships are cost effective compared to their ICE counterparts. Whereas tug (coastal-harbour) and tug (ATB) have higher average costs than ICEs, 76% and 44% of these ships, respectively, still reach or exceed cost parity with their ICE counterparts. Further discussion of each scenario appears in Supplementary Figs. 22–25.

Electricity requirements for BES charging in 150 major US ports

We estimate total annual electricity demand of the 2,722 ships in the AIS Analysed Subset to be 3.8 TWh. The electricity demand calculation for 2,722 ships incorporates historical activity data from 2021 for each vessel, encompassing parameters such as time, speed and location and integrates these with their respective vessel engine sizes. Because the combined gross tonnage of all 6,323 vessels in the Domestic Fleet is twice that of the AIS Analysed Subset, the Domestic Fleet's annual electricity demand is estimated at 7.7 TWh. Figure 5a shows the geospatial distribution of electricity requirements by state and port.

In Fig. 5b, tugboats exhibit the highest electricity requirements in every state, constituting 99.6% and 99.9% of total charging demand in Louisiana and Texas, respectively. In California, the demand for passenger ships is higher than in any other state, representing more

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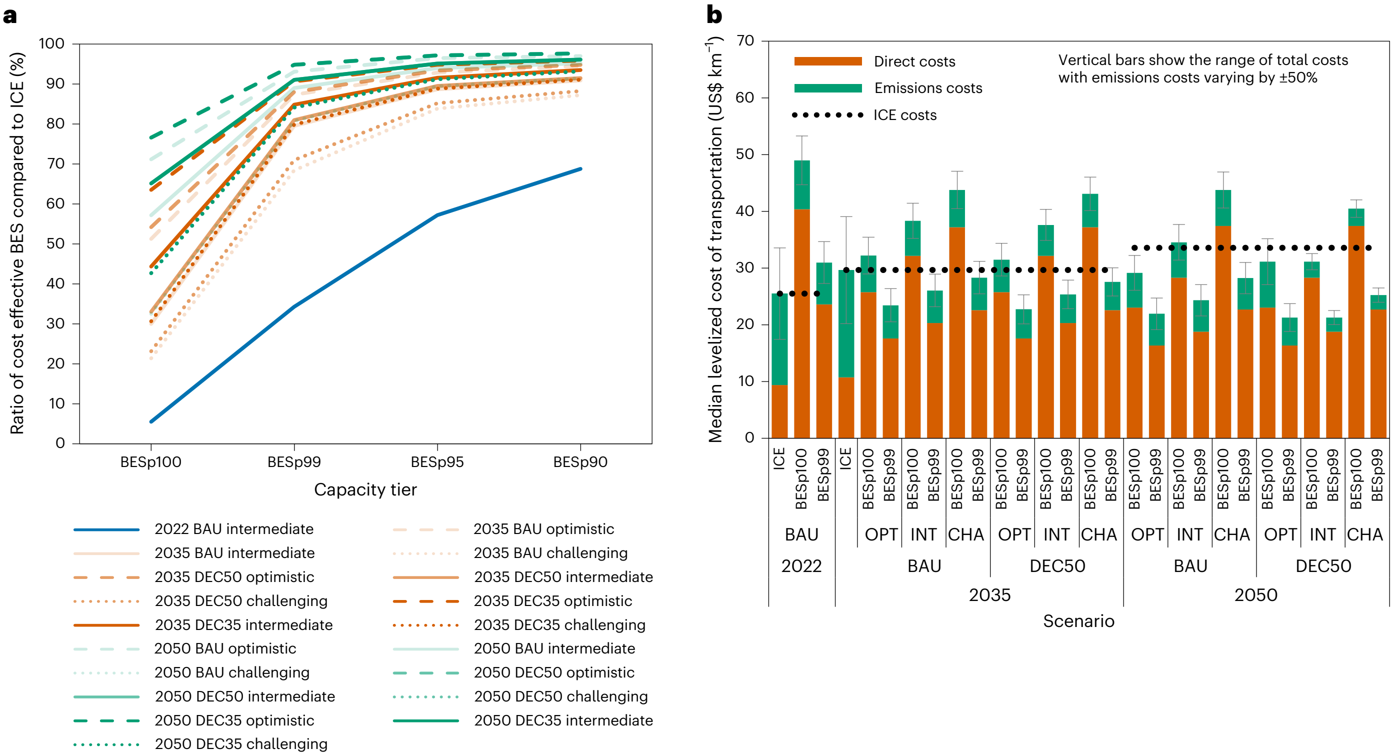

Fig. 3 | Cost effectiveness of BESs vs ICEs. We examine three years (2022, 2035 and 2050); four capacity tiers (BESp100, BESp99, BESp95 and BESp90); three emission scenarios (BAU, DEC50 and DEC35) and three cost scenarios (OPT, INT and CHA). The capacity tiers—BESp100, BESp99, BESp95 and BESp90—represent the percentage of ICEs' historical trips that the BES can serve. **a**, The ratio of cost-effective BESs compared to ICEs based on ship-to-ship comparisons of LCOT. As the capacity tier decreases, the ratio of cost-effective BESs increases: under the DEC50 INT scenario, the 2035 cost-effectiveness ratios are 33%, 81%, 90% and 91% for BESp100, BESp99, BESp95 and BESp90, respectively. Relative to INT cost scenarios, BES cost-effectiveness ratios increase by 7% in OPT scenarios and decrease by 8% in CHA scenarios on average; in DEC50 and DEC35 scenarios, these ratios increase by an average of 2% and 5%, respectively, compared to BAU. **b**, The median LCOT in each scenario. The dashed line depicts ICE LCOT for each year. Each error bar represents a range of 50–150% of emissions costs. By 2035, median ICE LCOT falls between BESp100 and BESp99.

than 30% of the total BES charging demand (Supplementary Fig. 2). The additional demand on the electric grid by state, plotted in black dots, suggests that increases due to BES charging would be manageable in terms of expanding supply at the state level, as electricity demand increases by less than 1% (0.1–0.8%) in the top ten states.

Figure 5c shows ports with disproportionately high charging needs. These findings underscore the critical need for concentrated power and energy infrastructure in select states and ports to effectively support vessel electrification (Supplementary Figs. 30–32). Battery electric tugboats require the largest portion of energy in all but one of the top 20 ports, indicating their role will be crucial in electrifying domestic maritime transportation.

Supplementary Fig. 43 indicates that a significant proportion of vessels (67% on average, 89% of passenger ships) would require charging infrastructure of 5 MW or less to support historical vessel activities. This result aligns with emerging charging infrastructure developments such as the CharIN Megawatt Charging System under development by the ISO and other entities in Europe and the United States, which can potentially deliver up to 4.5 MW of power[50].

Discussion and conclusions

We conducted exhaustive data analysis to evaluate the potential for electrifying US maritime vessels, but further research is needed to deepen understanding of other aspects of BES potential. We offer the following caveats about our research to clarify our approach and support future efforts.

Our DEC50 scenario aims for a 95% reduction in power sector CO_2e emissions by 2050[36]. Our DEC35 scenario accelerates this timeframe by 15 years, broadly aligning with the Biden–Harris administration's goal to fully decarbonize the US power sector by 2035[1]. Our analysis shows that relative to the DEC50 scenario, the DEC35 scenario could reduce cumulative CO_2e emissions from domestic shipping by an additional 15% through 2050 and lower the LCOT of battery electric ships by 10% in 2035.

The social cost of carbon has varied across different US administrations: it was 43 US\$ t^{-1} CO_2e during the Obama administration, reduced as low as US\$3 t^{-1} CO_2e under the Trump administration and officially estimated at US\$51 t^{-1} CO_2e by the Biden administration[51]. Here we use the most recent values from the US Environmental Protection Agency, which are US\$190 t^{-1} CO_2e in 2022, US\$250 t^{-1} CO_2e in 2035 and US\$310 t^{-1} CO_2e in 2050[40]. Because the economic value of BESs is highly dependent on the social cost of CO_2e, establishing a consistent, predictable value is essential for enabling stakeholders to make long-term investment decisions.

Our LCOT model is largely driven by fuel prices and charging costs, which can be highly uncertain and significantly impact LCOT results. For example, the Annual Energy Outlook 2023[52] projected diesel costs in 2050 to range from a 31% decrease to a 58% increase, compared to the Reference scenario. For ICE ships, fuel costs in 2050 account for 30% of the total LCOT, indicating LCOT could decrease by 10% or increase by 18% depending on the cost scenario. Additionally, in a cost scenario where diesel prices increase by 58%, electricity costs also rise by 8%, causing the LCOT for BESs to increase by 3%, given that 36% of BESs' LCOT is attributed to charging costs. Future research should update price projections to reduce uncertainties in LCOT modelling.

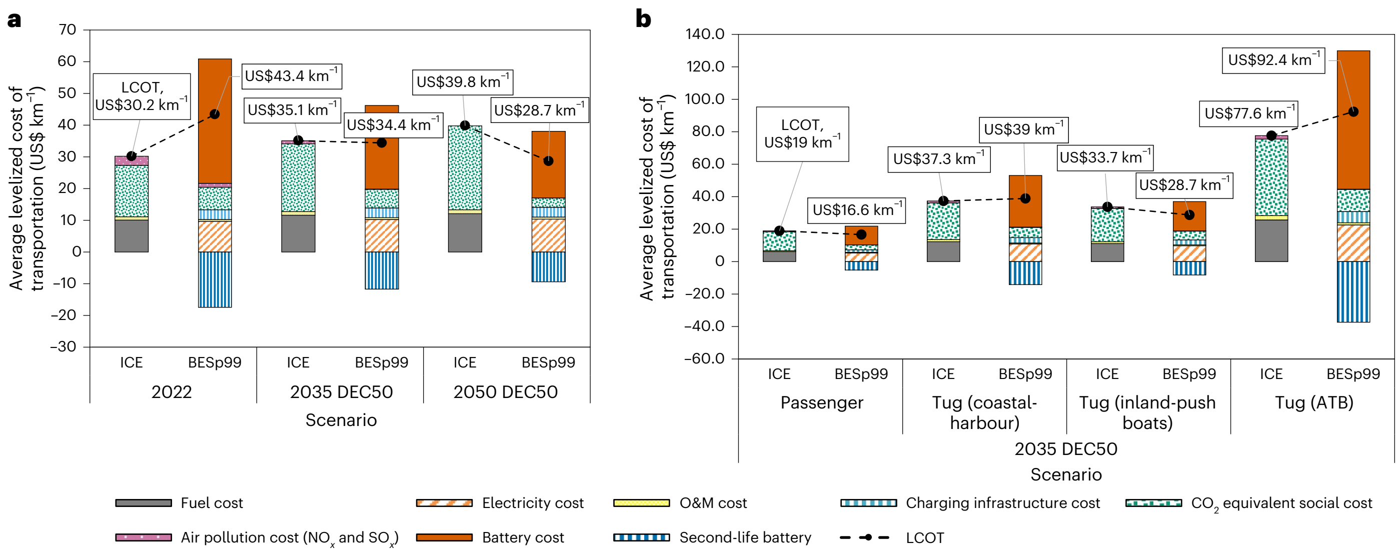

Fig. 4 | Cost breakdown of average LCOT for ICEs and BESs under DEC50 emissions scenario. Stacked bar graphs display each cost component. Because the salvage value of second-life batteries is negative, the black dots, which represent total cost, are located below the top of the bar graph. BESp99 represents the BESs capable of covering 99% of ICEs' historical trips. **a**, Compares the LCOT of ICE and BESp99 in 2022, 2035 and 2050 under the INT cost scenario. The results show that reimbursements from second-life batteries substantially alleviate the burden of battery cost, making BESs more economically viable where second-life battery values account for approximately 42–46% of battery system costs. **b**, Illustrates LCOT of ICE and BESp99 by ship type in 2035 under the INT cost scenario. Average LCOT of BESs is lower than that of ICEs for passenger ships and tug (inland-push boats). Comparing BESp99s to ICEs for each ship type, ATB tug and coastal-harbour tug showed 19% and 5% increases in LCOT, respectively. On the other hand, passenger and tug (inland-push boats) experienced reductions of 12% and 15%, respectively, which fell below the LCOT of ICE ships. O&M cost, operation and maintenance cost.

This study focuses on comparing the retention of ICEs versus retrofitting to BESs. Assuming a 60-year lifespan for these ships and given that the average age of ships in our study is 37 years, many currently operating ICEs will still be operational by 2050, as will new ICE ships purchased in the near future. On the basis of a 60-year lifespan, about 30% of US domestic ships will have more than 12 years remaining in their operational life by 2050. With average battery life estimated in this study at 12 years, 30% of existing and newly purchased ICE ships will probably be candidates for battery retrofitting in 2050. Therefore, it is important to assess the feasibility of retrofitting in that timeframe and the nearer term. For the purchasing decision between new ICE ships versus new BES ships when old ICE ships are retired, comparing the total cost of ownership—including both capital and operational expenditures—would be useful. This aspect, however, is not covered in the current study.

Going forward, further research in the following areas will improve understanding of the opportunities related to battery electric shipping.

First, shipping electrification opportunities should be prioritized based not only on cost-effectiveness comparisons between BESs and ICEs, but also on locations with renewable-based electricity grids. The carbon intensity of the electrical grid and charging costs vary depending on the time and location where BESs are charged. Whereas we used the national average to calculate emissions, charging strategies could vary considerably based on regional grid carbon intensity and local utility tariffs. In regions where shipping electrification may not lower GHG emissions, the installation of port microgrids using renewable energy generation could help accelerate regional decarbonization[6]. Second, future studies should examine the feasibility of using multiple smaller BESs as a cost-effective alternative to replacing a single large ICE vessel. This approach aligns with the business model of Fleetzero, a start-up company[53]. Third, costly energy infrastructure requirements can be mitigated through the advanced scheduling of ship activity and charging and the adoption of swap-based battery charging. Fourth, air pollution at ports can be alleviated with the introduction of battery electric ships. Because near-port communities tend to be disadvantaged[54], electrification would greatly reduce the disproportionate burden air pollution currently imposes on low socio-economic status and high minority populations[55]. Finally, ship activity can fluctuate year to year due to changes in shipments and economic conditions[56]. Our key findings, such as energy requirements for the grid, are based on one year of activity data and could change with different shipping activity levels. Similarly, the economic feasibility of retrofitting individual ships could vary annually based on each ship's operational activities.

We assessed the battery electrification potential of US domestic ships, in terms of their emissions and economic and physical feasibility, by using high-resolution temporal and spatial data along with ship engineering specifications. Our study reveals that the battery electrification of 6,323 vessels can reduce maritime CO_2e emissions as follows under each scenario. Under an ICE scenario, annual CO_2e emissions will be 2.5 MMTCO_2e, representing 11% of total GHG emissions from the US maritime sector; cumulative CO_2e emissions between 2022 and 2050 will be 72 MMTCO_2e. Under a BAU scenario, annual CO_2e emissions will be reduced by 34% in 2035 (1.6 MMTCO_2e) and 48% in 2050 (1.3 MMTCO_2e). Under a DEC50 scenario, annual CO_2e emissions will be reduced by 42% in 2035 (1.4 MMTCO_2e) and 75% in 2050 (0.6 MMTCO_2e). Under a DEC35 scenario, annual CO_2e emissions will be reduced by 73% in 2035 (0.7 MMTCO_2e) and cumulative CO_2e emissions between 2022 and 2050 will decrease by 58% (30 MMTCO_2e).

Previously, the expectation that battery electric ships would serve 100% of historical trips may have led to underestimations of their feasibility. In this analysis, we categorize BES capacity tiers based on the percentage of historical ICE trips a BES can perform. This allowed us to examine trade-offs in emissions and costs resulting from smaller battery requirements in lower-capacity tiers. As BES capacity tiers decrease and required battery sizes become smaller, cost advantages occur but the number of unserved trips increases. Using a BESp99 with high utilization rates as a reference for comparison, we observe that in 2022, only 34% of BESs are cost effective; in 2035, this percentage increases to 68–88%, depending on the scenario. Smaller, modular vessel design is key to enabling cost-effective battery retrofits.

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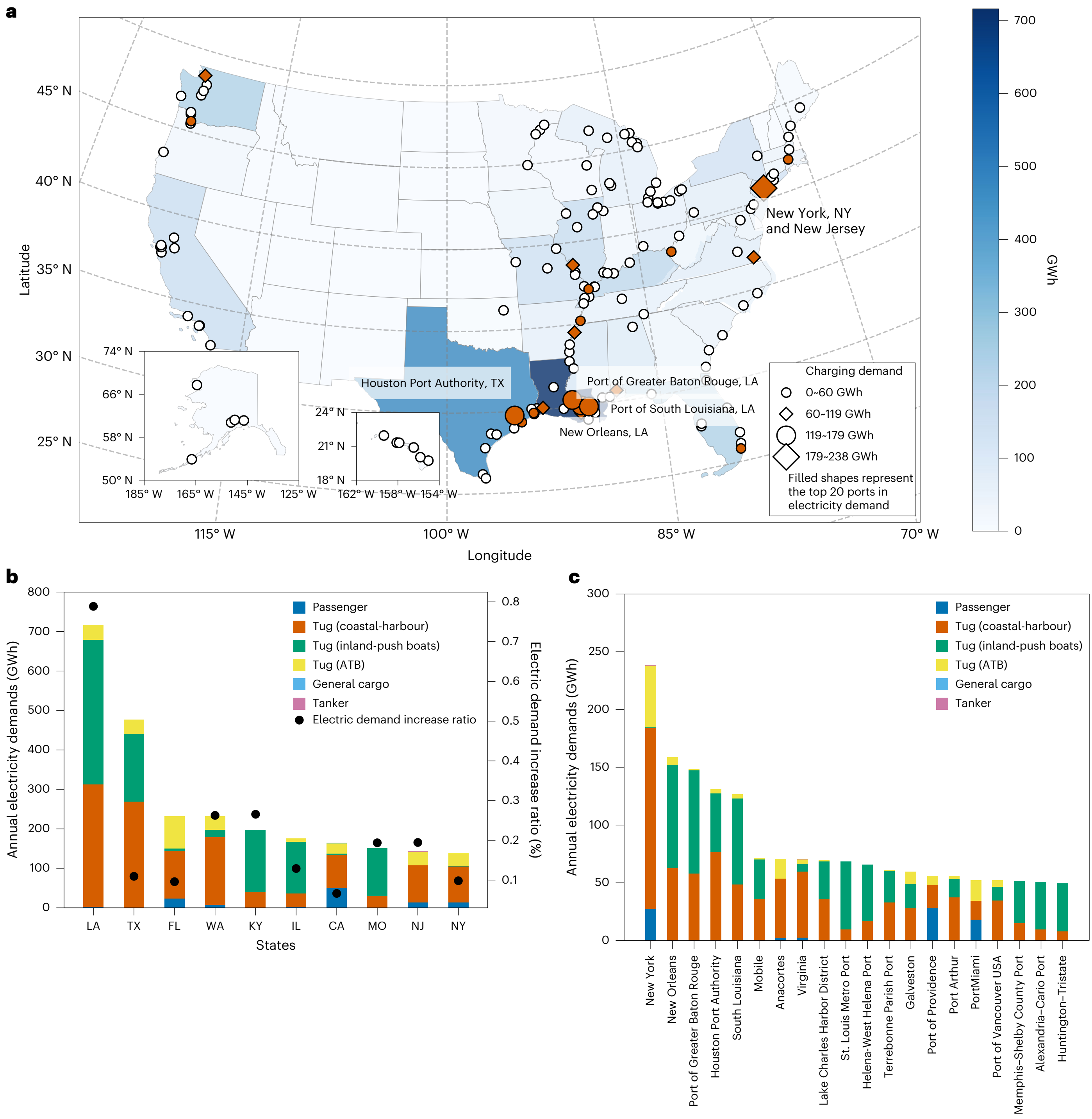

Fig. 5 | Annual electricity demand for BESs charging in the United States. **a**, Illustrates the electricity demand by state and port for BESp100, which covers all historical trips by ICEs, in the AIS Analysed Subset. The top 20 ports, coloured in red, collectively account for 46% of overall electricity demand at ports. **b**, Annual electricity demand by state and ship type for BESp100 in the AIS Analysed Subset. **c**, Annual electricity demand by port and ship type for BESp100 in the AIS Analysed Subset. Three of five ports with the highest electricity demand are in Louisiana. Among all 150 ports analysed, the Port of New York and New Jersey has the greatest electricity demand, at 238 gigawatt hours (GWh). Basemap in **a** from the US Census Bureau[64].

Incorporating emissions costs and the second-life value of batteries significantly enhances BES cost effectiveness.

Environmental costs must be incorporated for comparisons of ICEs and BESs to be accurate. Certain locations may exhibit much higher BES cost-effectiveness ratios, for example, where grid-supplied electricity is cleaner or where vessels have a more concentrated distribution of shorter trips. Such locations should be prioritized for battery electric shipping.

Large-scale BES implementation will require substantial investments in power infrastructure at ports, but we find that annual charging demands will probably be concentrated at just 20 of 150 major ports nationwide. Renewable-energy-based microgrids can meet

BES charging requirements while also reducing their lifetime GHG emissions[57].

In conclusion, this study examines the potential for electrifying US domestic shipping and its associated benefits. Further research is recommended to explore operational approaches for effectively managing the most energy-demanding trips, to develop microgrid plans for ports and to identify optimal locations based on specific vessel needs and local grid emissions.

Methods

Scope and data

We utilized three types of data to analyse ship activities: (1) stock and technical specifications of vessels, (2) AIS vessel location data and (3) port location data.

Ships in scope

Vessel stock and specification data were integrated from three data sources: US Coast Guard[27], US Army Corps of Engineers[28] and IHS Markit[29]. Ships considered in this study encompass six ship types including tankers, general cargo and passenger ships and three types of tug: coastal-harbour tugs, inland-push boat tugs and ATB tugs. Ship type mapping from initial data sources is available in Supplementary Tables 1 and 2, as is the detailed procedure for integrating the ship list. Supplementary Table 3 shows number of ships by the source of ship data. From this point forward, the term 'Integrated Ship Database' indicates the comprehensive list of 11,687 ships. 'Domestic Fleet' is used to designate the 6,323 ships that have a gross tonnage between 50 and 1,000, where the gross tonnage is a nonlinear measurement of a ship's internal volumes, derived from its volume rather than its weight.

Supplementary Fig. 33 illustrates the distribution of the AIS Analysed Subset by ship type. Among these ships, tug (coastal-harbour) comprises the majority with 1,395 ships (51.2%), followed by tug (inland-push boats) with 935 ships (34.3%) and passenger ships with 306 ships (11.2%). The three types of tug combined comprise 2,410 ships or 88.5% of the total. Apart from tugs and passenger ships, only six ships were selected, including two general cargoes and four tankers.

Supplementary Table 4 displays the average gross tonnage, main engine capacity and travel distance of vessels included in the AIS Analysed Subset. General cargo and tanker vessels were excluded from the table because the relevant subset, 50–1,000 gross tonnage, contains smaller-than-average ships for their type and is therefore not representative of those vessels.

AIS data

AIS data refer to the activity information transmitted by ships and received by shore stations. The dataset includes details such as the ship's unique identifier (that is, name, Maritime Mobile Service Identity (MMSI) and IMO number), location (that is, latitude and longitude), speed over ground (SOG), heading and other navigational information. The US Bureau of Ocean Energy Management and National Oceanic and Atmospheric Administration provide a publicly available historical AIS data pool within US territory[30]. This dataset allows us to analyse historical ship activities, including trip routes, ports visited and speed and to estimate electric power consumption and emissions during operations. To utilize the data, an extraction, data cleaning and transformation process is required, which is detailed in Supplementary Note 2.

On the basis of the historical AIS data for each ship, annual travel distance is calculated as presented in Supplementary Fig. 34. The bar graph shows the count of ships according to annual travel distance in km (left axis), and each line demonstrates the proportion of the count of ships by each type. Passenger ships tend to have shorter travel distances than other vessel types. In contrast, ATB tugs clearly tend to operate over longer distances. Overall, 90% of vessels travel less than 33,000 km, whereas for ATB vessels, more than 11% travel distances exceeding 60,000 km. Annual travel distance is used to calculate the LCOT in US\$ km^{-1} for each ship type.

Port data with coordinates

Port data include the name, state and coordinates of the top 150 US ports, based on total annual tonnage in 2020[58]. Total annual tonnage includes both domestic and foreign waterborne trade. Supplementary Fig. 35 shows locations of the 150 ports, along with their volumes of domestic commodities.

Estimating ship electrification potential

To assess which domestic vessels could be feasibly electrified, we developed an analysis tool that integrates battery system sizing, charging scheduling, associated electricity and cost requirements and lifetime GHG emissions. We used object-oriented programming in Python, which makes the analysis tool highly adjustable and flexible in accommodating various ship and port datasets.

Supplementary Fig. 44 depicts the four stages of workflow in this analysis, each of which is described in detail in the following subsections. First, we developed methods to estimate necessary battery sizing given certain specifications and operating conditions. Then, we integrated data on vessel specifications and operations to estimate energy requirements for each trip. Next, we aggregated these energy requirements in the appropriate locations to estimate grid infrastructure required to charge the requisite number of BES vessels. Finally, we conducted a life-cycle analysis (LCA) to estimate overall GHG emissions associated with BES vessels.

Supplementary Fig. 37 outlines the design of the programme, MariBES, used in this study. MariBES' adaptability to diverse ship ranges and port scopes allows it to explore electrification options in various maritime contexts and provide valuable insights for electrification planning.

Power system topology and power demand

BESs in need of charging get power from charging stations in ports. As the power supplied from the grid is in a.c. power, it is assumed that a shoreside a.c./d.c. converter is employed to convert the a.c. power into d.c. power for the BES. Supplementary Figs. 10 and 11 present a single-line diagram of the BES system and the shore power connection based on the battery propulsion for an all-electric vessel[59] and the single-line diagram of MF Ampere, an electric car ferry[18].

The first step in assessing the electrification potential of a ship involves calculating its power demand ($P^{\mathrm{ICE,D}}_{\mathrm{v,t}}$). Onboard energy consumption consists of two main components: propulsion demand ($P^{\mathrm{ME}}_{\mathrm{v,t}}$) and auxiliary demand ($P^{\mathrm{AE}}_{\mathrm{v,t}}$). The main engine provides propulsion energy, whereas the auxiliary engine supplies power for onboard electrical demand. To estimate the propulsion energy, the admiralty formula is widely used depending on the speed of the ship ($\mathrm{SOG}_{\mathrm{v,t}}$):

$$P^{\mathrm{ICE,D}}_{\mathrm{v,t}} = P^{\mathrm{ME}}_{\mathrm{v,t}} + P^{\mathrm{AE}}_{\mathrm{v,t}} \quad (1)$$

$$P^{\mathrm{ME}}_{\mathrm{v,t}} = \mathrm{CAP}^{\mathrm{ME}}_{\mathrm{v}} \times \min\left\{\delta_{\mathrm{ST_v}} \times \left(\frac{\mathrm{SOG}_{\mathrm{v,t}}}{V^{\mathrm{ref}}_{\mathrm{v}}}\right)^{n} \times n_{\mathrm{w}}^{-1} \times n_{\mathrm{f}}^{-1} \times \mathrm{SF},\ \overline{\mathrm{LF}^{\mathrm{ME}}}\right\} \quad (2)$$

where $\mathrm{CAP}^{\mathrm{ME}}_{\mathrm{v}}$ is capacity of main engine; $\delta_{\mathrm{ST_v}}$ is speed-power correction factor; $V^{\mathrm{ref}}_{\mathrm{v}}$ is the reference speed of vessel; n_{w} is a weather modifier to capture rough weather, which is assumed as 0.909 and leads to 10% increased power demand; n_{f} is fouling modifier to capture hull and propeller fouling, which is assumed as 0.917; n is a speed ratio exponent, representing the power correction factor for different speeds, which is assumed as 3; and SF is a safety factor accounting for any uncertainty in vessel total power demand, which is assumed as 1.05.

Auxiliary demand is estimated considering the operational mode ($\mathrm{OM}_{v,t}$) of the vessel at a given time, and is also dependent on the speed of the ship:

$$P^{\mathrm{AE}}_{v,t} = \mathrm{CAP}^{\mathrm{AE}}_{v} \times \mathrm{LF}^{\mathrm{AE}}_{v}\ (\mathrm{OM}_{v,t}, \mathrm{ST}_{v}) \times F^{\mathrm{AE}}_{v} \quad (3)$$

where $\mathrm{CAP}^{\mathrm{AE}}_{v}$ is the capacity of the auxiliary engine and $\mathrm{LF}^{\mathrm{AE}}_{v,t}$ is a function that returns the load factor of the auxiliary engine by operational mode $\mathrm{OM}_{v,t}$ and ship type ST_{v}. However, relying solely on the operational mode to compute the auxiliary demand led to excessive auxiliary power demand, especially when compared to the propulsion demand for certain ships. This situation often occurs when ships remain relatively stationary with the AIS system turned on, resulting in a consistent auxiliary demand. To address this, adjustment factor for auxiliary demand (F^{AE}_{v}) is introduced to incorporate the average ratio of energy consumption in the main engine to that in auxiliary engine, as presented in the IMO 4th Emission Study[12].

To calculate both propulsion and auxiliary demands for each ship, speed data from the AIS dataset is used. Further detailed procedures for calculating power demands are given in Supplementary Note 3.

Battery sizing based on trip energy demand

To determine BES battery size, we defined a 'trip' as a set of consecutive times the BES is moving and cannot be charged. Definitions and equations regarding the trip and battery size are also detailed in Supplementary Note 3. Supplementary Fig. 12 depicts example heatmaps of speed over time for passenger (Supplementary Fig. 12a) and tug (coastal-harbour) ships (Supplementary Fig. 12b). The passenger ship tends to exhibit more regular and shorter trip patterns, whereas the tug displays greater variability. These tendencies are not restricted to the examples presented here and can be observed within the same ship types, albeit to potentially varying extents across different vessels.

The energy demand for each trip ($E^{\mathrm{T}}_{v,tr}$) is the sum of the energy consumption during the time in $T_{v,tr}$:

$$E^{\mathrm{T}}_{v,tr} = \Sigma_{t\in T_{v,tr}} \left(P^{\mathrm{ME}}_{v,t} \times \eta^{-1}_{\mathrm{BP}} + P^{\mathrm{AE}}_{v,t} \times \eta^{-1}_{\mathrm{BA}}\right)/12 \quad (4)$$

where η_{BP} and η_{BA} are efficiencies from the battery to propulsion demand and auxiliary demand, respectively. The sum of power consumption in each hourly interval is divided into 12 because the power demand is estimated at 5-minute intervals, yielding 12 data points per hour to convert from kW to kWh.

To determine the battery size for each capacity tier (pX), we define a reference trip energy ($E^{\mathrm{ref}}_{v,pX}$) that is the Xth percentile trip energy among all trips:

$$E^{\mathrm{ref}}_{v,pX} = \mathrm{percentile}\left(\left[E^{\mathrm{T}}_{v,tr}\right], X\%\right) \quad (5)$$

The battery size vessel ($\mathrm{CAP}^{\mathrm{B}}_{v,pX}$) in each capacity tier is determined based on the reference trip energy ($E^{\mathrm{ref}}_{v,pX}$) that ensures even after degradation, BESpX can still meet the reference energy requirement:

$$\mathrm{CAP}^{\mathrm{B}}_{v,pX} = E^{\mathrm{ref}}_{v,pX} \times \mathrm{DOD}^{-1} \times \mathrm{SOH}^{-1}_{\mathrm{EoL}} \quad (6)$$

where DOD is depth of discharge which is assumed as 80% and $\mathrm{SOH}_{\mathrm{EoL}}$ is state of health of battery capacity at end of life, also assumed as 80%.

Supplementary Fig. 13 presents the trip energy distributions for two ship types: passenger (Supplementary Fig. 13a) and tug (coastal-harbour) (Supplementary Fig. 13b). Points p100, p99, p95 and p90 represent trip energy requirements at the 100th, 99th, 95th and 90th percentiles, respectively. Each ship type has a unique trip energy distribution, and in some cases unusually energy-demanding trips are observed. Excluding such trips and determining battery capacity based on less energy-intensive trips enables significant reductions in battery size. For example, in the two given examples, the trip energy ratio between the 99th percentile and the 100th percentile is 83% and 51%, respectively, reinforcing the idea that excluding certain trips could lead to a considerable reduction in battery size. These tendencies are not restricted to the examples presented here and can be observed within the same ship types, albeit to potentially varying extents across different vessels.

Supplementary Fig. 14 depicts the sum of energy in each interval based on the trip energy of the two vessels shown in Supplementary Fig. 13, along with the covered trip ratio and reference trip energy requirement. These examples show that lowering the capacity tier allows for a considerable reduction in battery size; the trade-off, however, is an increasing number of uncovered trips. These tendencies are not restricted to the examples presented here and can be observed within the same ship types, albeit to potentially varying extents across different vessels.

Charging scheduling

The need for efficient charging plays a crucial role in scheduling BES charging. Charging schedules ($\mathrm{ch}_{v,t}$) are determined based on an algorithmic approach, which charges the BES only when the state of charge (SOC) ($\mathrm{SOC}_{v,t}$) falls below a predetermined charging boundary, assumed at 70%. This ensures the BES is charged in a controlled manner and prevents the battery from being charged too frequently or unnecessarily. The SOC is bounded between 10% and 90% to prevent excessive charging or discharging that could lead to faster battery degradation. The SOC of a battery ($\mathrm{SOC}_{v,t}$) is calculated by adding the charging power ($\mathrm{ch}_{v,t}$) to the SOC from the preceding time slot and subtracting the discharging power ($\mathrm{dch}_{v,t}$):

$$\mathrm{SOC}_{v,t} = \mathrm{SOC}_{v,t-1} + (\mathrm{ch}_{v,t} \times \eta_{c} - \mathrm{dch}_{v,t}/\eta_{d})/12/\mathrm{CAP}^{\mathrm{B}}_{v,pX} \quad (7)$$

At the start of the simulation, battery SOC is set to 90%. While at port, if battery SOC is expected to fall below 70% after the subsequent trip, the battery is charged to 90%, its upper limit. This preemptive charging ensures the battery is sufficiently charged to meet the anticipated energy demands of the upcoming trip.

We assumed that charging is feasible only when the vessel is nearly stationary (below 0.5 knots) to align with historical vessel operation in battery scheduling. To estimate the charging power requirements of each vessel, we developed an optimal scheduling model aimed at minimizing the required maximum charging power while maintaining a higher SOC for batteries:

$$\min_{\mathrm{ch}_{v,t},\overline{\mathrm{ch}},\mathrm{SOC}_{v,t}} \overline{\mathrm{ch}_{v}} + \gamma \sum_{t} \mathrm{SOC}_{v,t} \quad (8\text{-}1)$$

s.t.

$$\mathrm{ch}_{v,t} \le \overline{\mathrm{ch}},\ \forall t \in T \quad (8\text{-}2)$$

$$\mathrm{ch}_{v,t} = 0 \text{ if } \mathrm{SOG}_{v,t} > 0.5\ \ \forall t \in T \quad (8\text{-}3)$$

$$\mathrm{SOC}_{v,t} = \mathrm{SOC}_{v,t-1} + (\mathrm{ch}_{v,t} \times \eta_{c} - \mathrm{DCH}_{v,t}/\eta_{d})/12/\mathrm{CAP}^{\mathrm{B}}_{v,pX}\ \ \forall t \in T \quad (8\text{-}4)$$

$$0.1 \le \mathrm{SOC}_{v,t} \le 0.9\ \forall t \in T \quad (8\text{-}5)$$

where $\overline{\mathrm{ch}_{v}}$ is maximum charging power for each vessel; γ is a parameter for higher SOC preference, which is set to 10^{-5}; charging power ($\mathrm{ch}_{v,t}$) is set to zero if the speed of the vessel is bigger than 0.5 knot; discharging power ($\mathrm{DCH}_{v,t}$) is given as an input for the optimization model; and SOC of the vessel is constrained to be between 10% and 90%.

To compare the power requirements at ports based on ships' different charging strategies, we compared two charging strategies:

historical activity-based charging and trip-based charging. The approach of each charging strategy is described in Supplementary Note 3 and the comparison of power requirements at ports is given in Supplementary Figs. 30–32.

Battery degradation and estimated lifetime

The performance of lithium-ion batteries tends to diminish over time due to degradation, which is attributed to factors such as a loss of cyclable lithium, a loss of electrode-active materials and an increase in cell resistance[60]. As a result of degradation, the energy that can be stored in the battery (that is, battery capacity) decreases. Battery degradation can be categorized into two types: calendar degradation and cycle degradation[61].

The economic value of a BES is significantly influenced by the lifetime of its battery. In this study, battery lifetimes were calculated, utilizing the battery degradation model outlined by Hoedemaker as illustrated in Supplementary Fig. 15. Detailed procedures used to calculate the lifetime of each battery are described in Supplementary Note 4[62]. Supplementary Fig. 41 shows the distribution of battery lifetimes across different capacity tiers. It reveals that the average lifetimes of batteries are 15.5 years for BESp100, 12 years for BESp99, 10.4 years for BESp95 and 10.0 years for BESp90, respectively.

Emissions

Emissions can be calculated using two approaches: the energy-based approach and the fuel-based approach[12]. This study uses the energy-based approach, which calculates emissions based on the output of each engine and its corresponding emission factor in grams per kilowatt hour ($g\,kWh^{-1}$). This facilitates the calculation of emissions from both ICEs and BESs using identical energy consumption data. Five types of air emission, CH_4, N_2O, CO_2, NO_x and SO_x, are estimated based on the energy consumption calculated in Supplementary Note 3. For GHG emissions, we applied their respective 100-year global warming potentials[63]. For CO_2e covering CH_4, N_2O and CO_2, an LCA-based approach is used. NO_x and SO_x emissions are counted at the ship's operational level (that is, fuel combustion).

We developed an LCA model to better account for supply chain energy demand and GHG emissions of battery electric shipping as shown in Supplementary Fig. 18. LCA is an analytical method that allows researchers to holistically assess the environmental impacts of a given product or process from raw materials extraction to final disposal (that is, 'cradle to grave'). More details regarding the LCA are given in Supplementary Note 8.

The emissions of an ICE ship, $EM^{ICE}_{e,v}$, are equal to the sum of the emissions from well to tank ($EM^{WtT}_{e,v,t}$) and engine combustion ($EM^{Cbst}_{e,v}$). On the other hand, emissions from BESs ($EM^{BES}_{e,v}$) are the sum of emissions from the well-to-tank phase ($EM^{WtT,BES}_{e,v,pX}$), power generators on the electricity grid ($EM^{Grid}_{e,v,pX,sc}$) and battery manufacturing ($EM^{Batt}_{e,v,pX,sc}$). Additionally, emissions credits from second-life battery (SLB) use after BES use ($EM^{SLB}_{e,v,pX,sc}$) are also considered because this study assumes end-of-life batteries can still be used for other purposes:

$$EM^{ICE}_{e,v} = EM^{WtT}_{e,v} + EM^{Cbst}_{e,v} \tag{9}$$

$$EM^{BES}_{e,v,pX,sc} = EM^{WtT,BES}_{e,v,pX} + EM^{Grid}_{e,v,pX,sc} + EM^{Batt}_{e,v,pX,sc} - EM^{SLB}_{e,v,pX,sc} \tag{10}$$

We estimated emissions under three emissions scenarios (BAU, DEC50 and DEC35) and three representative years (2022, 2035 and 2050). Further details of emissions calculation for both ICEs and BESs are in Supplementary Note 4.

Economic feasibility

To establish an economic comparison between continuing to utilize ICEs vs retrofitting them with BES technology, our analysis encompassed various factors, including operational costs and emissions costs related to ICE technology and battery system costs, operational costs and emissions costs specific to BES technology.

The costs of both ICEs and BESs include a significant share of operational costs; consequently, vessels covering greater distances have higher annual costs. However, the influence of historical travel distance on costs presents a challenge when interpreting the impact of cost parameters. To address this challenge, we calculate the LCOT in US\$ km^{-1}. This calculation involves dividing the total costs for both ICE and BES technologies by the travel distance. Lower LCOT values indicate that less expense is incurred to cover the same distance[25].

The LCOT of ICE ships ($LCOT^{ICE}_{v,sc}$), in US\$ km^{-1}, is total cost over travel distance (TD_v):

$$LCOT^{ICE}_{v,sc} = \left(C^{Fuel}_{v,sc} + C^{OM,ICE}_{v,sc} + C^{EM,ICE}_{v,sc}\right) \times TD_v^{-1} \tag{11}$$

where the total cost is the sum of fuel cost (C^{Fuel}_v) for the ICE ship's activity, operation and maintenance cost ($C^{OM,ICE}_{v,sc}$) and the cost of its emissions ($C^{EM,ICE}_{v,sc}$), including the social cost of CO_2e and damages from NO_x and SO_x air pollution.

On the other hand, the LCOT for the BES, $LCOT^{BES}_{v,pX,sc}$, is the total cost of the BES over its total travel distance ($TD_{v,pX}$):

$$LCOT^{BES}_{v,pX,sc} = \begin{pmatrix} C^{B}_{v,pX,sc} + C^{Ch}_{v,pX,sc} + C^{CI}_{v,pX,sc} + \\ C^{OM,BES}_{v,sc} + C^{Em,BES}_{v,pX,sc} - V^{SLB}_{v,pX,sc} \end{pmatrix} \times TD^{-1}_{v,pX} \tag{12}$$

where the total cost includes battery system cost ($C^{B}_{v,pX,sc}$), charging cost ($C^{Ch}_{v,pX,sc}$), charging infrastructure cost ($C^{CI}_{v,pX,sc}$) operation and maintenance cost ($C^{OM,BES}_{v,sc}$) and emissions cost ($C^{Em,BES}_{v,pX,sc}$), while reimbursing for SLB value ($V^{SLB}_{v,pX,sc}$). Detailed explanation of each cost component's calculation can be found in Supplementary Note 6.

Weight estimation

In the context of a physical feasibility assessment, we compared the weight of BESs and ICEs. To consider the entire weight of the vessels, we estimated their displacement based on gross tonnage as explained in Supplementary Note 1. As displacement includes the maximum fuel weight and engine weights, when estimating the weight of ICE ships corresponding to BESs with lower-capacity tiers, we subtracted the maximum fuel weight for their longest trip and added the fuel weight required to serve the reference trip of capacity tier *pX*. For BES ships, we excluded the estimated weight of the main and auxiliary engines and the maximum fuel weight from the displacement, while including the estimated weight of the battery system and electric motor.

Our focus is to emphasize the ship's structural capacity to accommodate the weight of the battery system. We also highlight the practicality of implementing a battery electric propulsion system, particularly in terms of its impact on the overall weight of the ship. Further description of estimating the weight of ICEs and BESs is presented in Supplementary Note 7.

Grid requirements for vessel electrification

The grid requirement for each port is calculated according to the process illustrated in Supplementary Fig. 39. The charging schedule for each vessel is determined in advance and then integrated into the nearest port. The energy requirements for each port are calculated by summing all charging requirements for all vessels over the year. The energy requirements for each port are then aggregated by state. If a port falls within multiple states, the requirements are divided among those states.

Data availability

We utilized three types of data to analyse ship activities: vessel stock and technical specifications, Automatic Identification System (AIS) vessel location data and port location data. The vessel stock and specification data were integrated from three data sources: the US Coast Guard, the US Army Corps of Engineers and IHS Markit. The US Coast Guard data are available at https://www.dco.uscg.mil/Our-Organization/Assistant-Commandant-for-Prevention-Policy-CG-5P/Commercial-Regulations-Standards-CG-5PS/Office-of-Standards-Evaluation-and-Development-CG-REG/Annual-Vessel-Statistics/ (2021). The US Army Corps of Engineers data are available at https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll2/id/7440 (2021). Vessel characteristics data are available from IHS Markit, though restrictions apply as these data are proprietary and require a user license to access. The port location data are available at https://geodata.bts.gov/datasets/usdot::principal-ports/about. IHS Markit can be contacted via https://ihsmarkit.com. The AIS data are available at https://marinecadastre.gov/ais/ (2022). Detailed descriptions of data and assumptions that support the findings of this study are presented in the Article, Methods and Supplementary Information. Source data are provided with this paper.

Code availability

The LCA tool is provided as Supplementary Software 1, available in the supplementary files. The mathematical description of the Maritime Battery Electrification Simulator (MariBES), including the objective functions, constraints and parameter assumptions, is documented in detail in the Article, Methods and Supplementary Information. Running the full code requires proprietary third-party data from IHS Markit as user licences are required to access the underlying data (as noted in the data availability statement). The source code is available under Maritime Battery Electrification Simulator (MariBES) v1 Copyright (c) 2024, The Regents of the University of California, through Lawrence Berkeley National Laboratory. Inquiries can be directed to the corresponding author or to IPO@lbl.gov.

References

1. *FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies* (White House, 2021); https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/
2. *Revised GHG Reduction Strategy for Global Shipping Adopted* (IMO, 2023); https://www.imo.org/en/MediaCentre/PressBriefings/pages/Revised-GHG-reduction-strategy-for-global-shipping-adopted-.aspx
3. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021* (US EPA, 2023); https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2021
4. Muratori, M. et al. *The U.S. National Blueprint for Transportation Decarbonization a Joint Strategy to Transform Transportation* (US Department of Energy, 2023); https://www.energy.gov/eere/us-national-blueprint-transportation-decarbonization-joint-strategy-transform-transportation
5. Gray, N., McDonagh, S., O'Shea, R., Smyth, B. & Murphy, J. D. Decarbonising ships, planes and trucks: an analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Adv. Appl. Energy* **1**, 100008 (2021).
6. Fang, S., Wang, Y., Gou, B. & Xu, Y. Toward future green maritime transportation: an overview of seaport microgrids and all-electric ships. *IEEE Trans. Veh. Technol.* **69**, 207–219 (2020).
7. Gordon, O. Lithium-ion battery pack prices rise for first time to an average of $151/kWh. *BloombergNEF* (6 December 2022); https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/
8. Stoikou, E. Battery prices are falling again as raw material costs drop. *Bloomberg* (26 November 2023); https://www.bloomberg.com/news/articles/2023-11-26/battery-prices-are-falling-again-as-raw-material-costs-drop
9. Liu, J. *Progress and Status of Battery500 Consortium Phase II* (PNNL, 2023); https://www1.eere.energy.gov/vehiclesandfuels/downloads/2023_AMR/bat317_liu_2023_o%20-%20jun%20liu.pdf
10. PROPEL-1K (ARPA-E, 2023); http://arpa-e.energy.gov/technologies/programs/propel-1k
11. Olmer, N., Comer, B., Roy, B., Mao, X. & Rutherford, D. *Greenhouse Gas Emissions from Global Shipping, 2013–2015* (ICCT, 2017); https://theicct.org/sites/default/files/publications/Global-shipping-GHG-emissions-2013-2015_ICCT-Report_17102017_vF.pdf
12. *Fourth IMO GHG Study 2020* (IMO, 2020); https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx
13. Moreno-Gutiérrez, J. et al. Methodologies for estimating shipping emissions and energy consumption: a comparative analysis of current methods. *Energy* **86**, 603–616 (2015).
14. Chen, S., Meng, Q., Jia, P. & Kuang, H. An operational-mode-based method for estimating ship emissions in port waters. *Transp. Res. Part D Transp. Environ.* **101**, 103080 (2021).
15. Weng, J., Shi, K., Gan, X., Li, G. & Huang, Z. Ship emission estimation with high spatial-temporal resolution in the Yangtze River estuary using AIS data. *J. Cleaner Prod.* **248**, 119297 (2020).
16. Meng, Z. & Comer, B. *Great Lakes-St. Lawrence Seaway Ship Emissions Inventory, 2019* (ICCT, 2022); https://theicct.org/publication/ships-great-lakes-emissions-mar22/
17. *Category 1 and 2 Commercial Marine Vessel 2020 Emissions Inventory* (ERG, 2022); https://gaftp.epa.gov/air/nei/2020/doc/supporting_data/nonpoint/CMV/2020NEI_C1C2_Documentation.pdf
18. Hansen, S. *MF Ampere, An Ocean of Opportunities* (Corvus Energy, 2016); https://corvusenergy.com/an-ocean-of-opportunities/
19. Richard. Japan's first battery ship by E-Oshima. *UPS Battery Center* (2019); https://www.upsbatterycenter.com/blog/japans-first-battery-ship-e-oshima/
20. Tunnicliffe, A. Ellen E-ferry: the world's glimpse of the future of ferries. *Ship Technology* (2019); https://www.ship-technology.com/features/ellen-e-ferry/
21. Crowley will build and operate the first fully electric U.S. tugboat. *Crowley* (2021); https://www.crowley.com/news-and-media/press-releases/ewolf-electric-tug/
22. Jeong, B. et al. Is electric battery propulsion for ships truly the lifecycle energy solution for marine environmental protection as a whole? *J. Cleaner Prod.* **355**, 131756 (2022).
23. Perčić, M., Vladimir, N. & Fan, A. Techno-economic assessment of alternative marine fuels for inland shipping in Croatia. *Renew. Sustain. Energy Rev.* **148**, 111363 (2021).
24. Perčić, M. et al. Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation. *Energy* **251**, 123895 (2022).
25. Kersey, J., Popovich, N. D. & Phadke, A. A. Rapid battery cost declines accelerate the prospects of all-electric interregional container shipping. *Nat. Energy* **7**, 664–674 (2022).
26. Feng, Y., Dai, L., Yue, M., Hu, H. & Fang, S. Assessing the decarbonization potential of electric ships for inland waterway freight transportation. *Transp. Res. Part D: Transp. Environ.* **129**, 104151 (2024).
27. *Annual Vessel Statistics* (US Coast Guard, 2021); https://www.dco.uscg.mil/Our-Organization/Assistant-Commandant-for-Prevention-Policy-CG-5P/Commercial-Regulations-Standards-CG-5PS/Office-of-Standards-Evaluation-and-Development-CG-REG/Annual-Vessel-Statistics/

28. *Vessel Company Summary and Vessel Characteristics in 2020* (US Army Corps of Engineers, 2021); https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll2/id/7440
29. *Lloyd's Register of Ships* (IHS Markit, 2021); https://www.spglobal.com/marketintelligence/en/mi/products/maritime-ships-register.html
30. *Vessel Traffic Data in 2021* (BOEM & NOAA, 2022); https://marinecadastre.gov/ais/
31. Gohlke, D., Zhou, Y., Wu, X. & Courtney, C. *Assessment of Light-Duty Plug-in Electric Vehicles in the United States, 2010–2021* (ANL, 2022); https://doi.org/10.2172/1898424
32. *Batteries on Board Ocean-Going Vessels* (MAN Energy Solutions, 2020); https://www.man-es.com/docs/default-source/marine/tools/batteries-on-board-ocean-going-vessels.pdf
33. Viswanathan, V. et al. The challenges and opportunities of battery-powered flight. *Nature* **601**, 519–525 (2022).
34. Wang, M. et al. *Summary of Expansions and Updates in GREET 2021* (ANL, 2021); https://doi.org/10.2172/1824336
35. Sathre, R., Scown, C. D., Kavvada, O. & Hendrickson, T. P. Energy and climate effects of second-life use of electric vehicle batteries in California through 2050. *J. Power Sources* **288**, 82–91 (2015).
36. Gagnon, P., Frazier, W., Cole, W. & Hale, E. *Cambium Documentation: Version 2021. Renewable Energy* (NREL, 2021); https://www.nrel.gov/docs/fy22osti/81611.pdf
37. *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* (U.S. Executive Office of the President, 2021); https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf
38. Cole, W. et al. *2021 Standard Scenarios Report: A U.S. Electricity Sector Outlook* (NREL, 2021); https://www.nrel.gov/docs/fy22osti/80641.pdf
39. *Nonroad Diesel Fuel Standards* (US EPA, 2022); https://www.epa.gov/diesel-fuel-standards/diesel-fuel-standards-and-rulemakings
40. *Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances* (US EPA, 2022); https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NCEE&dirEntryId=356357
41. Goodkind, A. L., Tessum, C. W., Coggins, J. S., Hill, J. D. & Marshall, J. D. Fine-scale damage estimates of particulate matter air pollution reveal opportunities for location-specific mitigation of emissions. *Proc. Natl Acad. Sci. USA* **116**, 8775–8780 (2019).
42. 2022 Annual Technology Baseline (NREL, 2022); https://atb.nrel.gov/electricity/2022/about
43. Popovich, N. D., Rajagopal, D., Tasar, E. & Phadke, A. Economic, environmental and grid-resilience benefits of converting diesel trains to battery-electric. *Nat. Energy* **6**, 1017–1025 (2021).
44. Shahjalal, M. et al. A review on second-life of Li-ion batteries: prospects, challenges, and issues. *Energy* **241**, 122881 (2022).
45. Martinez-Laserna, E. et al. Battery second life: hype, hope or reality? A critical review of the state of the art. *Renew. Sustain. Energy Rev.* **93**, 701–718 (2018).
46. Coker, E. EU ETS market outlook 2H 2023: cleared for the ascent. *BloombergNEF* (3 October 2023); https://about.bnef.com/blog/eu-ets-market-outlook-2h-2023-cleared-for-the-ascent/
47. Washington State's emissions allowance program held its first auctions in 2023. *American Journal of Transportation* (7 March 2024); https://www.ajot.com/news/washington-states-emissions-allowance-program-held-its-first-auctions-in-2023
48. AEGIS Hedging: California & Quebec Carbon Cap and Trade Report—September 2023. (accessed 19 March 2024); https://aegis-energy.com/insights/california-quebec-carbon-cap-and-trade-report-september-2023
49. Auction Results. *RGGI* https://www.rggi.org/auctions/auction-results (2024).
50. *Trends in Charging Infrastructure—Global EV Outlook 2023—Analysis* (IEA, 2023); https://www.iea.org/reports/global-ev-outlook-2023/trends-in-charging-infrastructure
51. Asdourian, E. & Wessel, D. What is the social cost of carbon? (Brookings, 2023); https://www.brookings.edu/articles/what-is-the-social-cost-of-carbon/
52. Annual Energy Outlook 2023. *U.S. Energy Information Administration* (US EIA, 2023); https://www.eia.gov/outlooks/aeo/index.php
53. Coldewey, D. Fleetzero looks to capsize the shipping world with electric vessels serving forgotten ports. *TechCrunch* (15 March 2022); https://techcrunch.com/2022/03/15/fleetzero-looks-to-capsize-the-shipping-world-with-electric-vessels-serving-forgotten-ports/
54. Greenberg, M. R. Ports and environmental justice in the United States: an exploratory statistical analysis. *Risk Anal.* **41**, 2112–2126 (2021).
55. Meng, Z. & Comer, B. *Electrifying Ports to Reduce Diesel Pollution from Ships and Trucks and Benefit Public Health: Case Studies of the Port of Seattle and the Port of New York and New Jersey* (ICCT, 2023); https://theicct.org/publication/marine-ports-electrification-feb23/
56. Bureau of Transportation Statistics *Freight Facts and Figures* (US DOT, 2022).
57. Misra, A., Venkataramani, G., Gowrishankar, S., Ayyasam, E. & Ramalingam, V. Renewable energy based smart microgrids—a pathway to green port development. *Strategic Plann. Energy Environ.* **37**, 17–32 (2017).
58. *Principal Ports* (US DOT, 2022); https://data-usdot.opendata.arcgis.com/datasets/usdot::principal-ports/about
59. *Study on Electrical Energy Storage for Ships* (EMSA, 2020); https://www.emsa.europa.eu/publications/item/3895-study-on-electrical-energy-storage-for-ships.html
60. Barré, A. et al. A review on lithium-ion battery ageing mechanisms and estimations for automotive applications. *J. Power Sources* **241**, 680–689 (2013).
61. Pelletier, S., Jabali, O., Laporte, G. & Veneroni, M. Battery degradation and behaviour for electric vehicles: review and numerical analyses of several models. *Transp. Res. Part B: Methodol.* **103**, 158–187 (2017).
62. ten Cate Hoedemaker, S. A. *An Assessment of the Relationship Between Battery Size, Charging Strategy and Battery Lifetime*. Master's Thesis, TU Delft (2017); https://repository.tudelft.nl/record/uuid:81aee798-31bc-4628-82a7-ab03937d1161
63. IPCC *Climate Change 2021: The Physical Science Basis* (Cambridge Univ. Press, 2023); https://doi.org/10.1017/9781009157896
64. *118th Congressional District Shapefiles* (US Census Bureau, 2023); https://www2.census.gov/geo/tiger/TIGER_RD18/LAYER/STATE/

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Author contributions

H.S.M. developed the methods for LCOT analysis and the simulation tool, conducted the analysis and wrote the paper. W.Y.P. contributed to the analysis tool, wrote sections of the paper and managed the project. T.H. conducted the LCA and wrote sections of the paper. A.P. conceived the idea and secured funding for the project. N.P conceived the idea, wrote sections of the paper and secured funding for the project.

Competing interests

The authors declare no competing interests.

Additional information

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