Sustainable Energy & Environmental Systems Department
Energy Analysis and Environmental Impacts Division
Lawrence Berkeley National Laboratory

Battery Electrification of U.S. Domestic Shipping

Exploring the Cost and Emissions Impacts, Feasibility, and Scalability of Battery-Electric Ships

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Abstract

The United States' ambitious greenhouse gas (GHG) emission reduction goals, along with targets set by the International Maritime Organization, create an important opportunity to explore battery-electric options for the shipping industry. Despite the current emphasis on alternative clean fuels, battery-electric solutions are considered behind other clean fuels due to questions about scaling up battery sizes. In light of this, we investigate the battery electrification potential of the U.S. domestic shipping industry by integrating existing ship databases and analyzing high-resolution temporal data on ship operations. Our analysis assesses both the technical and economic feasibility of electrified shipping, as well as its GHG emissions impacts. Our findings show that electrifying 6,323 domestic ships under 1,000 gross tonnage could significantly reduce GHG emissions, achieving a 34-42% decrease in 2035 below 2022 levels, while meeting 100% of historical trip demand. Moreover, under a scenario of 95% economy-wide decarbonization by 2050, GHG reductions from shipping can reach at least 75% below 2022 levels by mid-century. We estimate the annual electricity required by these ships to be 7.7 terawatt-hours (TWh), if all historical trips are fully served. Ports will require a substantial increase in charging infrastructure, but roughly 46% of electricity demand will be concentrated at only 20 of 150 major U.S. ports. Our analysis also shows that in 2035, 69-88% of the 6,323 battery-electric ships we analyzed could become more economically viable if they covered 99% of their historical trip demand, which would reduce the cost of electrifying these ships by 33%. Among ship types, passenger ships and inland/push-boat tugs are the most affordable to retrofit to battery-electric. Our research highlights both the significant electrification potential in the domestic shipping sector as well as its benefits: achieving substantial emission reductions, ensuring economic viability, and contributing to a more sustainable future for the U.S. maritime industry.

Executive Summary

The United States has set ambitious goals to reduce greenhouse gas (GHG) emissions, and these together with targets established by the International Maritime Organization create a significant opportunity to explore battery-electric options in the shipping industry. Although battery-electric ships (BESs) have received considerable attention, they are still considered behind other alternative clean fuels due to questions about scaling up battery sizes. To address these and related questions, our study analyzes the potential for battery electrification of the U.S. domestic shipping industry. By integrating multiple ship databases and examining high-resolution temporal data on ship operations, we evaluate the technical and economic feasibility of electrified shipping, as well as potential GHG emissions impacts, for 6,323 vessels. 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 analysis. This tool uses object-oriented programming in Python, which makes it highly adjustable and flexible in accommodating various ship and port datasets.

Our study is based on historical activity data from internal combustion engine (ICE) ships, which includes energy-intensive trips. Some such trips are not appropriate for battery-electric ships (BESs), as they would result in excessive battery requirements and costs. To address this concern, our study models BESs with four different capacity tiers – BESp100, BESp99, BESp95, and BESp90 – to represent the BESs serving different percentages of historical trips. The trips that BESs do not serve are referred to as "unserved trips" (i.e., for BESp95 ships, 5% of trips are unserved).

Battery capacity trend: Higher for tugs, lower for passenger ships.

Lower capacity tier BESs require smaller batteries, as those ships do not serve the most demanding trips and therefore need less energy. As ship size, expressed in gross tonnage (GT), increases, battery size also tends to increase, which is attributable to the larger main and auxiliary engines in bigger ships (Table EA-1). Articulated tug barges (ATBs) show the highest battery capacity requirements, followed by coastal-harbor tugs and inland and push tugs. Comparing ships within the same GT range, passenger ships generally require smaller battery capacities than any type of tug. As the BES capacity tier decreases, battery size also decreases significantly by an average of 67%, 86%, and 92%, respectively. Comparing BESp99, the most significant reduction in battery size is observed for passenger ships of 500-1000 GT, followed by inland and push tugs of 500-1000 GT. Conversely, ATBs with 500-1000 GT exhibit the smallest reduction trend, which is attributable to the unique trip characteristics of this ship type.

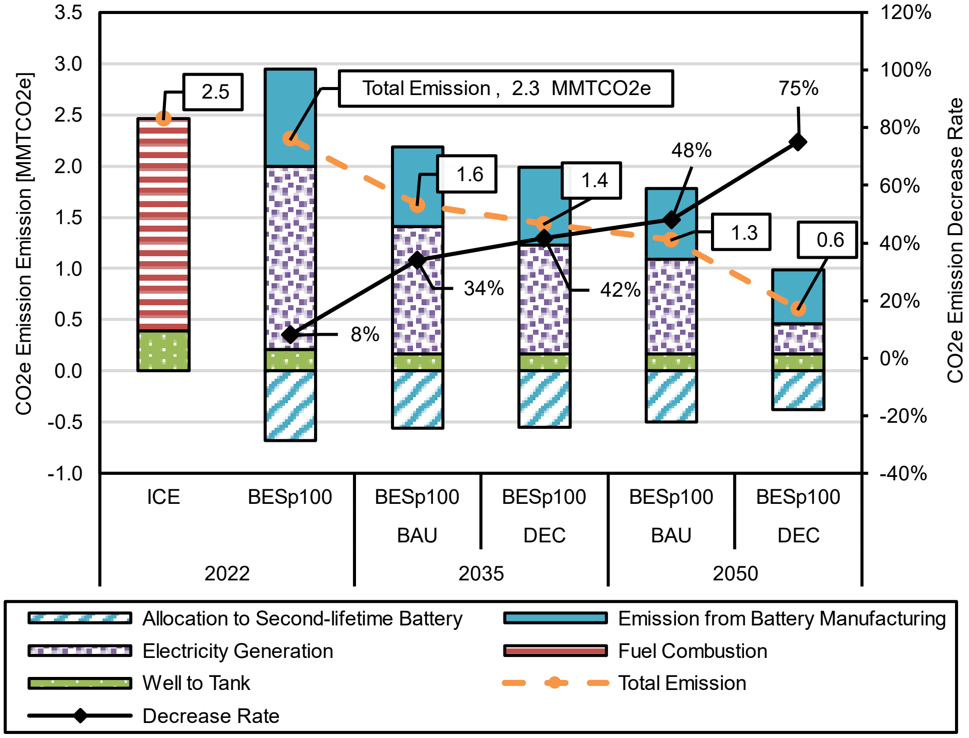
Table EA-1. Median Battery Capacity of BESs by Ship Size, Ship Type and Capacity Tier

	GT		Ship Count	Capacity Tier			
	Min	Max		BESp100	BESp99	BESp95	BESp90
				Median Battery Capacity [MWh] (Percentage Reduction Below BESp100)			
Passenger	50	500	272	6.2	1.5(77%)	0.8(87%)	0.6(90%)
	500	1000	34	62.9	11.1(82%)	5.0(92%)	3.5(94%)
Tug (Coastal-Harbor)	50	500	1311	30.2	8.2(73%)	2.9(91%)	1.4(95%)
	500	1000	84	98.5	35(64%)	13.3(87%)	5.8(94%)
Tug (Inland-Push Boats)	50	500	776	19	5.8(69%)	2.0(90%)	1.0(95%)
	500	1000	159	118.4	24.5(79%)	8.2(93%)	4.1(97%)
Tug (ATB)	50	500	30	165.2	61.7(63%)	28.5(83%)	11.4(93%)
	500	1000	50	289.6	124.7(57%)	53.0(82%)	26.8(91%)

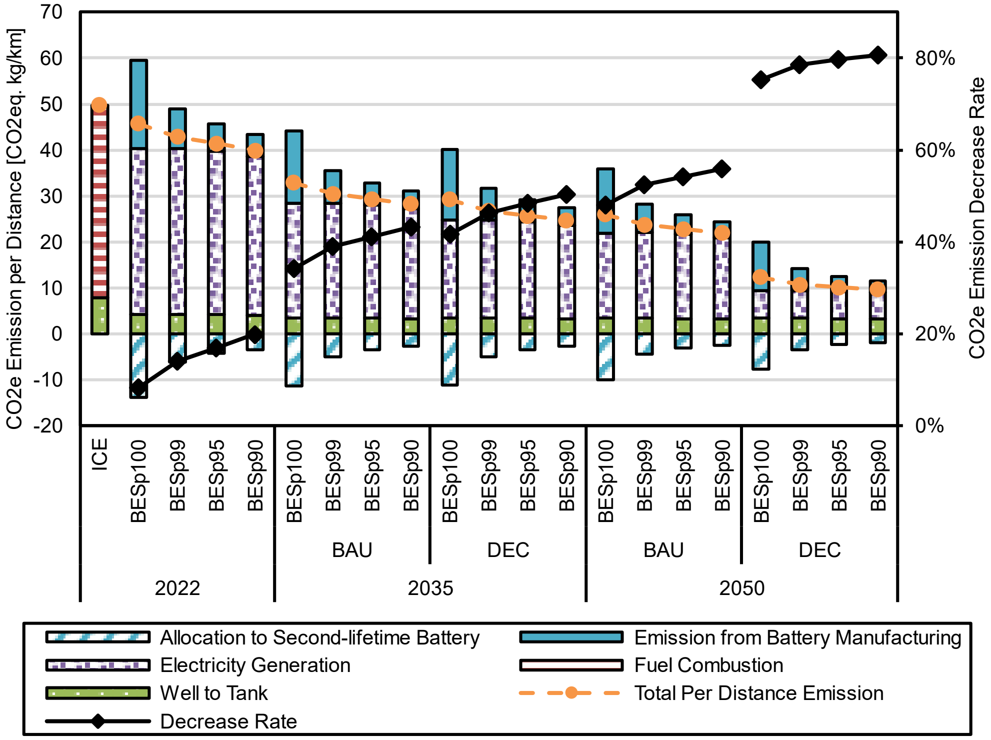
Battery electrification can reduce GHG emissions from U.S. shipping 35-42% by 2035 and 75% or more by 2050.

Figure EA-1 (a) presents emissions from ICE ships and BESp100 under two scenarios: business as usual (BAU) and 95% decarbonization by 2050 (DEC). Under the BAU scenario, BES emissions are initially only 8% lower than those from ICE ships. However, BES emissions decrease significantly over time, declining to 1.6 million metric tonnes of CO_2 equivalent (MMTCO$_2$e) in 2035 and 1.3 MMTCO$_2$e in 2050 under BAU. Under the DEC scenario, BES emissions decrease to 1.4 MMTCO$_2$e in 2035 and 0.6 MMTCO$_2$e in 2050 – substantially below BAU, with reductions of 42% and 75% in 2035 and 2050, respectively. Notably, the decrease in BES emissions seen in 2050 could be observed in 2035 or earlier given the Biden-Harris administration's goal to achieve 100% power system decarbonization by 2035 (USEOP, 2021). The differences in emissions between BAU and DEC scenarios highlight the importance of decarbonization efforts in the power sector and throughout the BES life cycle, including battery manufacturing.

Figure EA-1 (b) presents detailed CO_2 equivalent (CO_2e) emission results for BES based on their capacity tiers. Again, "BESpX" represents BES ships that perform only X% of total ICE trips. To make a fair comparison between ICE ships (which serve all trips) and BESs of lower capacity tiers (which do not), we analyzed per distance CO_2e emissions. This revealed a clear trend: as the capacity tier decreases, the CO_2e emissions from BESs also decrease. This is attributed to smaller battery sizes in lower capacity tier ships, leading to lower CO_2e emissions from battery manufacturing. The share that battery manufacturing contributes to total BES CO_2e emissions decreases for lower capacity tiers, with values of 56.8%, 28.1%, 20.3%, and 16.8% for capacity tiers p100, p99, p95, and p90, respectively. Notably, these values do not consider battery manufacturing emissions that could be allocated to second-life batteries. Making this allocation reduces battery manufacturing CO_2e emissions by 72% for all BESs, and reduces the contribution of battery manufacturing to total BES CO_2e emissions to 5-16%. Further, if unserved trips can be divided into smaller parts and serviced by ships with smaller batteries, CO_2e emissions will be significantly reduced (even though the split trips will emit twice as much CO_2e).



(a)



(b)

Figure EA-1. CO$_2$e Emissions from ICE Ships and BESs: (a) Annual Emissions, (b) Per Distance Emissions by Capacity Tier

Ports will require a substantial increase in charging infrastructure, but ~46% of total electricity demand will be concentrated at only 20 of 150 major U.S. ports.

Figure EA-2 shows the charging demand for BESs. Three of five U.S. ports with the highest electricity demand are in Louisiana, the highest-ranking state for BES electricity demand, where the 716 GWh needed for BES charging represents an 0.8% increase above statewide 2021 demand levels. Tugboats have the largest electricity requirements in nearly every state and constitute 99.6% and 99.9% of total BES charging demand in Louisiana and Texas, respectively. California is unique in that passenger ships represent the greatest demand, accounting for 30.6% of the total. The top 20 ports, colored red, collectively account for 46% of total nationwide electricity demand from BES charging, highlighting the disproportionately high needs of a relatively small number of ports.

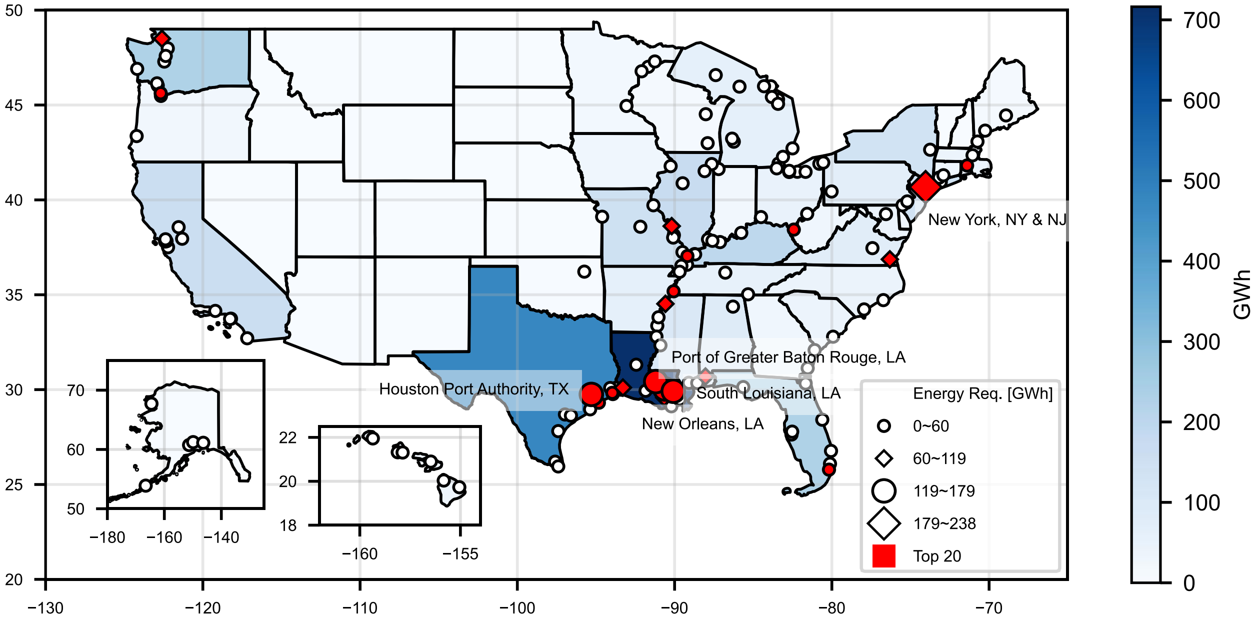


Figure EA-2. Electricity Requirements for BES Charging at U.S. Ports

In 2035, up to 88% of the 6,323 battery-electric ships analyzed could become more economically viable with up to 23% less cost.

Figure EA-3 presents the ratio of cost-effective BESs compared to ICE ships based on ship-to-ship cost comparisons. The analysis examines three years (2022, 2035, 2050), four capacity tiers (BESp100, BESp99, BESp95, and BESp90), two emission scenarios (BAU and DEC), and three cost scenarios (Optimistic, Intermediate, and Challenging). Detailed descriptions of each scenario can be found in sections 3.2 and 3.2.2. The results show that when the capacity tier decreases, the ratio of cost-effective BESs compared to ICEs increases; average cost-effectiveness ratios are 44%, 81%, 89%, and 92% for BESp100, BESp99, BESp95, and BESp90, respectively. Under Intermediate cost scenarios, these ratios increase by 7% in Optimistic scenarios and decrease by 8% in Challenging scenarios on average. In DEC scenarios, these ratios increase by an average of 2% compared to BAU. Moreover, as the year extends to 2035 and 2050, these ratios also increase – by an average of 28% and 38%, respectively. These results clearly indicate that changing the capacity tier has the most significant impact on BES cost-effectiveness, followed by extending the year, improving the cost scenario, and changing the emission scenario.

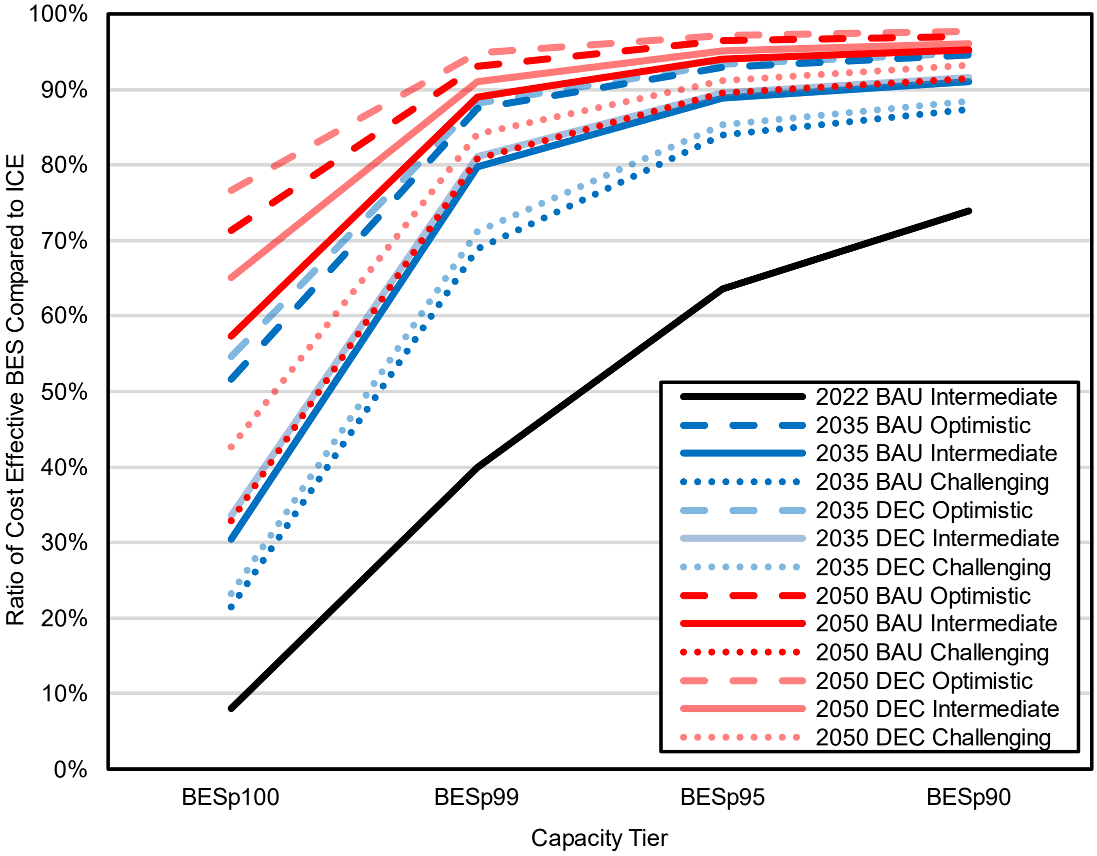


Figure EA-3. Ratio of Cost-effective BESs Compared to ICE Ships Under Intermediate, Optimistic, and Challenging Cost Scenarios, and BAU and DEC Emission Scenarios, by BES Capacity Tier (p100, p99, p95, and p90)

In 2035, lower capacity tier BES Passenger Ships and Inland-Push Boat Tugs are more economic than their ICE equivalents.

In Figure EA-4 (a), Levelized Cost of Transportation (LCOT), which measures total annualized cost per distance, is compared for ICEs and BESs of all capacity tiers. In 2035, all BES tiers except BESp100 have lower average LCOT than ICEs, whose average cost is $35 per kilometer (km), or $65 per nautical mile (nm). For ICE ships, emission costs account for 64% of total LCOT, of which 61% is attributed to CO_2e social cost and 3% to air pollution cost (NO_x and SO_x). Direct costs, excluding emissions, make up only 36% of the total LCOT for ICE ships in 2035.

Conversely, BESs exhibit a clear trend of decreasing LCOT as capacity tiers decrease. In 2035, the average LCOT of BESp100, BESp99, BESp95, and BESp90 are $55/km ($102/nm), $34/km ($64/nm), $29/km ($54/nm), and $28/km ($52/nm), respectively. This trend is primarily attributed to lower capacity tier BESs having smaller batteries. For example, the cost of a BESp100 battery system is $60/km

($111/nm), while the BESp90 battery costs only a quarter of that ($15/km, or $28/nm). Notably, 81% of ships analyzed are cost-effective to retrofit to BESp99 ships in 2035, based on ship-to-ship comparisons.

Figure EA-4 (b) looks specifically at the LCOT of different BESp99 ships versus their ICE counterparts in 2035. Average LCOT for BESp99 Tug (ATB) and Tug (Coastal-Harbor) ships is 19% and 4% higher than ICE ships, but for Passenger and Tug (Inland-Push Boats) ships it is 13% and 15% lower, respectively. Notably, many BESp99 ships are more cost-effective than ICEs. Based on ship-to-ship comparisons, 90%, 76%, 89%, and 45% of BESp99s in Passenger, Tug (Coastal-Harbor), Tug (Inland-Push Boats), and Tug (ATB) categories, respectively, are cost-effective compared to ICEs. Moreover, despite having higher average costs than ICEs, nearly half (45%) of Tug (ATB) BESp99s are cost-effective. This highlights the importance of direct, ship-to-ship comparisons in finding ships with higher BES potential.

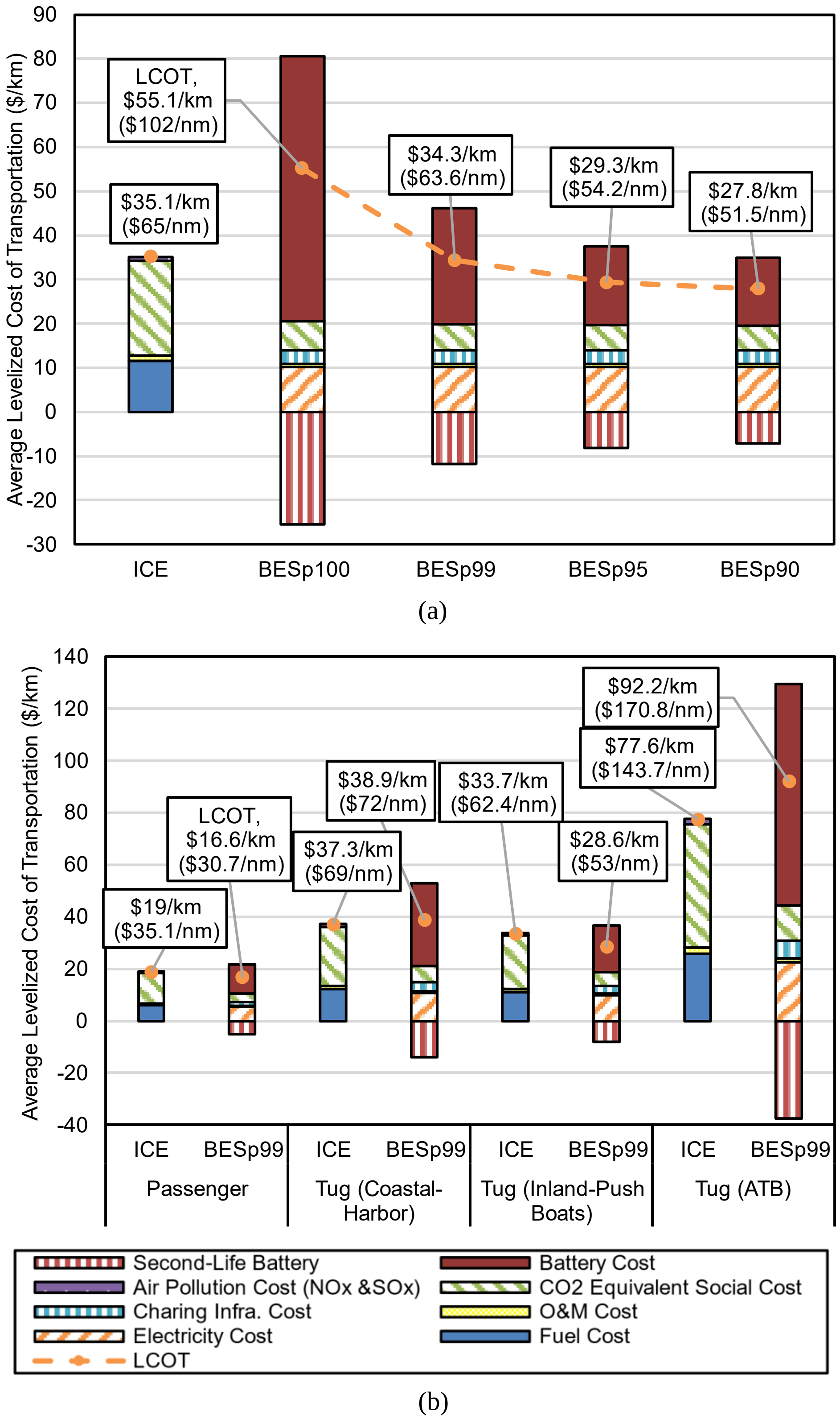


Figure EA-4. LCOT for ICE Ships and BESs in 2035 under DEC Emission Scenario and Intermediate Cost Scenario: (a) Comparison by Capacity Tier, (b) Comparison by Ship Type for BESs with Capacity Tier p99 (BESp99)

Passenger ships and inland/push-boat tugs are the most affordable ship types to retrofit to battery-electric.

One full equivalent cycle (FEC) is equal to fully charging a battery and then fully discharging it. Each BES battery has a finite number of FECs before it reaches end of life. FEC until battery end of life is calculated using battery lifetime and FECs for each year based on a battery degradation model.

Figure EA-5 shows the relationship between FEC until battery end of life and the cost of BESs versus ICEs. Higher FECs lower the cost of BESs and can make them less expensive than ICEs. Under favorable cost scenarios, a smaller number of FECs are needed for BESs to become cost-effective. For example, around 1,358, 671, and 385 FECs are needed for BESp100s to be cost-effective under 2022, 2035 DEC INT, and 2050 DEC INT scenarios, respectively. This can be interpreted as smaller batteries being used to serve the same amount of trip energy, amassing higher FECs and lowering battery system costs and overall costs.

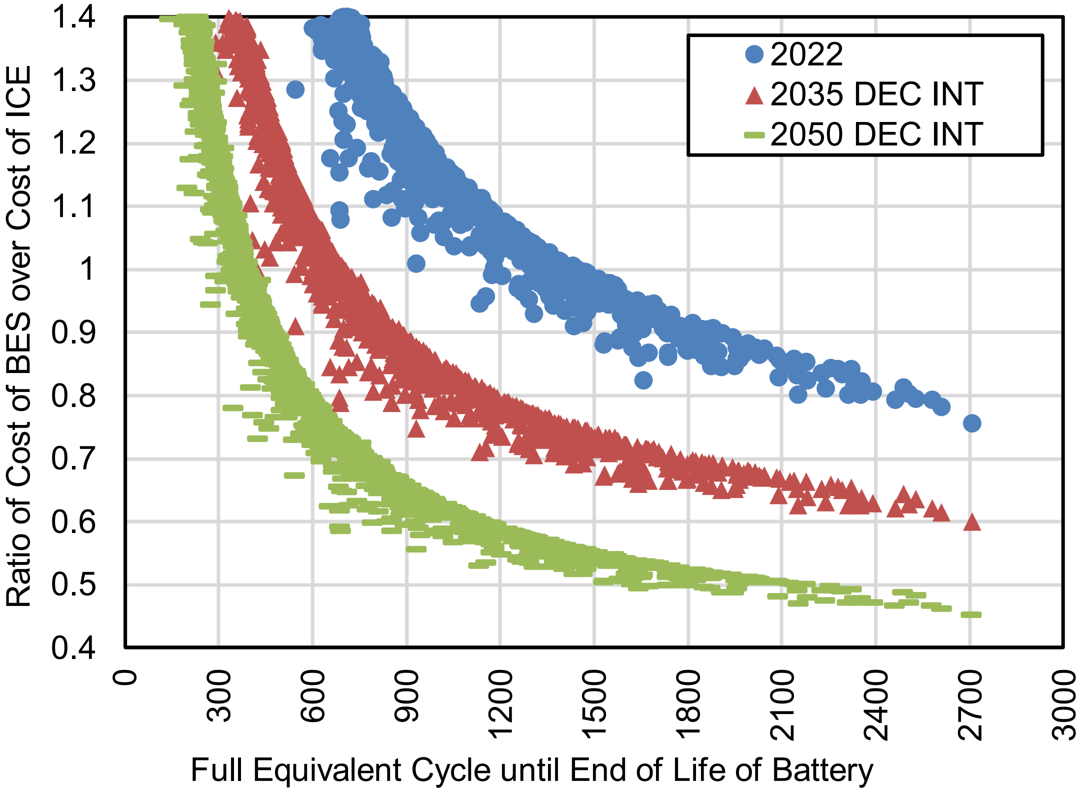


Figure EA-5. Distribution of Ratio of Cost of BESs over Cost of ICE Ships, by FEC of Battery

FEC distribution by ship type is shown in Figure EA-6. Passenger ships have the highest FECs (1,705), followed by Tug (Inland-Push Boats) (1,447), Tug (Coastal-Harbor) (1,150), and Tug (ATB) (603). This suggests that Passenger ships will have the most favorable economics for retrofitting to BES compared to other ship types.

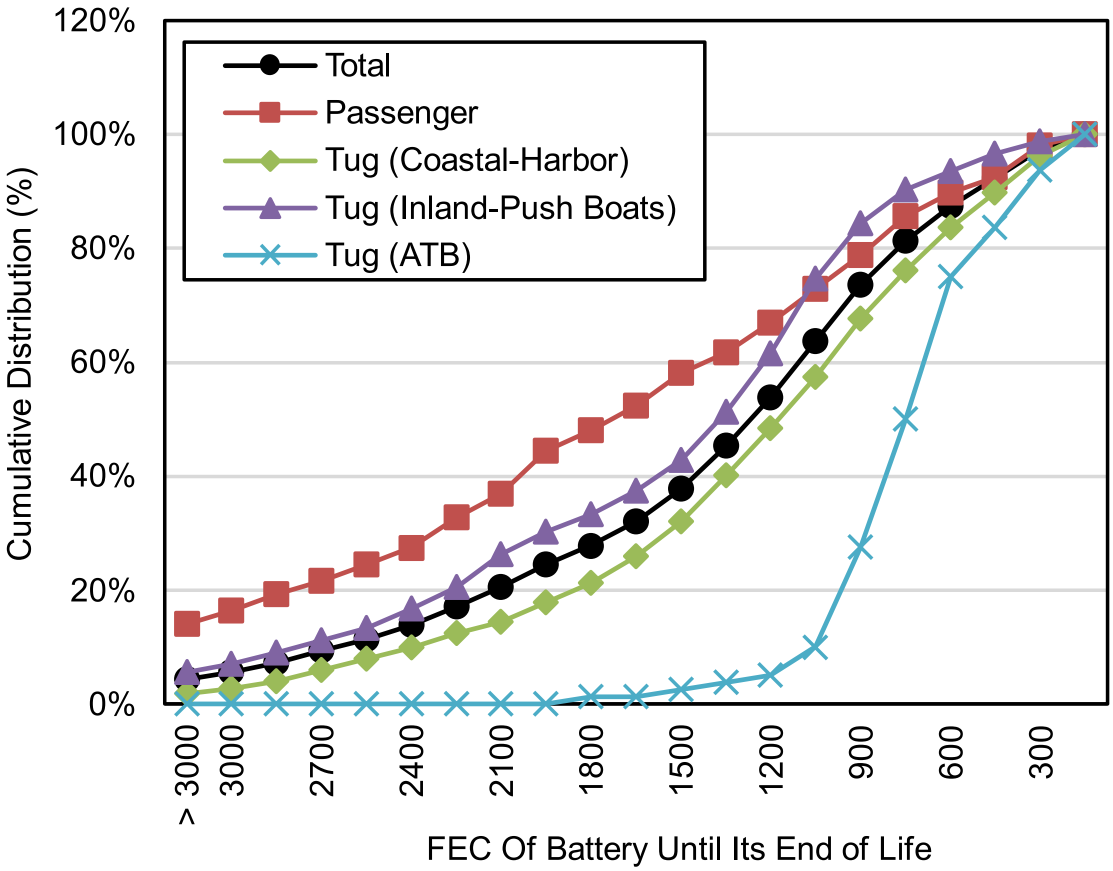


Figure EA-6. Cumulative Distribution of FEC Until Battery End of Life, by Ship Type

Figure EA-7 shows that different ship types exhibit varied trends in their unserved trip ratios. Passenger ships tend to have a smaller ratio of unserved trip energy, with about 63% of ships having a ratio below 25%. By contrast, Tug (ATB) shows the highest unserved trip ratio, with around 66% of ships having an unserved trip ratio exceeding 50%. Our analysis of unserved trips by different ship types suggests the following preferential order for retrofitting ICEs to BESs: Passenger, Tug (Coastal-Harbor), Tug (Inland-Push Boats) (both are quite similar), and finally Tug (ATB).

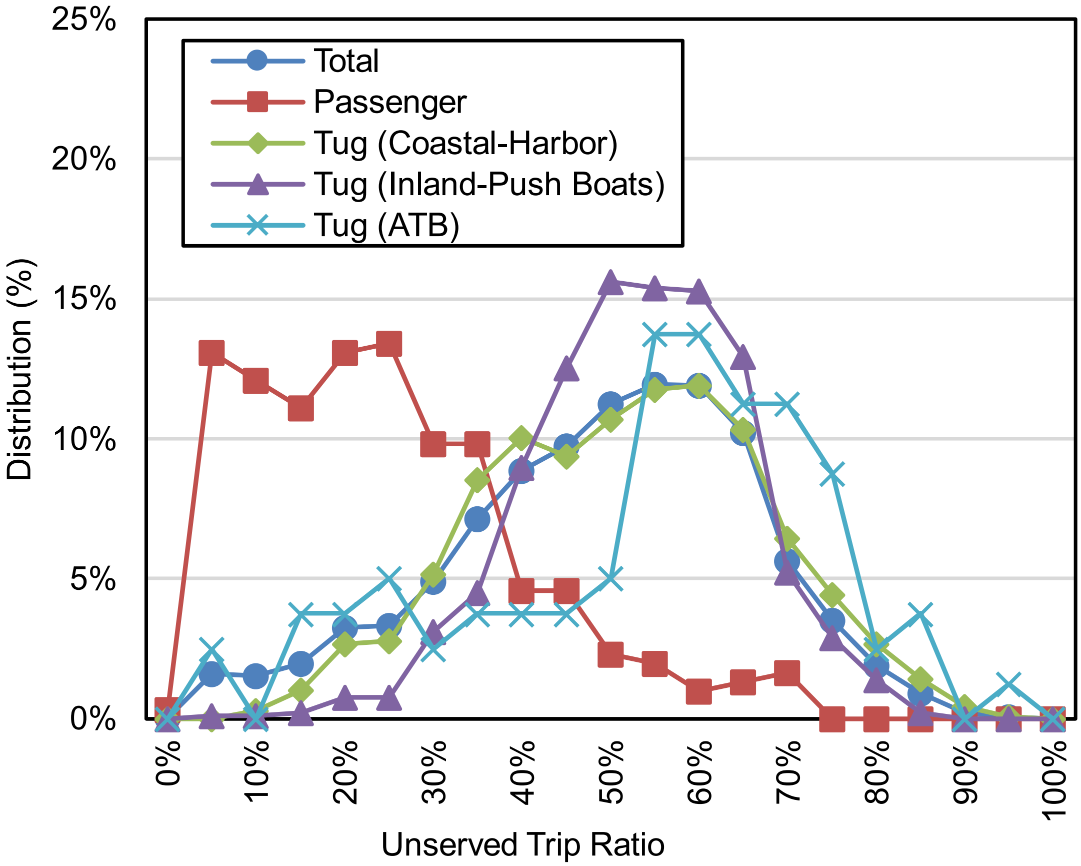


Figure EA-7. Distribution of Unserved Trip Ratios for BES p95

Figure EA-8 shows that the weight of BESs compared to ICEs also varies significantly by ship type. Passenger BESs have the lowest weight increase, with 94% having a weight ratio of 1.5 or less compared to ICEs. For Tug (coastal-harbor) and Tug (inland-push boats) BESs, 60% and 69% respectively have a weight ratio of 1.5 or less compared to ICEs. By contrast, only 10% of Tug (ATB) BESs weigh 1.5 times or less than their ICE counterparts. From a weight perspective, these results indicate that Passenger ships are most suitable for battery electrification, and Tug (ATB) is least suitable. Improvements in battery system weight can reduce the BES-to-ICE weight ratio.

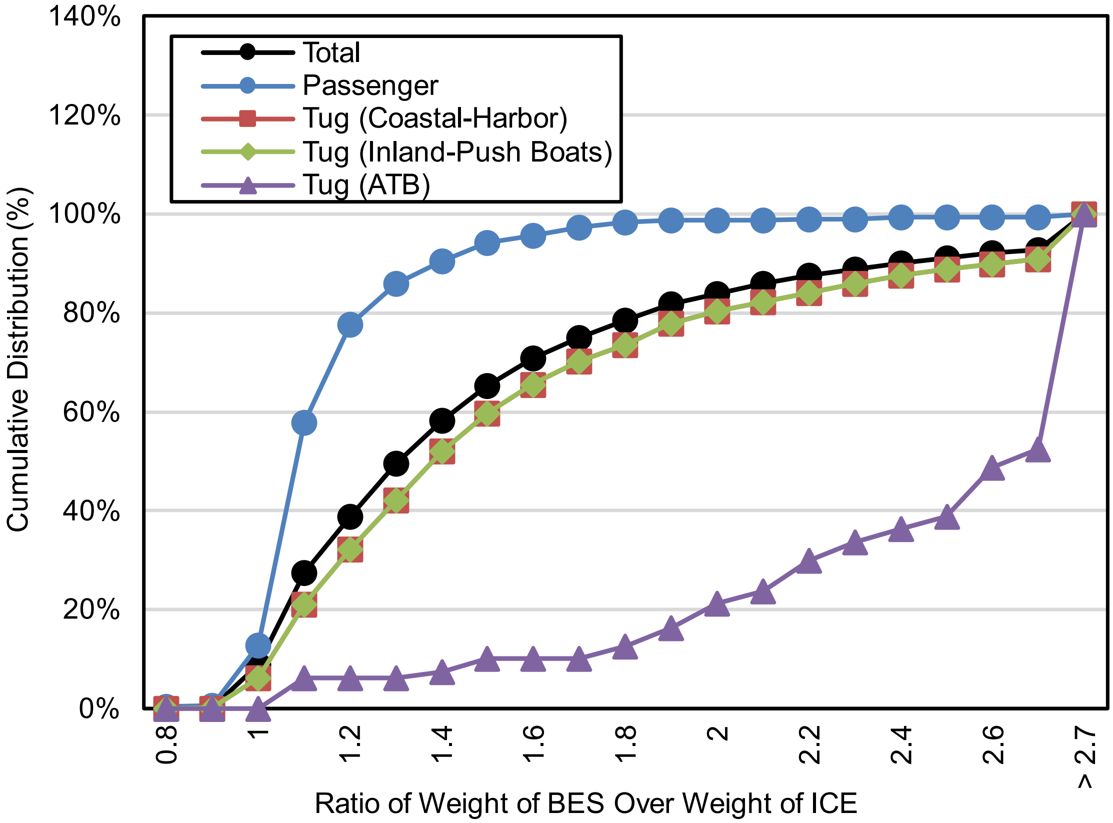


Figure EA-8. Ratio of BES Weight over ICE Weight for BES p99

As the foregoing suggests, our analysis identified passenger ships as the most suitable candidates among all ship types for conversion to BES, as they demonstrated the highest cost-effectiveness levels while experiencing the lowest increases in unserved trips as their capacity tiers decreased. Moreover, the weight increase resulting from the BES conversion was minimal for passenger ships. Among the three tug types, inland/push boats emerged as the most attractive option due to their lower costs, which can be attributed to their higher battery utilization rates. In contrast, ATB tugs encounter challenges with high costs, significant weight increases, and high unserved trip ratios when retrofitted to battery electric.

Our study emphasizes the considerable potential for electrification in the domestic shipping sector and the benefits it offers. Embracing battery-electric solutions can lead to significant emissions reductions, promote economic viability, and contribute to a more sustainable future for the U.S. maritime industry.

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List of Acronyms

AC	Alternating Current
ATB	Articulated Tug Barges
AIS	Automatic Identification System
BES	Battery-Electric Ship
BOEM	Bureau of Ocean Energy Management
CO_2e	Carbon dioxide equivalent
DC	Direct Current
GHG	Greenhouse Gas
GT	Gross Tonnage
HAC	Historical Activity-based Charging
IHS	Information Handling Services
ICE	Internal Combustion Engine
IMO	International Maritime Organization
km	Kilometer
kW/GW/TW	kilowatt/Gigawatt/Terawatt(s)
kWh/GWh/TWh	kilowatt/Gigawatt/Terawatt-hour(s)
LCOT	Levelized Cost of Transportation
LCA	Life Cycle Analysis
LNG	Liquefied Natural Gas
MDO	Marine Diesel Oil
MMSI	Maritime Mobile Service Identity
MMT	Million Metric Tons
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
nm	Nautical Mile
NO_x	Nitrogen Oxides
SLB	Second-Life Battery
SPC	Shore Power Connection
SOG	Speed Over Ground
SO_x	Sulfur Oxides
TBC	Trip-Based Charging
USACE	U.S. Army Corps of Engineers
USCG	U.S. Coast Guard
ULSD	Ultra-Low Sulfur Diesel

1. Introduction

The Biden-Harris administration has announced its intention to cut greenhouse gas (GHG) emissions in the United States 52% by 2030 and 100% by 2050 (U.S. Administration, 2021). The International Maritime Organization (IMO) has targeted GHG emissions reductions from international shipping, starting with 20-30% reductions by 2030 and 70-80% by 2040 (from 2008 levels) before realizing net-zero GHG emissions near mid-century (IMO, 2023). U.S. domestic marine vessels with internal combustion engines (ICEs) emitted 21.9 million metric tons (MMT) of carbon dioxide equivalent (CO_2e) in 2021 (EPA, 2023; U.S. Administration, 2023).[1]

Although battery-electric ships (BESs) have received considerable attention, they are still considered behind other energy sources such as hydrogen and sustainable liquid fuels due to ongoing questions about scaling up battery sizes (U.S. Administration, 2023). This is partly due to batteries' historically lower energy densities, the difficulty of bringing electricity to vessels for charging, and ship weight constraints. However, plummeting battery costs coupled with their increasing energy densities create an opportunity for battery-powered shipping to serve as a potential solution for zero-emission freight. While battery pack prices recently increased for the first time, rising 7% from 2021 to 2022, it is anticipated they will resume decreasing in 2024 (BNEF, 2022).

Several recent studies have estimated emissions from ship activities, including two comprehensive assessments of global ship emissions (Olmer et al., 2017; IMO, 2020). Gutiérrez (2015) compared various methods for estimating emissions from maritime transportation. Chen et al. (2021) delved into emissions estimates for tugboats by distinguishing different operational modes (e.g., berthing and un-berthing) and analyzing the positions of tugboats in relation to containers. Several other studies conducted region-specific analyses, including a spatial-temporal estimation of ship emissions along the Yangtze River (Weng et al., 2020), emissions from ships operating within the Great Lakes-St. Lawrence Seaway (Meng and Comer, 2022), and emissions from non-oceangoing vessels in the U.S. (ERG, 2022). These studies focused on estimating emissions and did not explicitly consider BESs as alternatives to ICEs.

Significant advancements in battery technology led to the introduction of MF Ampere, the world's first battery-powered car ferry, in Norway in 2015 (Ampere Electric-Powered Ferry, 2015). Soon after, in 2019, electric ferries such as E-Oshima (Richard, 2019) and E-ferry Ellen (Tunnicliffe, 2019) were deployed in Japan and Denmark, respectively. Ferries provided a straightforward initial application for ship electrification due to their regular and predictable service routes. Increasingly, other ship types, including tugboats, are being considered for electrification. In 2023, Crowley Maritime Corp. will deploy a 6 MWh battery-electric tugboat called the eWolf (Crowley, 2021).

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[1] 50.2 $MMTCO_2e$ from Ships and Boats and 22.7 $MMTCO_2e$ from International Bunker Fuels, yielding 72.9 $MMTCO_2e$ in total (EPA, 2023). Domestic shipping accounts for roughly 30% of these emissions (U.S. Administration, 2023).

A few recent studies have begun exploring the potential of BESs as alternatives to ICEs for achieving decarbonization objectives. Inal et al. (2022) conducted a comparative analysis of alternative energy sources and energy storage systems for different ship types, highlighting the significant potential of battery storage in vessel types such as tugboats and ferries. Fan et al. (2022) focused on the coordinated operation of a BES with hybrid propulsion systems and hydrogen fuel cells, emphasizing the importance of robust optimization. Perčić et al. (2021) performed emission and economic assessments, employing a life cycle analysis (LCA) approach for inland shipping vessels in Croatia. The study compared various alternative fuels, including Liquefied Natural Gas (LNG), methanol, and hydrogen. Kersey et al. (2022) examined the prospects of electrifying the container ships employed in international trade. None of these studies, however, specifically addresses the broader regional or national-level implications associated with the replacement of ICEs with BESs.

Several studies have examined emissions from port activities. The U.S. Environmental Protection Agency (EPA) assessed GHG emissions from ports, emphasizing the need for further research on electrification to reduce emissions (EPA, 2016). Additionally, Meng and Comer (2023) assessed the air quality and health impacts of port electrification at the Ports of Seattle and New York/New Jersey, revealing that full electrification, including shore power for oceangoing vessels, could reduce fine particulate matter emissions by 75% and 69% respectively at those ports.

In this context, we assess the battery electrification potential of the U.S. domestic shipping sector. We first consider the techno-economic feasibility of such a transition. Given energy requirements, distribution and length of shipping routes, and vessel engineering considerations, we assess the routes and ship types that can feasibly be electrified at current and near-future battery costs and energy densities. Then, we estimate the grid and port infrastructure requirements to enable such a nationwide transition. We quantify lifetime environmental impacts of the transition to battery-electric shipping, including potential reductions in criteria air pollutants and CO_2e emissions. Finally, we identify priority ports and regions for electrification based on electricity requirements and environmental impacts. This analysis of zero-emissions domestic shipping provides a necessary first step toward a zero-emissions global shipping sector.

In contrast to other studies that have either provided generalized assessments of ship types (Olmer et al., 2017; IMO, 2020; Gutiérrez, 2015) or highly detailed assessments of specific ships (Fan et al., 2022; Perčić et al., 2021), this study provides a guiding framework to assess the amenability of ship types to battery electrification based on real-world operational conditions. Leveraging ship-level geocoded Automatic Identification System (AIS) data of ship locations along with ship engineering specifications, we developed a typology of vessel types for all self-propelled U.S. flag ships according to their potential for battery electrification. For ship types that can be feasibly electrified in the near term, we estimate GHG emission reductions over the roughly 30 years between 2022 and 2050, under different energy mix scenarios, using an LCA method.

The remainder of this report proceeds as follows. Section 2 describes the analysis scope and data, data processing methodology, and typology of inland shipping vessels according to their operational profiles. Section 3 describes the methods used to estimate battery sizes, ship charging schedules, electricity requirements, GHG emission and air pollution reductions, and the LCA. Section 4 shows the analysis results, including estimated electricity requirements and the locations of charging infrastructure needed to support battery electrification for amenable vessel types. It also describes the potential emissions impacts of battery electrification, including operational emissions and life cycle emissions from production through end-of-life. Section 5 offers discussions and policy insights. Section 6 concludes with a summary of findings. The results in this report can help inform future directions for deeper investments in zero-emissions technologies for the shipping sector.

2. Scope and Data

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

2.1 Ships in Scope

Vessel stock and specification data were integrated from three data sources:

- U.S. Coast Guard (USCG, 2021)
- U.S. Army Corps of Engineers (USACE, 2021)
- IHS Markit (IHS, 2021)

The ship types considered in this study encompass six ship types including tankers, general cargo, and passenger ships as well as three types of tugs: Coastal-Harbor tugs, Inland-Push Boat tugs, and articulated tug barge (ATB) tugs. Ship type mapping from initial data sources is available in this report's Technical Documentation, as is the detailed procedure for integrating the ship list. Table 2-1 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[2] (GT) ranging between 50 and 1,000. Meanwhile, "AIS Analyzed Subset" denotes the subset of 2,722 ships that traveled more than 1,500 km in 2021, based on AIS data (BOEM and NOAA, 2022).

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[2] Gross tonnage is a nonlinear measurement of a ship's internal volumes, derived from its volume rather than its weight.

Table 2-1. Ship Statistics by Type

Number of ships			
Ships Categories **Ship type**	**Integrated Ship Database**	**Domestic Fleet (50<GT<1000)**	**AIS Analyzed Subset (annual travel > 1,500 km)**
Bulk Carrier	45	1	0
General Cargo	150	51	2
Tanker	135	18	4
Container	69	0	0
Ro-Ro	90	14	0
Passenger	5,213	1,439	306
Tug (Coastal-Harbor)	3,647	2,846	1,395
Tug (Inland-Push-Boats)	2,168	1,817	935
Tug (ATB)	170	137	80
Sum	**11,687**	**6,323**	**2,722**

Source: USCG (2021), USACE (2021), and IHS (2021)

Figure 2-1 illustrates the distribution of the AIS Analyzed Subset by ship type. Among these ships, tug (Coastal-Harbor) 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 tugs combined comprise 2,410 ships, or 88.5% of the total. Apart from tugs and passenger ships, only 6 ships were selected, including 2 general cargos and 4 tankers.

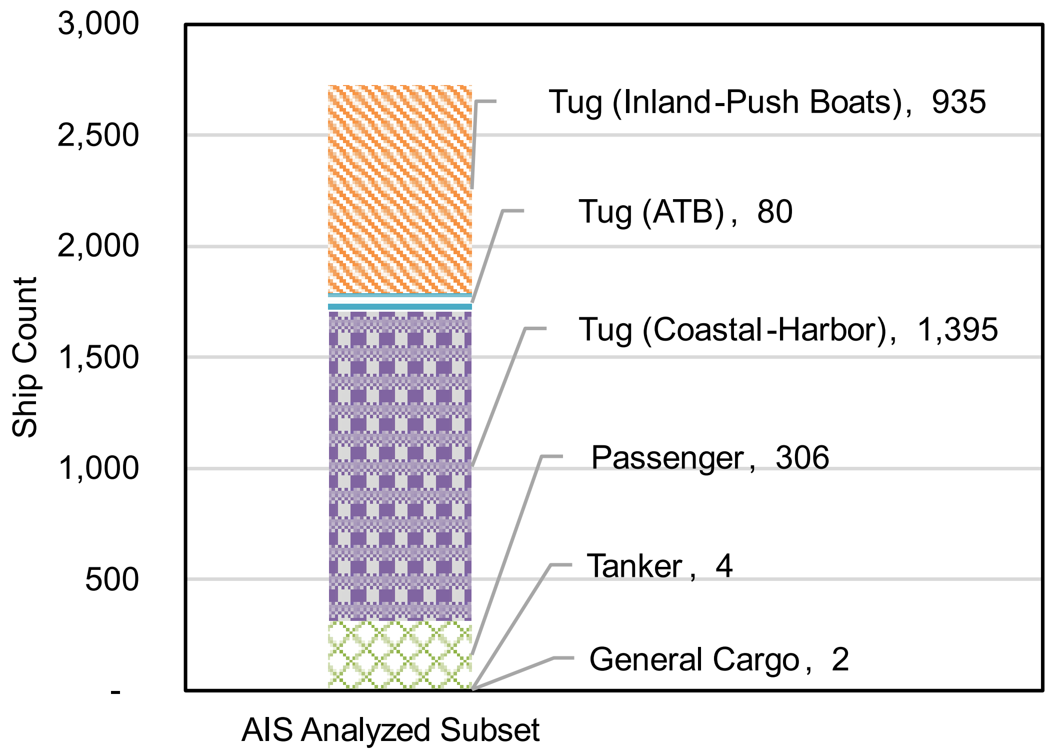


Figure 2-1. Count of Ships in the AIS Analyzed Subset, by Ship Type

Table 2-2 displays the average GT, main engine capacity, and travel distance of vessels included in the AIS Analyzed Subset, segmented by ship type. This table facilitates understanding of the characteristics inherent to each ship type. General Cargo and Tanker vessels were excluded from the table because the relevant subset, 50-1000 GT, contains smaller-than-average ships for their type and is therefore not representative of those vessels.

The subtotal of the four vessel types is 2,716, with an average GT of 266, average main engine capacity of 1.9 MW, and average 2021 distance travelled of 29,835 km. Among the four ship types, the Tug (ATB) presented the most notable differences among the three categories: GT, engine capacity, and travel distance are 2.3, 2.0, and 1.8 times higher than the overall averages, respectively. By contrast, the three non-ATB ship types showed more similarities across categories.

Table 2-2. Average GT, Main Engine Capacity, and Travel Distance by Ship Type

Ship type	# of ships	Average gross tonnage [GT]	Average main engine capacity* [MW]	Average annual travel distance [km]
Passenger	306	221	1.3	28,963
Tug (Coastal-Harbor)	1,395	251	2.1	28,823
Tug (Inland-Push Boats)	935	272	1.8	29,641
Tug (ATB)	80	618	4.0	53,071
Sub-Total	2,716	266	1.9	29,835

* For ships where the main engine capacity data is unavailable, estimated values are used as described in the Technical Documentation.

2.2 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 (name, MMSI and IMO number), location (latitude and longitude), SOG, heading, and other navigational information. BOEM and NOAA (2022) provide a publicly available historical AIS data pool within U.S. territory. This dataset allows us to analyze 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 the Technical Documentation.

Based on the historical AIS data from each ship, annual travel distance is calculated as presented in Figure 2-2. 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, while for ATB vessels, more than 11% travel distances exceeding 60,000 km. Annual travel distance is used to calculate the Levelized Cost of Transportation (LCOT) in USD/km for each ship type in Section 4.5.

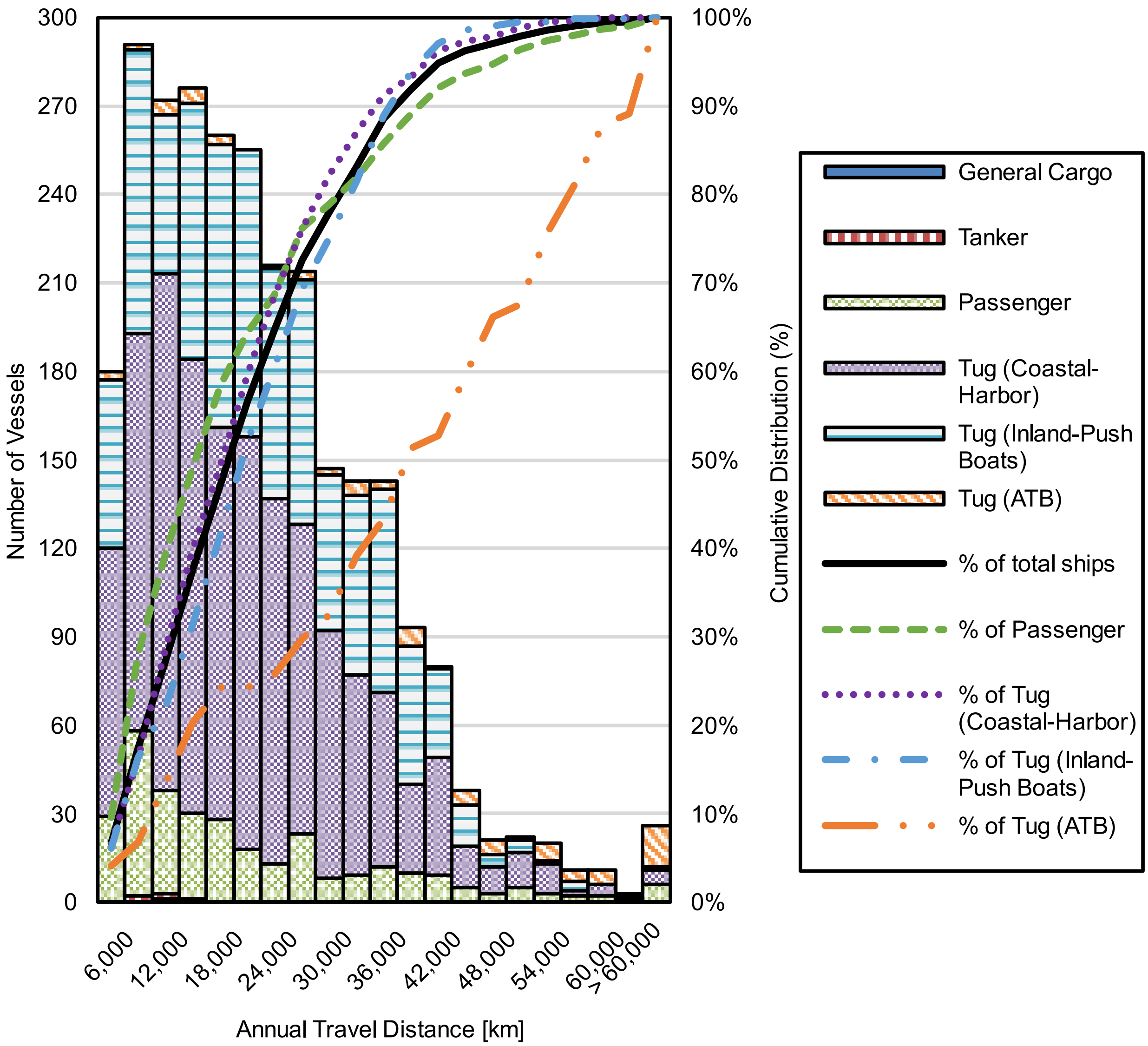
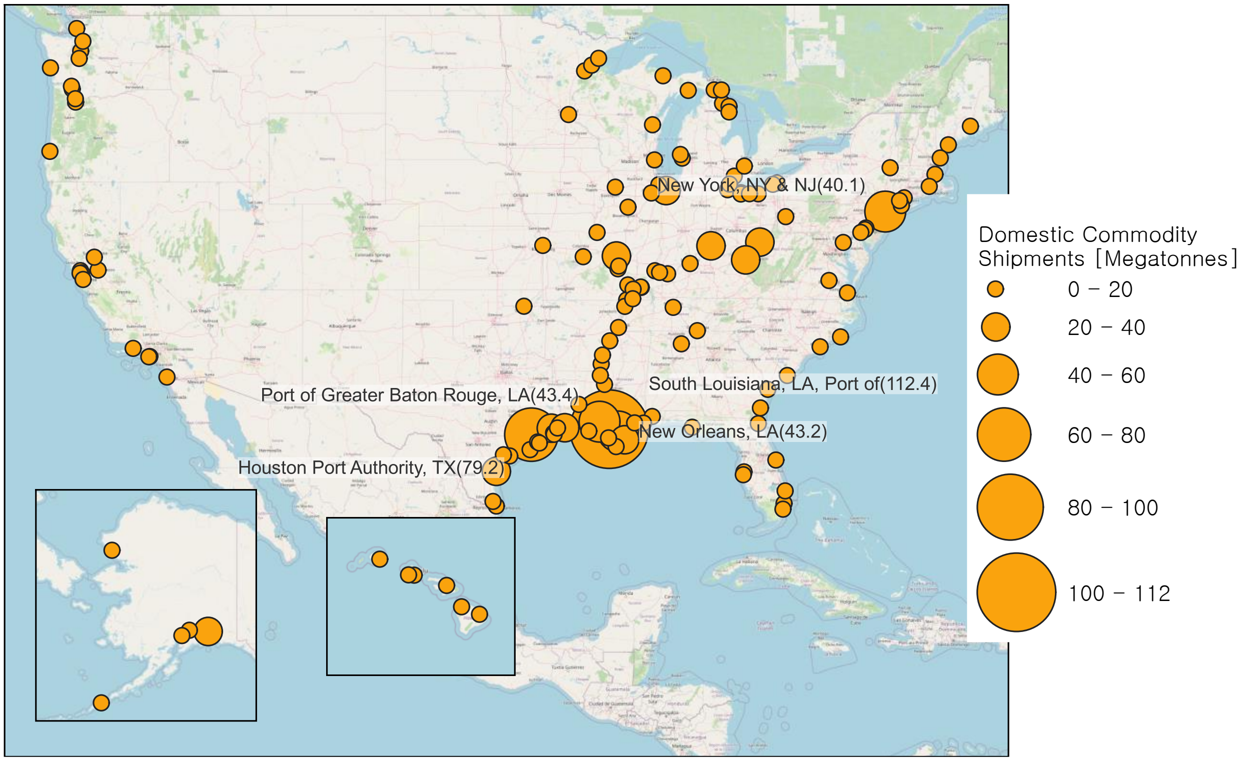


Figure 2-2. Distribution of Annual Travel Distance by Ship Type in the AIS Analyzed Subset

2.3 Port Data

2.3.1 Port Data with Coordinates

Port data includes the name, state, and coordinates of the top 150 U.S. ports, based upon total annual tonnage in 2020 (USDOT, 2022). Total annual tonnage includes both domestic and foreign waterborne trade. Figure 2-3 shows locations of the 150 ports, along with their volumes of domestic commodities.[3]



Authors' work based on USDOT (2022).

Figure 2-3. Locations and Domestic Commodity Shipments at 150 Major U.S. Ports

3. 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 analysis. We used object-oriented programming in Python, which makes the tool highly adjustable and flexible in terms of accommodating various ship and port datasets. Figure 3-1 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,

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[3] The following are not included as domestic commodity shipments: cargo carried on general ferries, coal and petroleum products loaded from shore facilities directly into bunkers of vessels for fuel, and insignificant amounts of government materials (less than 100 tons) moved on government-owned equipment in support of Corps projects (USACE, 2023).

we conducted a life cycle analysis (LCA) to estimate overall emissions associated with BES vessels.

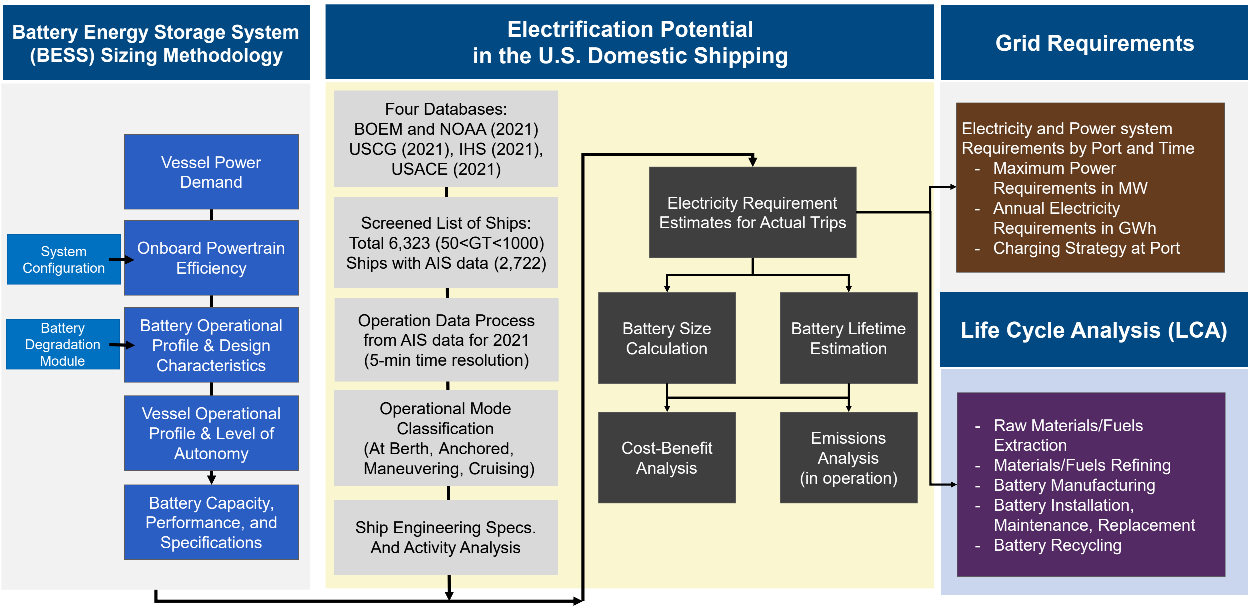


Figure 3-1. Process for Estimating Ship Electrification Potential and GHG Emissions

Figure 3-2 outlines the design of the program, Maritime Battery Electrification Simulator (MariBES), used in this study, divided into six primary modules. The Raw Data Processor module undertakes the cleaning and structuring of preprocessed data for utilization by other modules. The Ship Activity Estimator module applies AIS data from individual ships to assess energy consumption and emissions. It also calculates the requisite battery size, manages charging and discharging schedules, and estimates battery degradation under electrification scenarios. The Port Power Estimator module determines the energy and power demands that arise when ships undergo electrification. For these calculations, this module employs the charging and discharging schedules provided by the Ship Activity Estimator module.

The Emission Study, Economic Study, and Physical Viability Study modules offer a comparative analysis between BESs and their ICE counterparts. This analysis covers emissions, economics, and weight comparisons based on the data from the Ship Activity Estimator and Port Power Estimator modules, enabling informed decision-making in the transition to electrification under various scenarios.

MariBES’s notable advantages include its flexibility and scalability. Its adaptability to diverse ship ranges and port scopes allows it to effectively explore electrification options in various maritime contexts, promoting sustainable and efficient operations. Overall, the MariBES’s potential lies in its comprehensive analytical capabilities, insights for electrification planning, and adaptability to different maritime scenarios, making it a valuable tool for the industry.

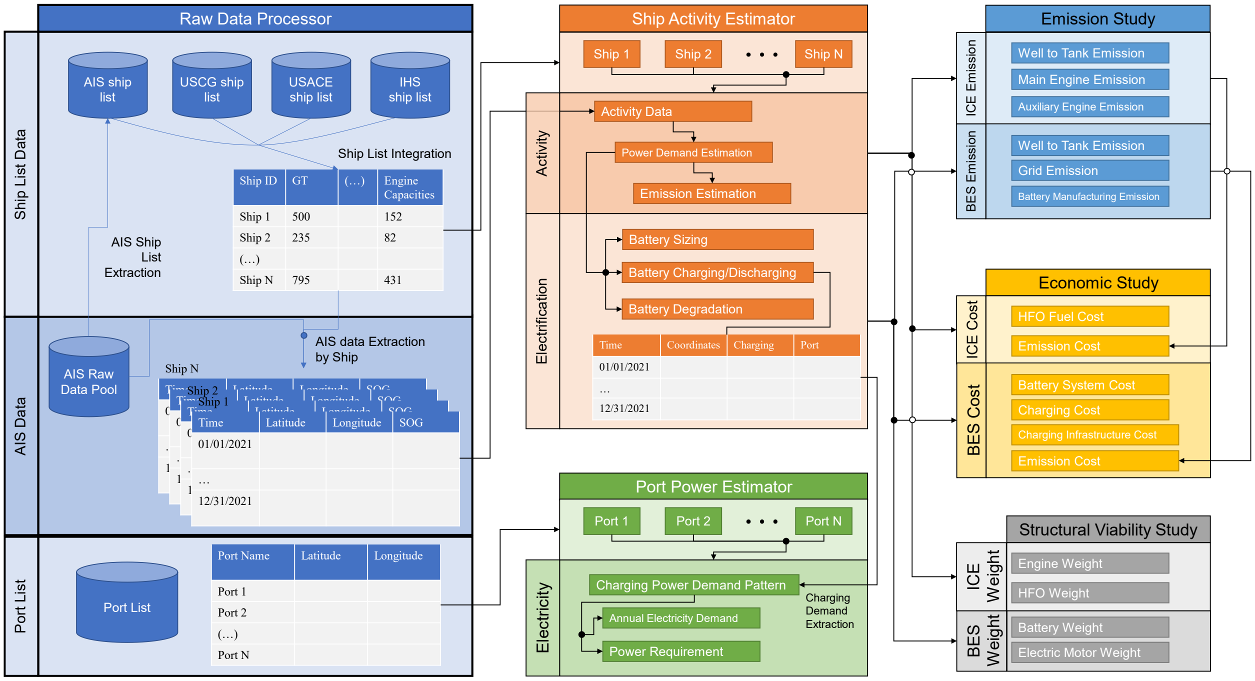


Figure 3-2. Design of the Maritime Battery Electrification Simulator (MariBES) Developed for This Study

3.1 Battery Size, Charging Strategy, and Battery Degradation

Figure 3-3 presents a single-line diagram of the BES system and the shore power connection (SPC) based on the battery propulsion for an all-electric vessel (EMSA, 2020) and the single-line diagram of MF Ampere, an electric car ferry (Corvus Energy, 2016). Each figure shows power flow when the BES is charging and discharging, respectively. While the depicted topology is simplified and does not include redundancy, it is important to note that in practical applications, the system is typically divided into port and starboard sections. The configuration assumes the presence of a main switchboard that operates on direct current (DC). To facilitate voltage level conversion, there is a DC/DC converter between the switchboard and the battery pack. Since it is assumed that the propulsion and auxiliary loads operate on alternating current (AC), the power is transformed between the switchboard and the loads using DC/AC inverters. Although the AC auxiliary demand can be directly supplied from the SPC, the direct connection is not considered for the sake of simplicity. BESs in need of charging get power from charging stations in ports. As the power supplied from the grid is in AC power, it is assumed that a shoreside AC/DC converter is employed to convert the AC power into DC power for the BES.

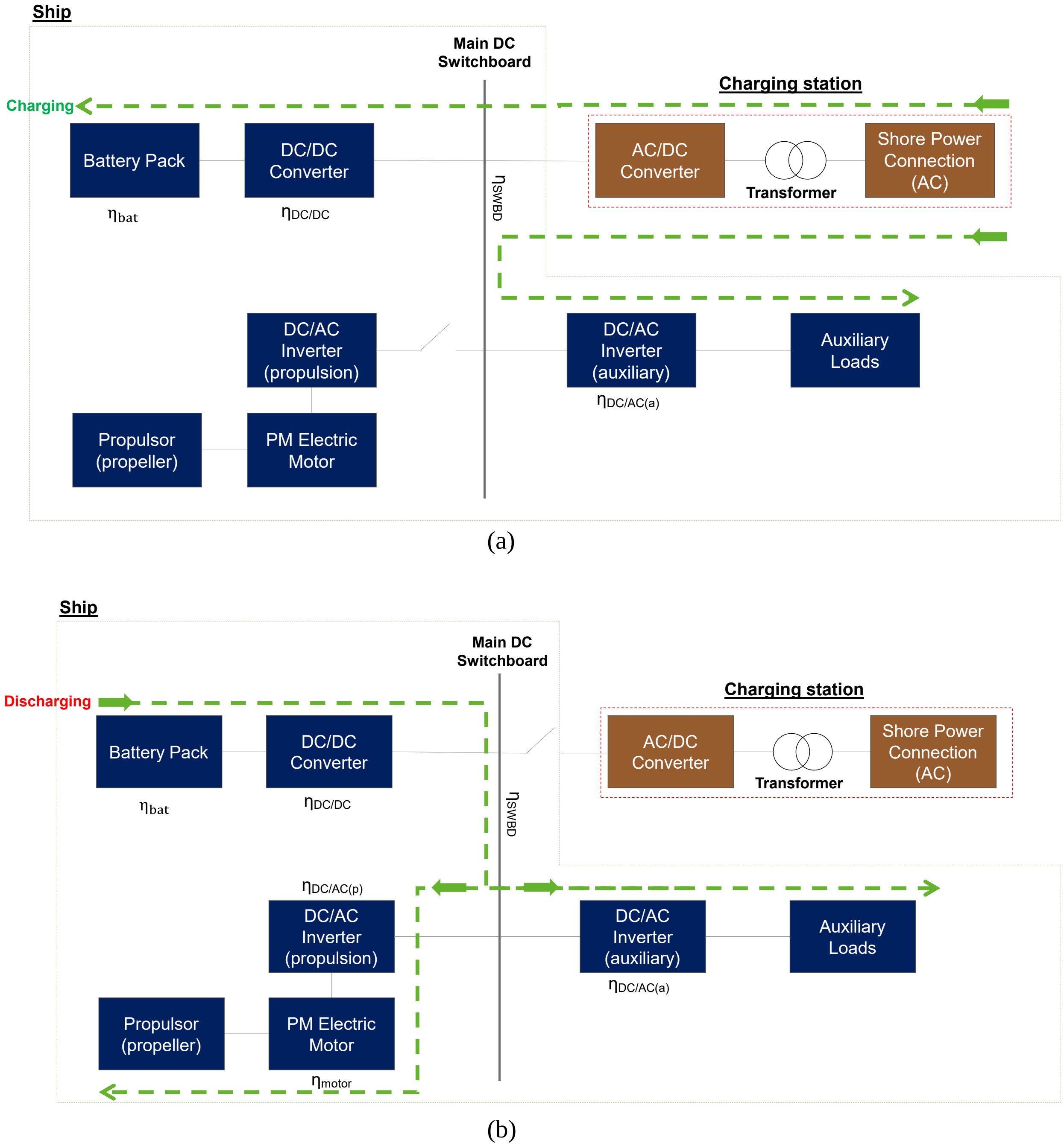
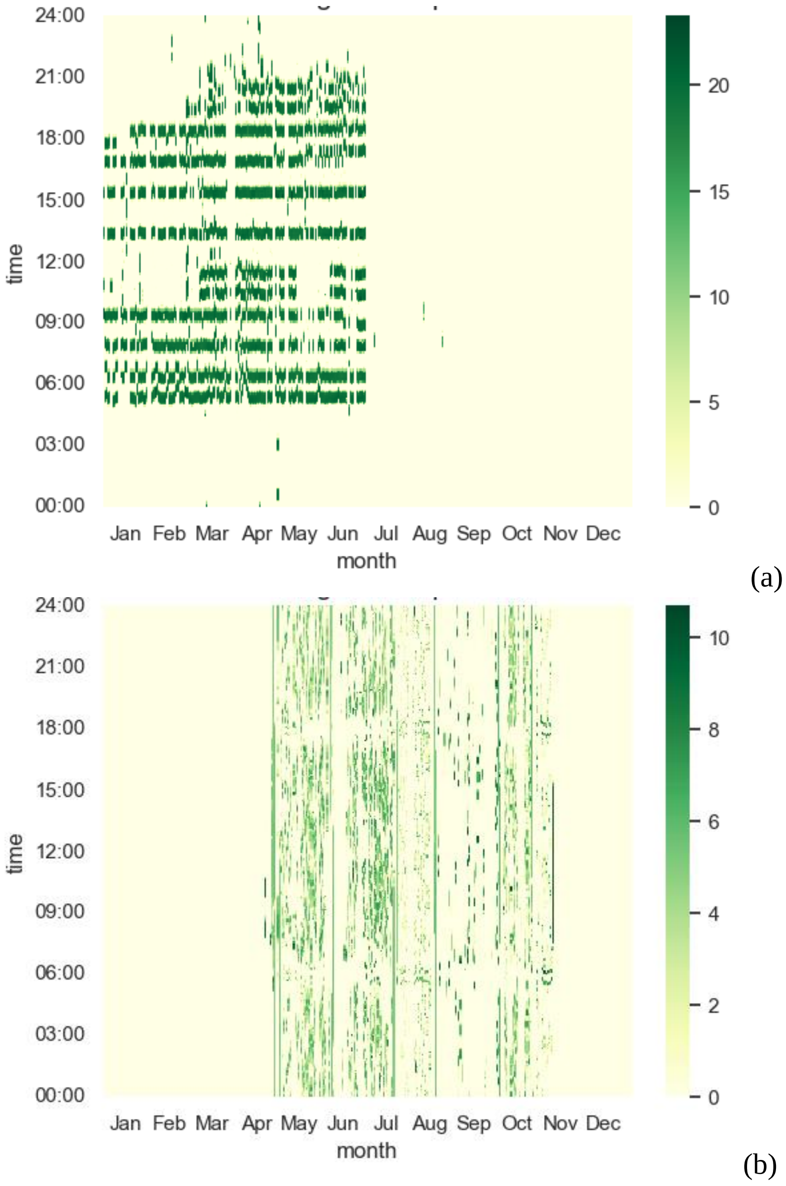


Figure 3-3. Power Flow of Battery-Electric Ship (BES) When it is (a) Charging at Port and (b) Discharging During Ship Activity

The first step in assessing the electrification potential of a ship involves calculating its power demand. Onboard energy consumption consists of two main components: propulsion demand and auxiliary demand. The main engine provides propulsion energy, while the auxiliary engine supplies power for onboard electrical demand. To calculate both propulsion and auxiliary demands for each ship, speed data from the AIS dataset is used. Detailed procedures for calculating power demands are given in the Technical Documentation. 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 the Technical Documentation.

3.1.1 Battery Sizing Based on Trip Energy Demand

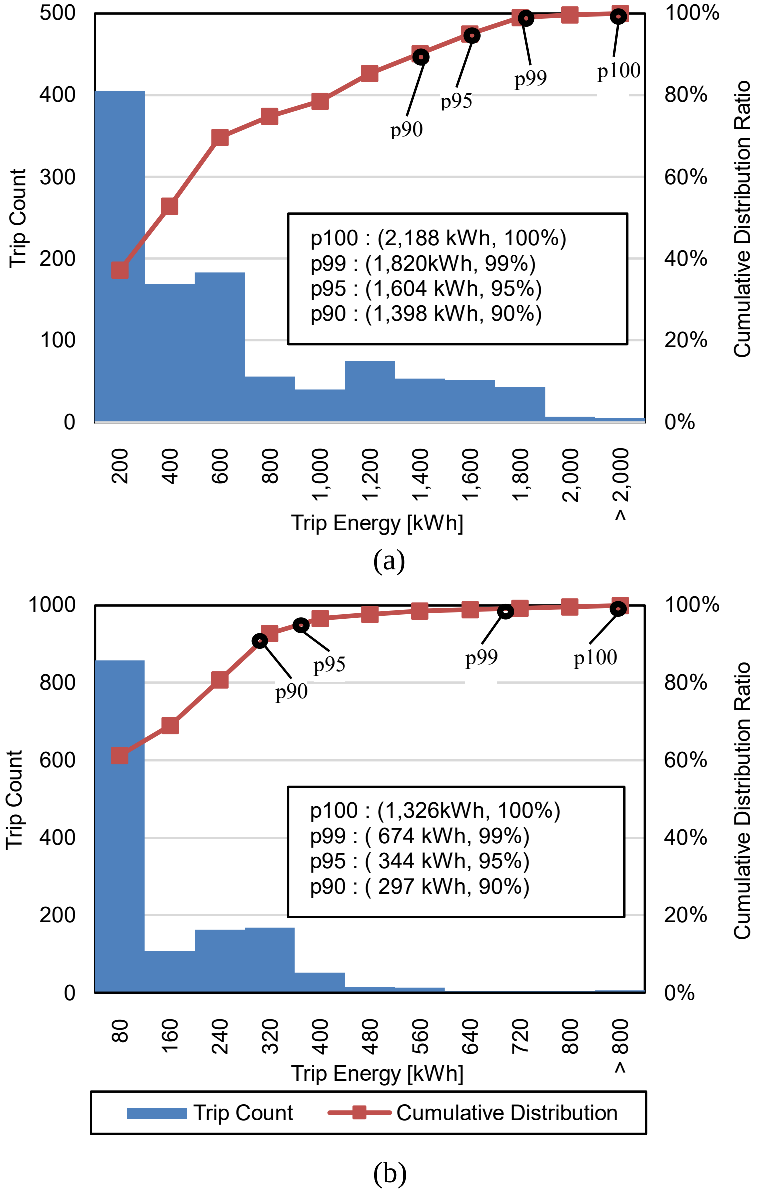
Figure 3-4 depicts example heatmaps of speed over time for (a) Passenger and (b) Tug (Coastal-Harbor) ships. The passenger ship tends to exhibit more regular and shorter trip patterns, whereas the tug displays greater variability with occasional longer trips. These tendencies are not restricted to the examples presented here and can be observed within the same ship types, albeit to potentially varying extents across different vessels.



Greener shades indicate higher speeds, while yellow regions indicate no motion. Connected green dots can be considered as trips or periods of Moving, while yellow regions correspond to Chargeable or inter-trip periods. Ship details: (a) Passenger: MMSI 367618070, 735 GT; and (b) Tug (Coastal-Harbor): MMSI 368004190, 148 GT.

Figure 3-4. Speed Patterns of (a) Passenger and (b) Tug (Coastal-Harbor) Ships

Figure 3-5 presents the trip energy distributions for two ship types: (a) Passenger and (b) Tug (Coastal-Harbor). 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.

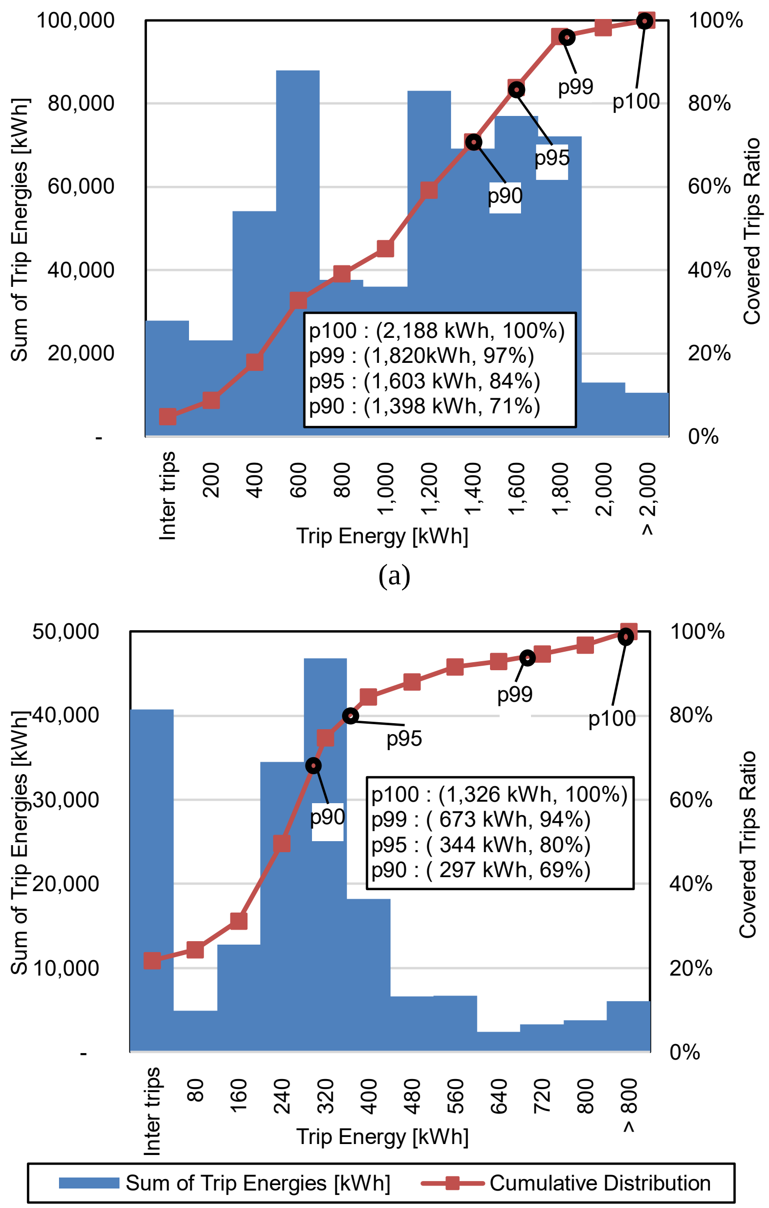


Points p100, p99, p95, and p90 refer to 100th, 99th, 95th, and 90th percentile trip energy requirements, respectively.
Ship details: (a) MMSI 367026710, Passenger; and (b) MMSI 367673660, Tug (Coastal-Harbor).

Figure 3-5. Examples of Distribution of Trip Energy

Because this study is based on historical activity data from ICE ships, energy demanding trips are included in the dataset for each ship. Such trips are not suitable for BESs because they would result in oversized batteries and higher costs. To address this issue, we established four capacity tiers for BESs, expressed as “BESpX,” to represent BESs capable of accommodating X% of the total trips previously served by ICE ships. The four capacity tiers are p100, p99, p95, and p90. The notation ‘X’ is used to represent each capacity tier.

Figure 3-6 depicts the sum of energy in each interval based on the trip energy of the two vessels shown in Figure 3-5, along with the covered trip ratio and reference trip energy requirement. For both ships, as the capacity tier decreases, the reference trip energy decreases, leading to a simultaneous decrease in the covered trip ratio. As the capacity tier decreases, the reduction in reference trip energy is more significant for the tug, but the covered trip ratio appears to decrease at a similar level for both vessels. 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.



(a)

(b)

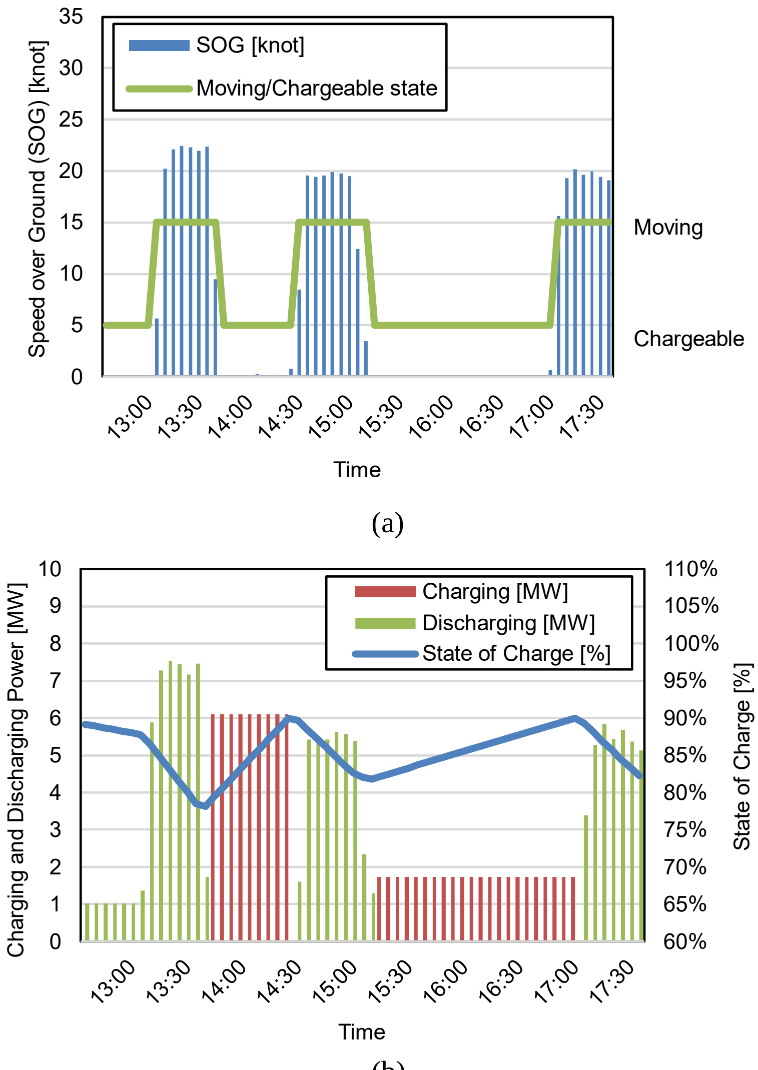
Points p100, p99, p95, and p90 refer to 100th, 99th, 95th, and 90th percentile energy, respectively. Ship details: (a) MMSI 367026710, Passenger; and (b) MMSI 367673660, Tug (Coastal-Harbor).

Figure 3-6. Sum of Trip Energies for Two Ships

3.1.2 Charging Scheduling

The need for efficient charging plays a crucial role in scheduling BES charging. Charging schedules are determined based on an algorithmic approach, which charges the BES only when the state of charge (SOC) falls below a predetermined charging boundary, assumed as 70%. This ensures the BES is charged in a controlled manner and prevents the battery from being charged too frequently or charged when it is not required. At the start of the simulation, the battery SOC is set to 90%. While at port, if the 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. Furthermore, the SOC is bounded between 10% and 90% to prevent excessive charging or discharging that could lead to faster battery degradation.

Figure 3-7 depicts an illustrative example of the SOC and charging/discharging scheduling for the BESp100 of a passenger ship (IMO 9607679). The figure demonstrates that the distinction between Moving and Chargeable states is determined by the ship's SOG: when speed is below 0.5 knot, the ship is considered Chargeable; otherwise, it is Moving. Additionally, based on the Moving/Chargeable state and battery SOC, the BES's battery is charged. Because the SOC is expected to drop below the charging boundary (70%), the ship is scheduled to charge during two specific time intervals: 13:45-14:25 and 15:15-17:00.



(a)

(b)

Figure 3-7. Illustrative Passenger Ship: (a) Speed over Ground (SOG) and Moving/Chargeable State, (b) Battery Charging, Discharging, and SOC

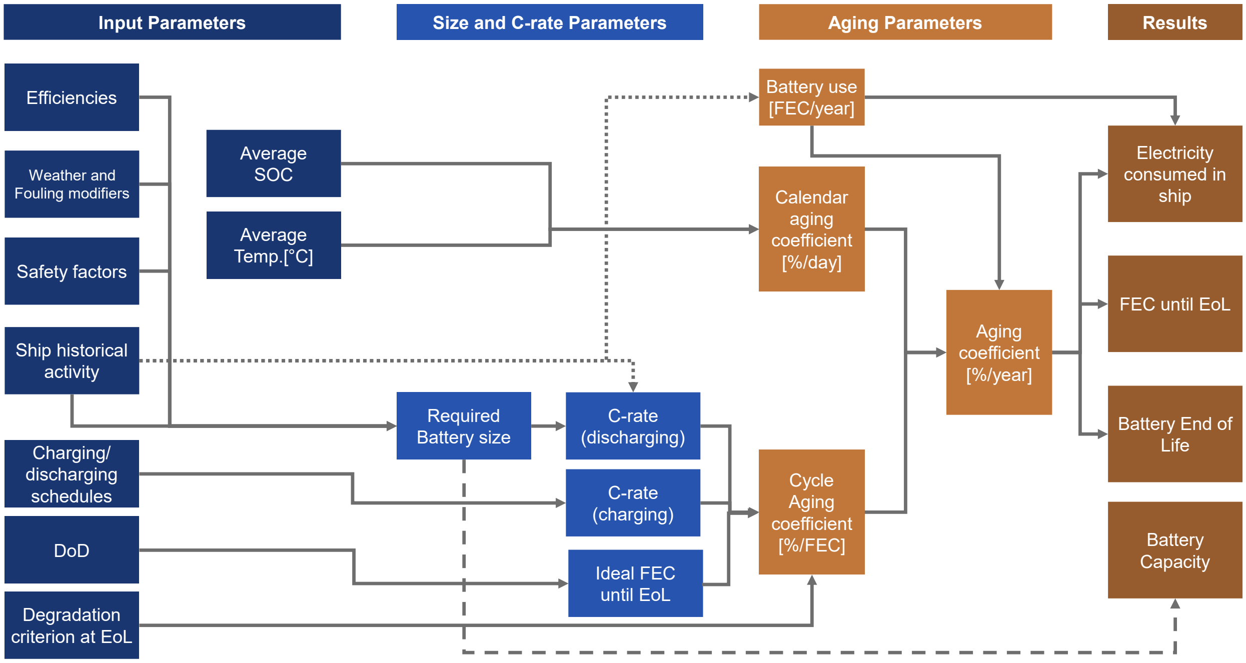
To compare the power requirements at ports based on ships' different charging strategies, we will refer to the charging strategy described above as Historical Activity-based Charging since it aligns with each ship's historical activity. We also considered an alternative charging strategy, Trip-Based Charging. Under Trip-Based Charging, we assumed the charging time to be half the duration of the previous trip, rather than the historical chargeable time. For instance, if a ship stayed at port to charge for 10 minutes after a 60-minute trip under Historical Activity-based Charging, under Trip-Based Charging the ship would charge for 30 minutes (half of the 60-minute trip). Under Trip-Based Charging, BESs would remain at port longer than ICEs have historically done; this scenario aligns with real-world conditions, due to the limited power capacity of charging facilities.

Implementing Trip-Based Charging and adjusting ship activity patterns with longer port stays may alleviate power requirements at ports. However, the Trip-Based Charging assumption of longer charging times for BESs may require ship activity adjustments that are beyond this study's scope. Unless stated otherwise, Historical Activity-based Charging serves as our baseline strategy for BES charging.

3.1.3 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 (Barré et al., 2013). As a result of degradation, the energy that can be stored in the battery (i.e., battery capacity) decreases. Battery degradation can be categorized into two types: calendar degradation and cycle degradation (Pelletier et al., 2017). Calendar degradation refers to the gradual deterioration that occurs over time, even when the battery is not in use. It tends to result in a greater loss of capacity over the same time period if the average SOC is higher and/or the temperature is higher. Cycle degradation results from battery usage: the higher the number of charging and discharging cycles, the more the battery degrades. Cycle degradation is accelerated when charging or discharging at high power.

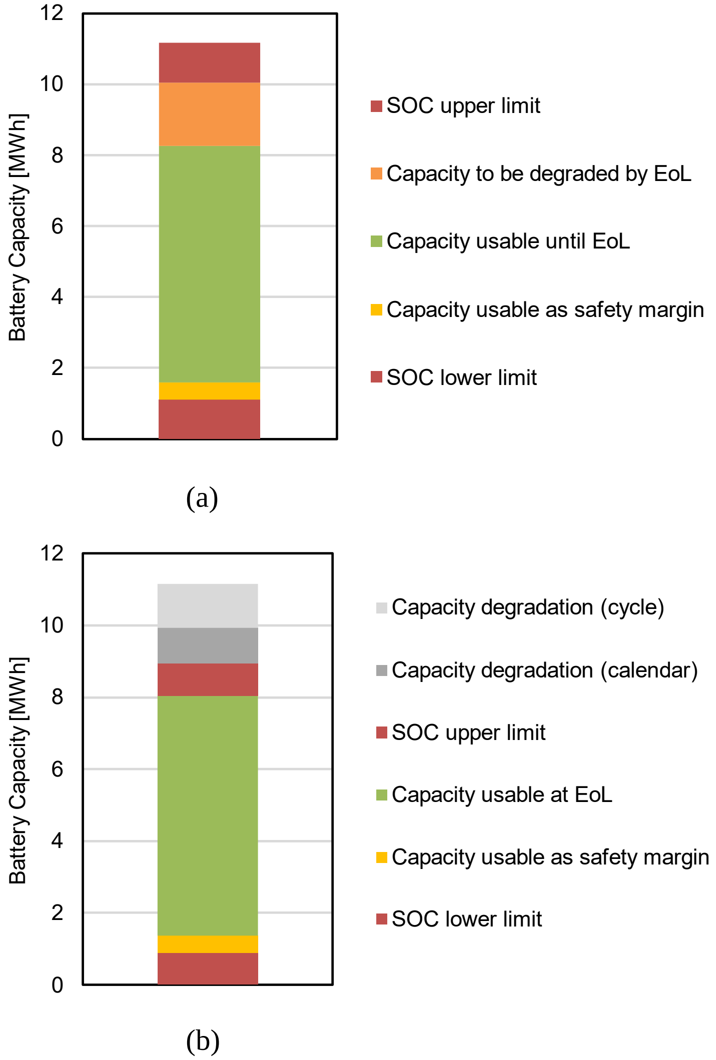
The economic value of a BES is significantly influenced by the lifetime of its battery. In this study, battery lifetimes were calculated based on the battery schedules described in Section 3.1.2, utilizing the battery degradation model outlined by Hoedemaker (2017) as illustrated in Figure 3-8. Detailed procedures used to calculate the lifetime of each battery are described in the Technical Documentation.



Different types of lines are used to visually separate them from overlapped lines.

Figure 3-8. A Schematic Diagram of Battery Sizing with Degradation Reflected

Figure 3-9 illustrates our approach to battery sizing, which accounts for battery capacity degradation. On the left, the total capacity of the battery is allocated with 20% for upper and lower SOC limits, 3% for a safety margin, and 20% reserved for degradation. The right side of the figure demonstrates that even after degradation, the available capacity at end of life can still serve energy requirements.



(a) At Year 0 (left), the usable energy (orange + green + yellow), or 80% of depth of discharge (DoD), is greater than the energy required for one trip.
(b) At EoL (right), the usable energy (orange + yellow), or 80% of DoD, is equivalent to the energy required for one trip.

Figure 3-9. Battery Sizing and Usable Capacity: (a) Initial Battery Composition, (b) End of Life (EoL)

3.2 Estimating Battery-Electric Ship Potential

3.2.1 Emissions

Emissions can be calculated using two approaches: the energy-based approach and the fuel-based approach (IMO, 2020). 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). This facilitates the calculation of emissions from both ICEs and BESs using identical energy consumption data. Five types of air emissions, CH_4, N_2O, CO_2, NO_x, and SO_x, are estimated based on the energy consumption calculated in Section 3.1 (detailed in Technical Documentation) and considering their respective 100-year global warming potentials (Forster et al., 2021). For CO_2e covering CH_4, N_2O, and CO_2, an LCA-based approach is used, whereas NO_x, and SO_x emissions are counted at the ship's operational level.

We developed a LCA model to better account for supply chain energy demand and GHG emissions of battery-electric shipping as shown in Figure 3-10. 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 (i.e., "cradle to grave"). More details regarding the LCA are given in the Technical Documentation.

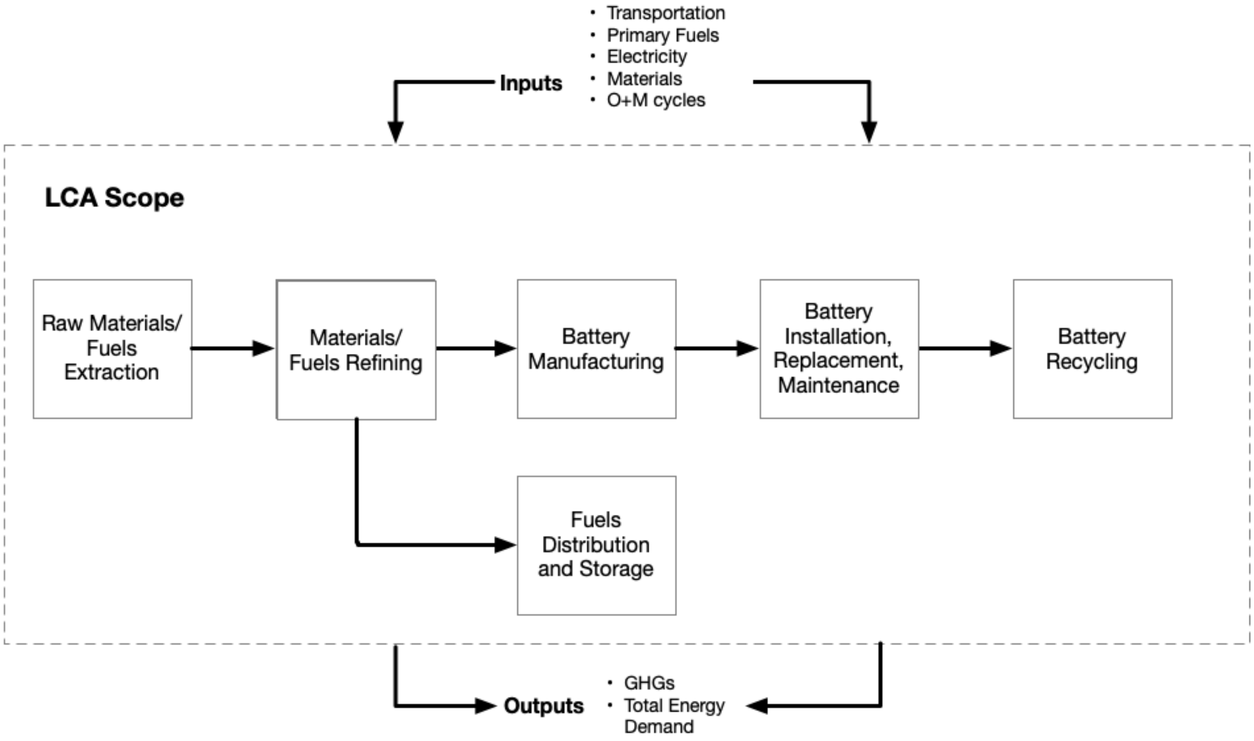


Figure 3-10. LCA of BESs

We estimated emissions under two emission scenarios and three representative years: 2022, 2035, and 2050. We also assessed life cycle energy demands and GHG emissions of electricity generation by modeling two projected generation scenarios for all U.S. states through 2050 and combining those scenarios with life cycle emission factors. We modeled these projections using the National Renewable Energy Laboratory (NREL)'s Cambium model (Gagnon et al., 2021) for a "Business as Usual (BAU)" scenario (defined by NREL as the "Mid-case") and a "95% Electricity Decarbonization by 2050 (DEC)" scenario (defined by NREL as "Mid-case 95 by 2050"). We used GREET's electricity generation model to develop energy and GHG impacts for different generation technologies, and then applied the most relevant emission factors to the projected generation scenarios to obtain life cycle energy and GHG emission factors for each U.S. state through 2050 (Want et al., 2021). NO_x and SO_x emissions are not considered with BESs, as we assumed they would only apply to ships' operational stage.

3.2.2 Economic Feasibility

To establish an economic comparison between continuing to utilize ICEs vs. retrofitting them with BES technology, we conducted a comprehensive analysis of the total costs associated with each approach. Our analysis encompassed various factors, including operational costs and emission costs related to ICE technology as well as battery system costs, operational costs, and emission costs specific to BES technology. For ICE ships, the total cost includes that for fuel (ultra-low sulfur diesel, or ULSD), the social cost of CO_2 equivalent, and air pollution (NO_x and SO_x). For BESs, the total cost comprises costs for the battery, operations and maintenance (O&M), charging infrastructure (Popovich et al., 2021), GHGs (EPA, 2022b), and air pollution (NO_x and SO_x) (Goodkind et al., 2019), minus the salvage value of the battery at end of life (Sathre et al., 2015). Emissions for both ICEs and BESs are derived from the calculation in Section 3.2.

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 USD/km. 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 (Kersey et al., 2022).

LCOT does not account for factors such as the quantity of shipments delivered or the relative efficiency in transporting passengers, vehicles, cargo, or other vessels. But because the purpose of estimating costs is to compare maintaining vessels as ICEs vs. retrofitting to BES and recommend the more favorable option, the presented LCOT is considered sufficient.

In this study, emission costs are estimated based on the emission results obtained from two emission scenarios as detailed in Section 3.2. The cost estimation is carried out for three specific years: 2022, 2035, and 2050. For BESs, three cost scenarios are considered: Optimistic (OPT), Intermediate (INT), and Challenging (CHA). Each scenario is identified by a combination of year, emission scenario, and cost scenario. For instance, “2035 BAU INT” refers to the results obtained for the year 2035, using the BAU emission scenario and the Intermediate cost scenario. The parameters for each scenario are provided in Table 3-1. Detailed explanation of each cost component’s calculation can be found in the Technical Documentation

Table 3-1. Parameters Used in Economic Feasibility Assessment

Parameters (Unit)	Symbol	Scenario (sc)				Notes
		Year*	Optimistic (OPT)	Intermediate (INT)	Challenging (CHA)	
Fuel cost (\$/kWh)	λ_{sc}^{ULSD}	2022	0.081			Diesel fuel cost for transportation in Reference case in Annual Energy Outlook 2023 (EIA, 2023)
		2035	0.093			
		2050	0.097			
Charging cost (\$/kWh)	λ_{sc}^{Ch}	2022	0.133			Costs under Optimistic, Intermediate, and Challenging scenarios are from electricity costs under Low Zero-Carbon Technology, Reference case, and High Zero-Carbon Technology scenarios for the transportation sector in Annual Energy Outlook 2023, respectively (EIA, 2023)
		2035	0.138	0.140	0.142	
		2050	0.136	0.142	0.144	
Charging infra cost (\$/kWh)	λ_{sc}^{CI}		0.042			Sum of costs of electric vehicle supply equipment, grid connection, and operations and maintenance costs for Tens-MW scale charging facility (Popovich et al., 2021)
Battery system cost (\$/kWh)	λ_{sc}^{B}	2022	377.5			- \$151/kWh battery pack cost (BNEF, 2022) - 40% of battery pack share in battery system cost (MANES, 2020) - Cost projection of 1-hour commercial battery storage from Annual Technology Baseline, NREL (NREL, 2022)
		2035	173.7	253.5	319.8	
		2050	139.0	202.8	319.8	
CO_2e social cost (\$/CO_2e tonnes)	$\lambda_{CO_2e,sc}$	2022	190			Social cost of CO_2 under a 2% interest rate (EPA, 2022b)
		2035	250			
		2050	310			
NO_x emission cost (\$/NO_x tonnes)	λ_{NO_x}		13,000			Average marginal damages per tonnes of emissions (Goodkind et al., 2019)
SO_x emission cost (\$/SO_x tonnes)	λ_{SO_x}		24,000			
Discount rate	r^D		2.0			Authors' assumption
ICE O&M cost factor	F_{ICE}^{OM}		10%			O&M cost ratio to ICE fuel cost. The ratio is from that of small feeder ships (Kersey et al., 2022)
O&M for Electric Ship as Percent of ICE	F_{BES}^{OM}		50%			Authors' assumption
Battery system cost decrease rate	r^B		2.2 %			Average cost decrease rate of battery system is extracted from Annual Technology Baseline, NREL (NREL, 2022)
Factor of delivered energy for second life battery (SLB)	F^{SLB}		72%			Assuming the battery, at end of life, can be used for second-life usage from a state of health of 80% to 40% (Sathre et al., 2015)
Factor of re-purposing cost of SLB	F^{RP}		15%			Re-purposing cost of SLB (Shahjalal et al., 2022)

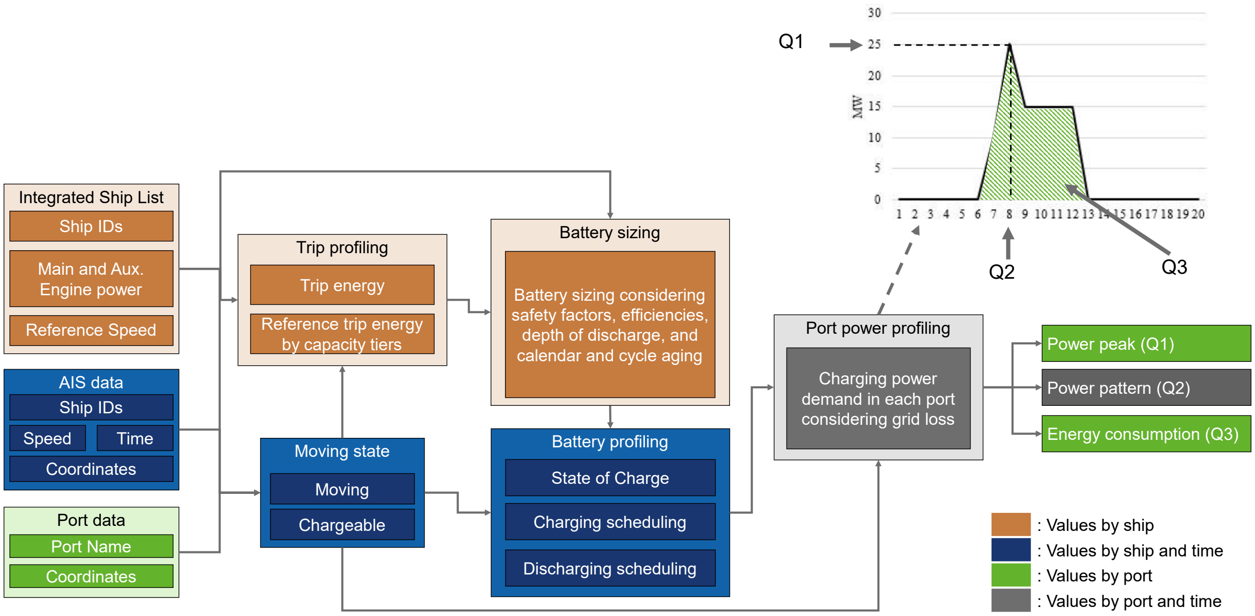
* All costs by year are in 2022 USD.

3.2.3 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 GT as explained in the Technical Documentation. 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 the Technical Documentation.

3.3 Grid Requirements for Vessel Electrification

The grid requirement for each port is calculated according to the process illustrated in Figure 3-11. 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.



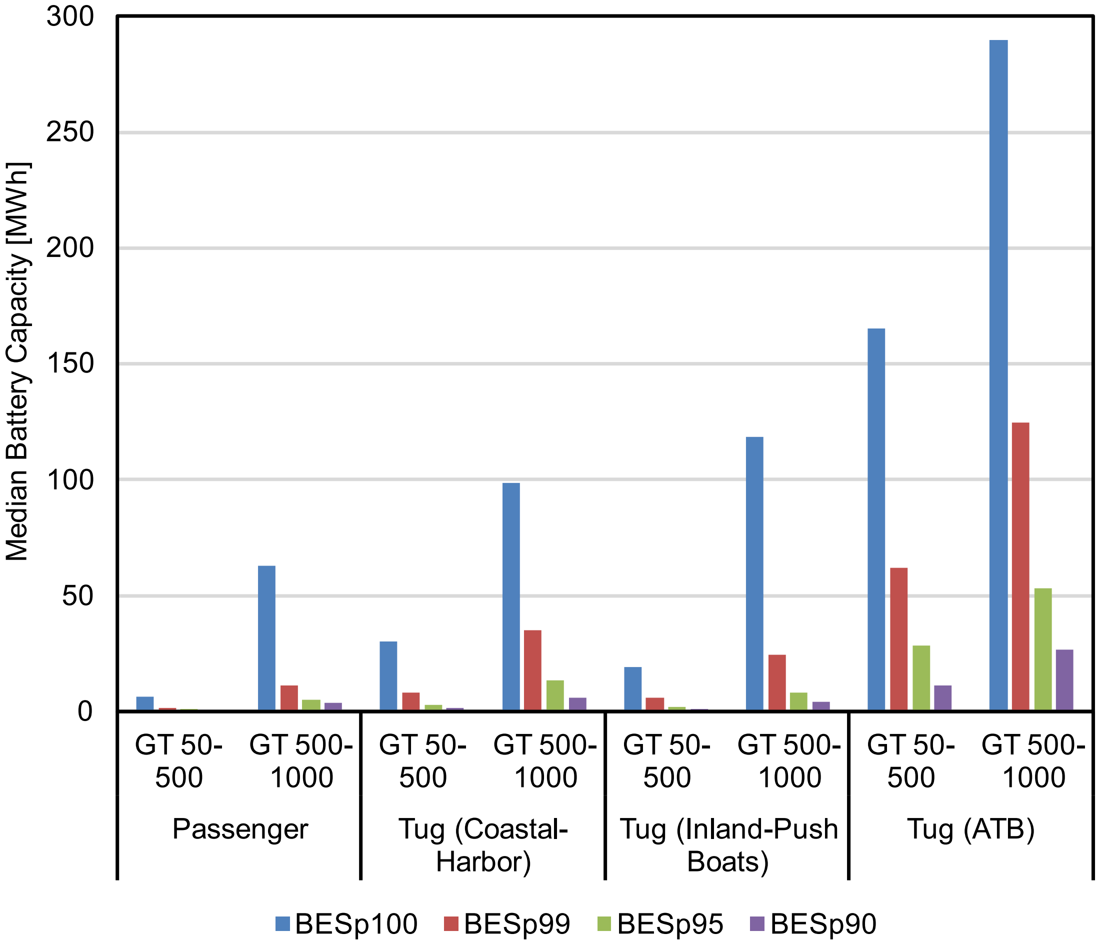
Q1 (far right) will answer how much maximum power will be needed by the port.
Q2 will answer when and how often power will be required during the year.
Q3 will answer how much energy will be required for BESs during the year.

Figure 3-11. Conceptual Framework for Estimating BES Grid Charging Requirements

4. Results

4.1 Battery Size by Ship Type and GT

Figure 4-1 presents a comparison of median battery capacities by capacity tier, ship size in GT, and ship type. The analysis shows a consistent trend wherein the required battery capacity decreases as the capacity tier decreases across all ship types and ship sizes. This is intuitive, since battery sizes for BESs with lower capacity tiers are calculated using a lower reference trip energy $E_{v,pX}^{ref}$ as in equation (16) (see Technical Documentation). Similarly, as GT increases, battery size also tends to increase. This correlation can be attributed to the larger capacity of main and auxiliary engines that are typically found in ships with higher GT. ATB tugs exhibit the largest battery capacity requirements, followed by coastal-harbor tugs and inland and push tugs, because ATB tugs have more energy demanding trips than other tugs. When comparing ships within the same GT range, passenger ships tend to require smaller battery capacities than any type of tug (see Section 5.2).



Only categories with ship counts over 10 are shown.

Figure 4-1. Median Battery Capacity by Ship Size, Ship Type, and Capacity Tier

Table 4-1 presents the median battery capacity according to ship type and GT. It also shows the reduction ratio in battery size compared with that of BESp100 in each capacity tier. As the capacity tier decreases from BESp100 to BESp99, BESp95, and BESp90, the battery size shows an average reduction of 67%, 86%, and 92%, respectively. When comparing BESp99, the largest reduction in battery size is observed for Passenger ships with 500-1000 GT, followed by Tug (Inland-Push Boats) with 500-1000 GT. The smallest reduction trend is observed for Tug (ATB) with 500-1000 GT. These reductions can be attributed to the specific trip characteristics of each ship type. Further discussion of this topic can be found in Section 5.2.

Additionally, BESp99 and BESp95 demonstrate the potential to reduce battery size by excluding the top 1% and 5% energy demanding trips from BES trips, resulting in battery size reductions ranging from a minimum of 57% to a maximum of 93% compared to BESp100. However, it should be noted that the actual ratio of unserved trip energy is higher than that of the top 1% and 5%. This ratio varies among different ships, and the ratio of unserved trip energy also exhibits different trends based on ship types. This aspect of the analysis is also discussed in Section 5.2.

Table 4-1. Median Battery Capacity by Ship Size, Ship Type, and Capacity Tier

	GT		Ship Count	Capacity Tier			
	Min	Max		BESp100	BESp99	BESp95	BESp90
				Median Battery Capacity [MWh] (Percentage Reduction Below BESp100)			
Passenger	50	500	272	6.2	1.5(77%)	0.8(87%)	0.6(90%)
	500	1000	34	62.9	11.1(82%)	5.0(92%)	3.5(94%)
Tug (Coastal-Harbor)	50	500	1311	30.2	8.2(73%)	2.9(91%)	1.4(95%)
	500	1000	84	98.5	35(64%)	13.3(87%)	5.8(94%)
Tug (Inland-Push Boats)	50	500	776	19	5.8(69%)	2.0(90%)	1.0(95%)
	500	1000	159	118.4	24.5(79%)	8.2(93%)	4.1(97%)
Tug (ATB)	50	500	30	165.2	61.7(63%)	28.5(83%)	11.4(93%)
	500	1000	50	289.6	124.7(57%)	53.0(82%)	26.8(91%)

4.2 Electricity Requirements for BES Charging

For the 2,722 ships in the AIS Analyzed Subset (of all 6,323 Domestic Fleet ships meeting our study's specified range between 50 and 1000 GT), we estimated their total annual electricity demand to be 3.8 TWh. Because the combined GT of all 6,323 Domestic Fleet is twice that of the AIS Analyzed Subset, the Domestic Fleet's projected annual electricity demand is expected to reach 7.7 TWh.

Figure 4-2 illustrates the electricity requirements for BESp100s of the AIS Analyzed Subset by state and port. Three of the top five ports with the highest electricity demand are located in Louisiana. Among all 150 ports analyzed, New York's port has the greatest electricity demand, totaling 238 GWh. The top 20 ports, colored red, collectively account for 46% of the overall electricity demand, highlighting the disproportionately high needs of a relatively small number of ports. These findings underscore the critical need for concentrated power and energy infrastructure in select states and ports to effectively support vessel electrification.

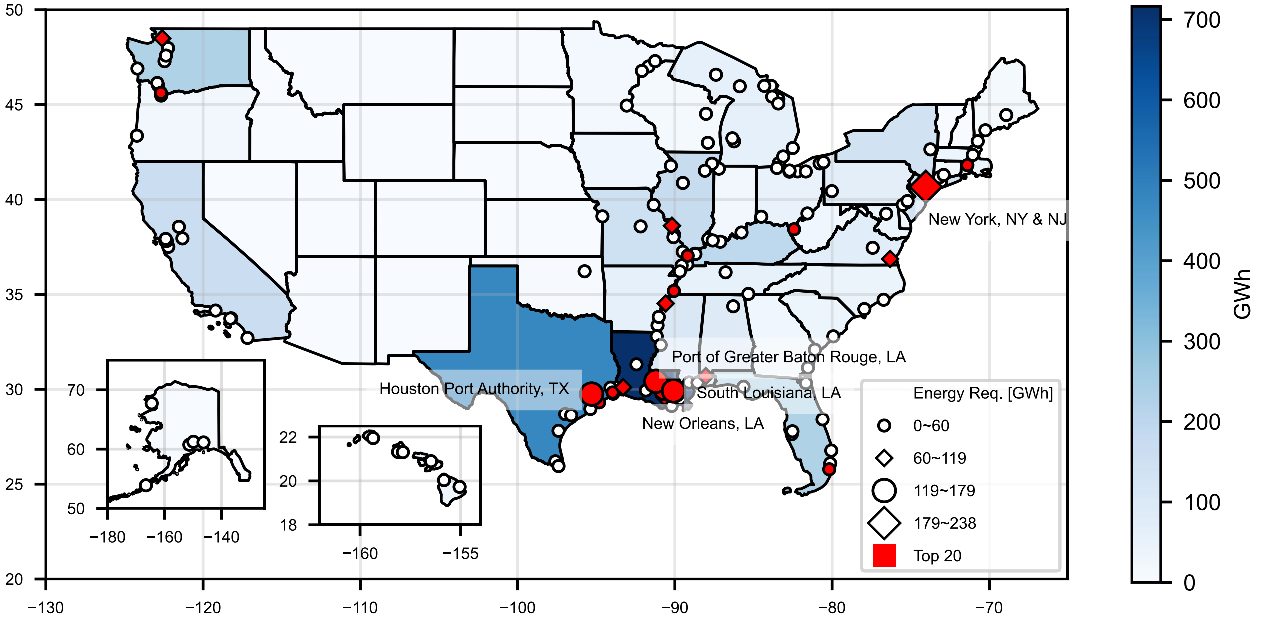


Figure 4-2. Electricity Demand by State and Port for BESp100s in the AIS Analyzed Subset

Figure 4-3 shows the charging demand for BESp100s by state and ship type. Louisiana emerges as the leading state in terms of electricity demand, requiring 716 GWh, or a 0.8% increase over statewide 2021 electricity demand. Texas and Florida follow with 477 GWh and 231 GWh, respectively. Most electricity demand for BES charging in New Jersey and New York occurs at New York's port, which has the highest electricity demand among all U.S. ports. Tugboats exhibit the highest electricity requirements in every state, constituting 99.6% and 99.9% of the total charging demand in Louisiana and Texas, respectively. California is unique in that passenger ships (not tugs) account for the greatest demand, representing 30.6% of total BES charging demand. This is primarily attributed to the large share of passenger ships in the state, as depicted in Figure 4-3. The additional demand ratio on the electric grid by state, plotted in black dots, suggests that the increase in electricity demand from BES charging is manageable in terms of expanding supply at the state level, as electricity demand on the grid increases by only 0.1% to 0.8 % in the top 10 states. While these ships do not account for the entire fleet of potentially electrifiable domestic vessels, they represent 49% of tonnage on average in each state.

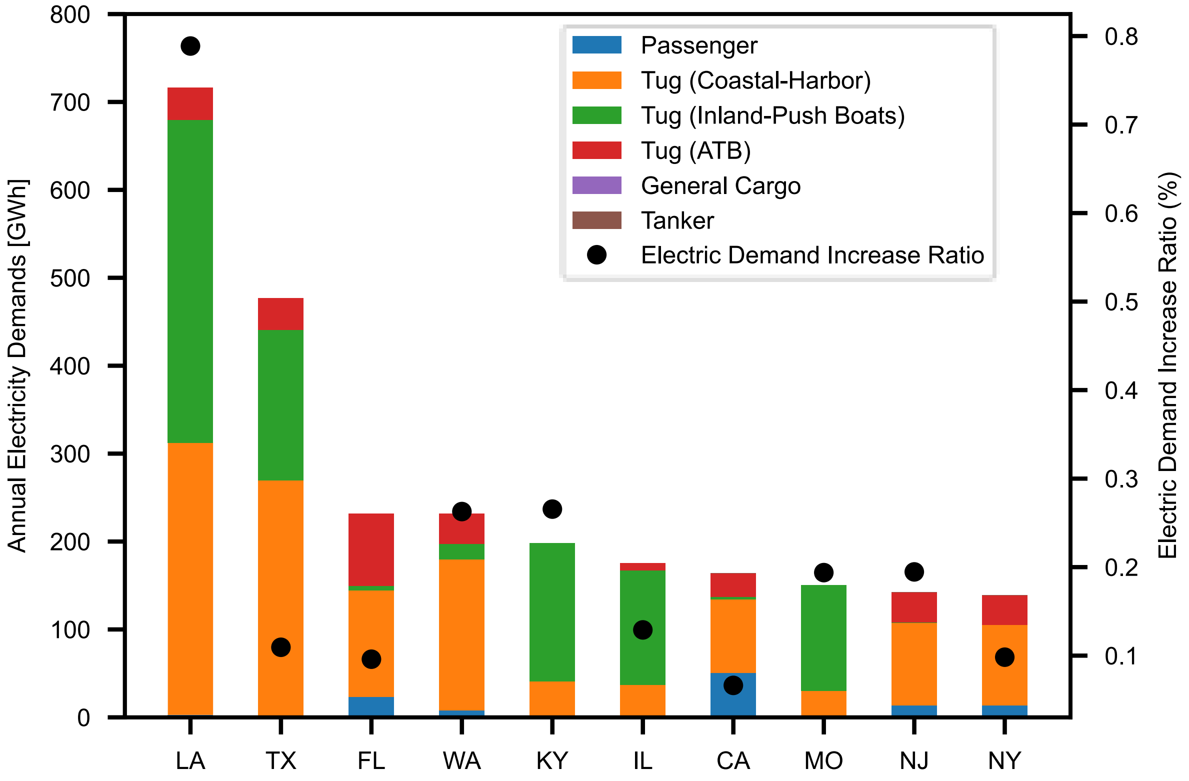


Figure 4-3. Annual Electricity Demand by State and Ship Type for BESp100s in the AIS Analyzed Subset

Figure 4-4 shows that the top 20 ports account for 46% of the total electricity required for BESp100s in the AIS Analyzed Subset. The port with the highest electricity requirement is New York (238 GWh), followed by New Orleans (159 GWh) and the Port of Greater Baton Rouge (148 GWh). Of the top 20 ports, tugboats require the largest portion of energy in all but one. (Only in the Port of Providence, where passenger ships' electricity demand constitutes 50.4%, does the electricity demand from tugs fall below 50%.) These results indicate that battery-electric tugs will play a crucial role in the electrification of domestic maritime transportation.

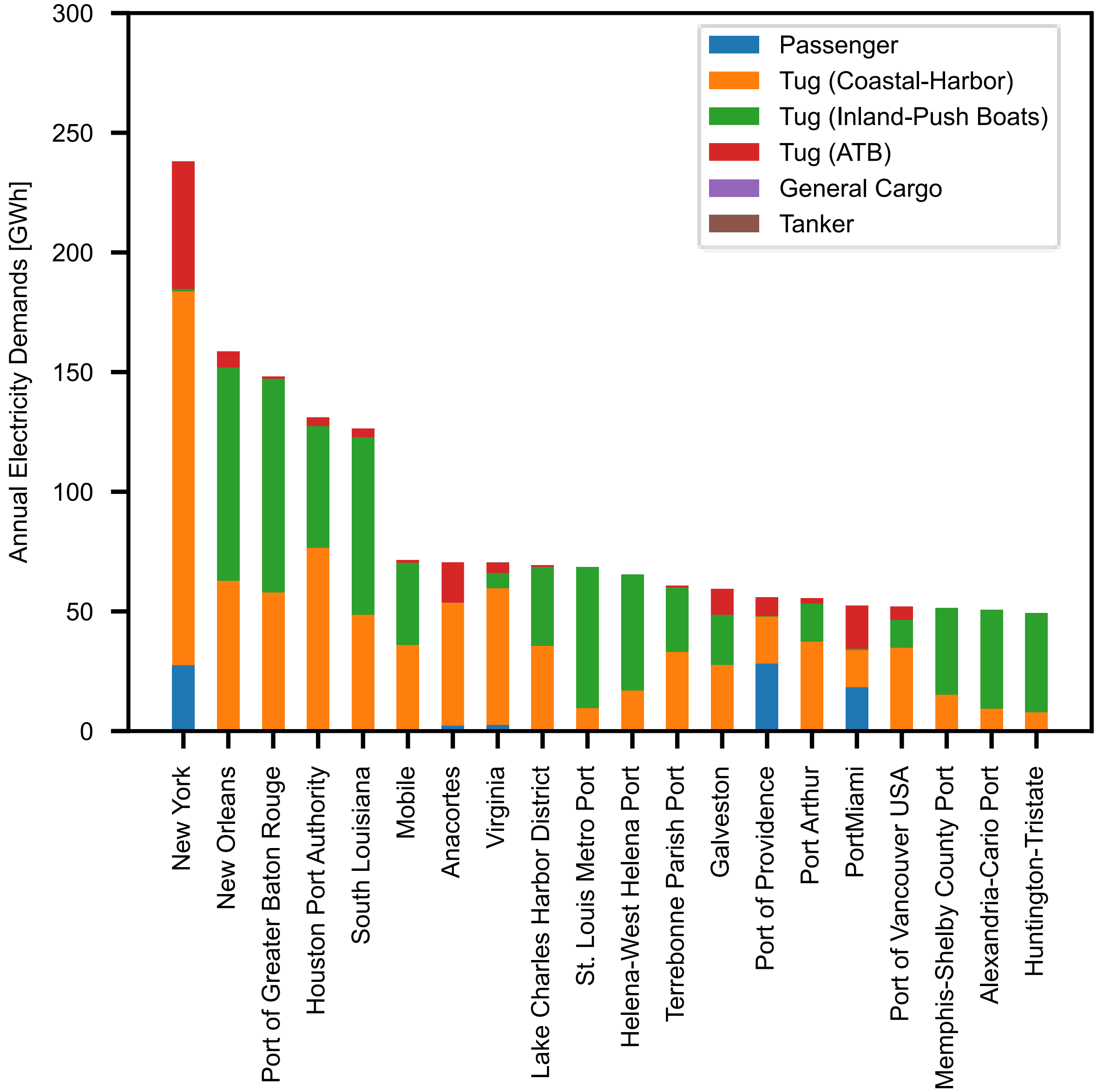


Figure 4-4. Annual Electricity Demand by Port and Ship Type for BESp100s in the AIS Analyzed Subset

Additional electricity demand varies by state, but in most cases it is less than 1% of 2021 statewide electricity demand, indicating that this is an achievable expansion of electricity supply. However, the concentrated charging needs for BESs at specific port locations is likely to create a significant burden on ports' existing power systems. For example, according to a recent survey by GSGP and ABS (2022), the existing power capacity at the Illinois International Port, a large port in the Great Lakes region, is 700 kW, perhaps suggesting that existing power facilities could be sufficient to power BES charging. Using a simple calculation (700 kW × 24 h × 365 days), we see that this port can consume 6.1 GWh annually. However, the port's SPC capacity is 300 A with 480 V, which is 144 kW, and thus the port's SPC can only supply a maximum of 1.3 GWh per year.

Based on our analysis, charging demand at this port will be 15.4 GWh per year, which is 2.5 times its theoretical maximum consumption of 6.1 GWh and 12 times its actual maximum supply of 1.3 GWh. This indicates that the port will require significant additional capacity, both in terms of power and charging facilities, to supply electrified ships. While this need may vary by port, our analysis reveals that there are 76 ports with even greater charging requirements than the Illinois International Port.

Figure 4-5 shows the ratio of supplied electricity at the Illinois International Port under Historical Activity-based Charging and Trip-Based Charging by charging capacity. Again, Historical Activity-based Charging is a charging strategy that aligns with each ship's historical activity, while Trip-Based Charging involves charging for a longer duration than the ship actually stayed at port (see Section 3.1.2) It is shown that the existing 114 kW of its SPC could only cover 0.3% of charging demand, which is 52 MWh under Historical Activity-based Charging. To meet 50% of charging demand under Historical Activity-based Charging, a substantially greater power capacity of 17 MW is required. However, this requirement can be significantly alleviated with the implementation of Trip-Based Charging, which only needs 4.9 MW of capacity.

With a capacity of 10.8 MW, 95% of charging needs can be met under Trip-Based Charging, whereas only 33.8% of needs are met under Historical Activity-based Charging. These results indicate that adjusting ship activity can help alleviate charging power requirements. Nevertheless, despite the benefits of Trip-Based Charging in serving a larger share of charging demand with less power capacity, the port would still need to add a substantial amount of power infrastructure to meet overall BES charging demand. In this regard, other potential solutions – such as installation of a port microgrid with renewable energy generation and storage around the port site, or implementation of a battery swapping-based BES-SPC system – could be considered (Zhang et al., 2023).

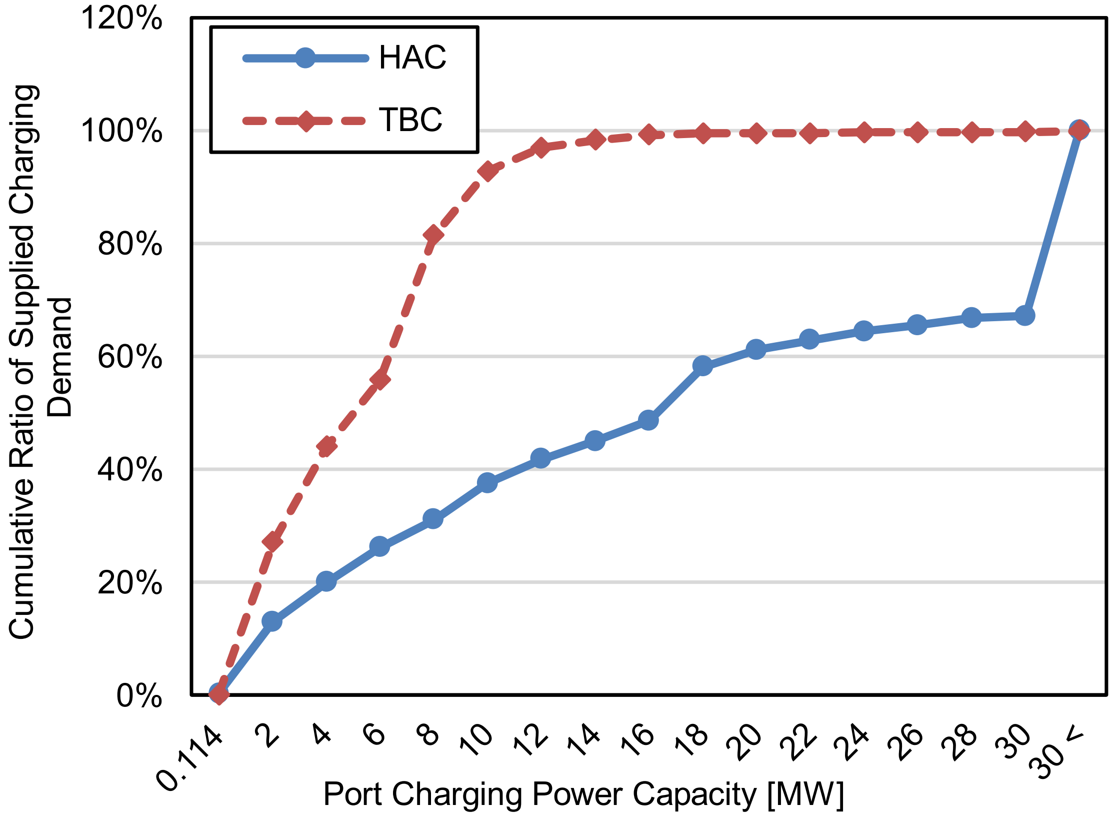


Figure 4-5. Ratio of Supplied Charging Demand under Historical Activity-Based Charging (HAC) and Trip-Based Charging (TBC) at the Illinois International Port

4.3 Emissions

We estimate total operational emissions of ICEs from the AIS Analyzed Subset to be approximately 2.1 $MMTCO_2e$. This figure represents 9.5% of the 21.9 $MMTCO_2e$ emitted by the U.S. domestic shipping fleet in 2021. The geographical distribution of ship activities and their associated emissions are shown in Figure 4-6. This emissions map reveals that ship activities within the AIS Analyzed Subset of this analysis are mainly concentrated in the East Coast, Gulf Coast, and inland waterways. This trend is also seen in the major ports with high charging requirements, which are presented in the following subsection.

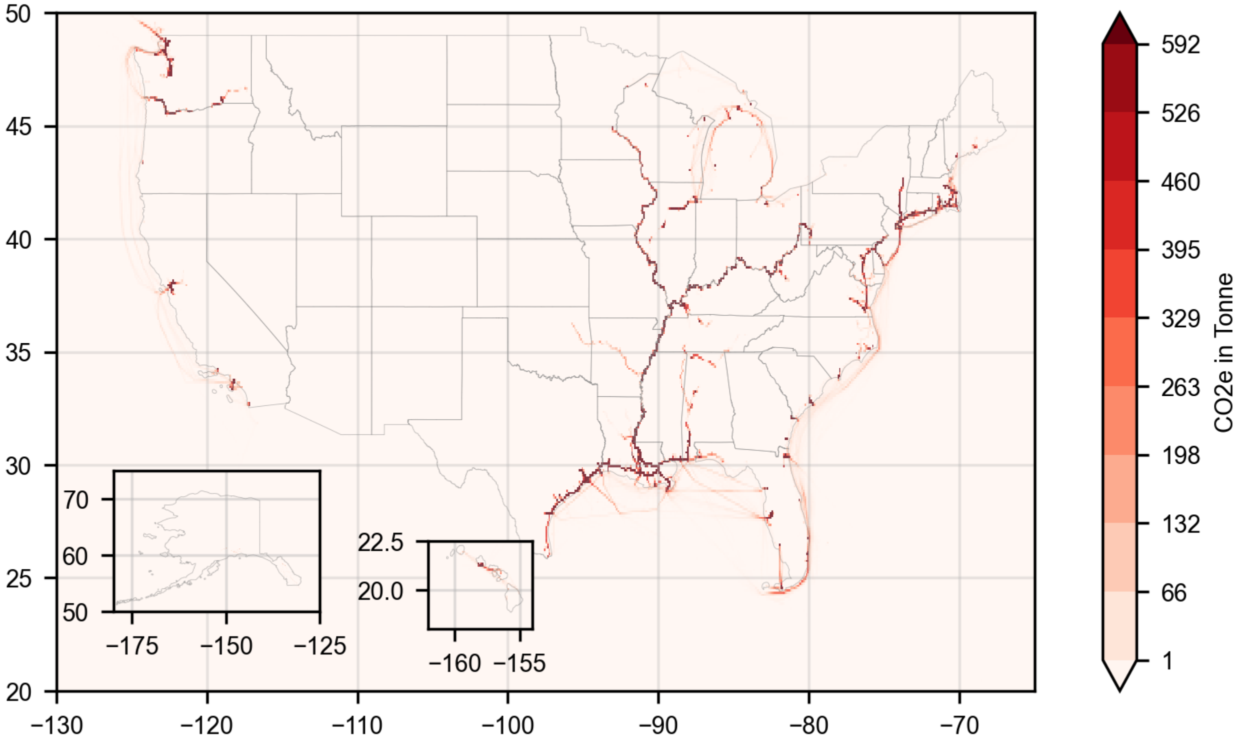


Figure 4-6. CO_2e Emissions from ICE Ships in the AIS Analyzed Subset

Figure 4-7 shows emissions from ICEs and BESp100, encompassing all ICE trips. BES emissions are estimated under BAU and DEC scenarios using NREL's Cambium model, referring to the "Mid-case" and "Mid-case 95 by 2050" scenarios (Gagnon et al., 2021), respectively (see Section 3.4.2). The AIS Analyzed Subset's ICE ships emitted 2.5 $MMTCO_2e$ annually, with 2.1 $MMTCO_2e$ from operation and 0.4 $MMTCO_2e$ from ULSD Well-to-Tank.

Under BAU, BES emissions are 2.3 $MMTCO_2e$, only 8% less than ICE. However, emissions decrease over time to 1.6 $MMTCO_2e$ in 2035 and 1.3 $MMTCO_2e$ in 2050 under BAU. More notably, under DEC, emissions decrease significantly to 1.4 $MMTCO_2e$ in 2035 and 0.6 $MMTCO_2e$ in 2050. Thus, BES emissions are substantially lower under DEC compared to BAU. For BAU, emissions decrease by 34% and 48% in 2035 and 2050, respectively; under DEC, these reductions are much more substantial, at 42% and 75%. When transitioning from BAU to DEC, emissions decrease by 8% in 2035; in 2050, the decrease is even more substantial at 27%. When comparing the BAU and DEC scenarios, differences in emissions are observed not only from electricity generation but also from battery manufacturing. This occurs because the emission factor for battery manufacturing assumes that around 40% of the energy required for battery production comes from domestic electricity. Power sector decarbonization therefore influences emissions not only during BES operation but throughout the BES life cycle. Furthermore, in consideration of the Biden-Harris administration's goal of 100% power system decarbonization by 2035, the emissions reduction trend this study assumes for BESs in 2050 could be accelerated to 2035 (USEOP, 2021).

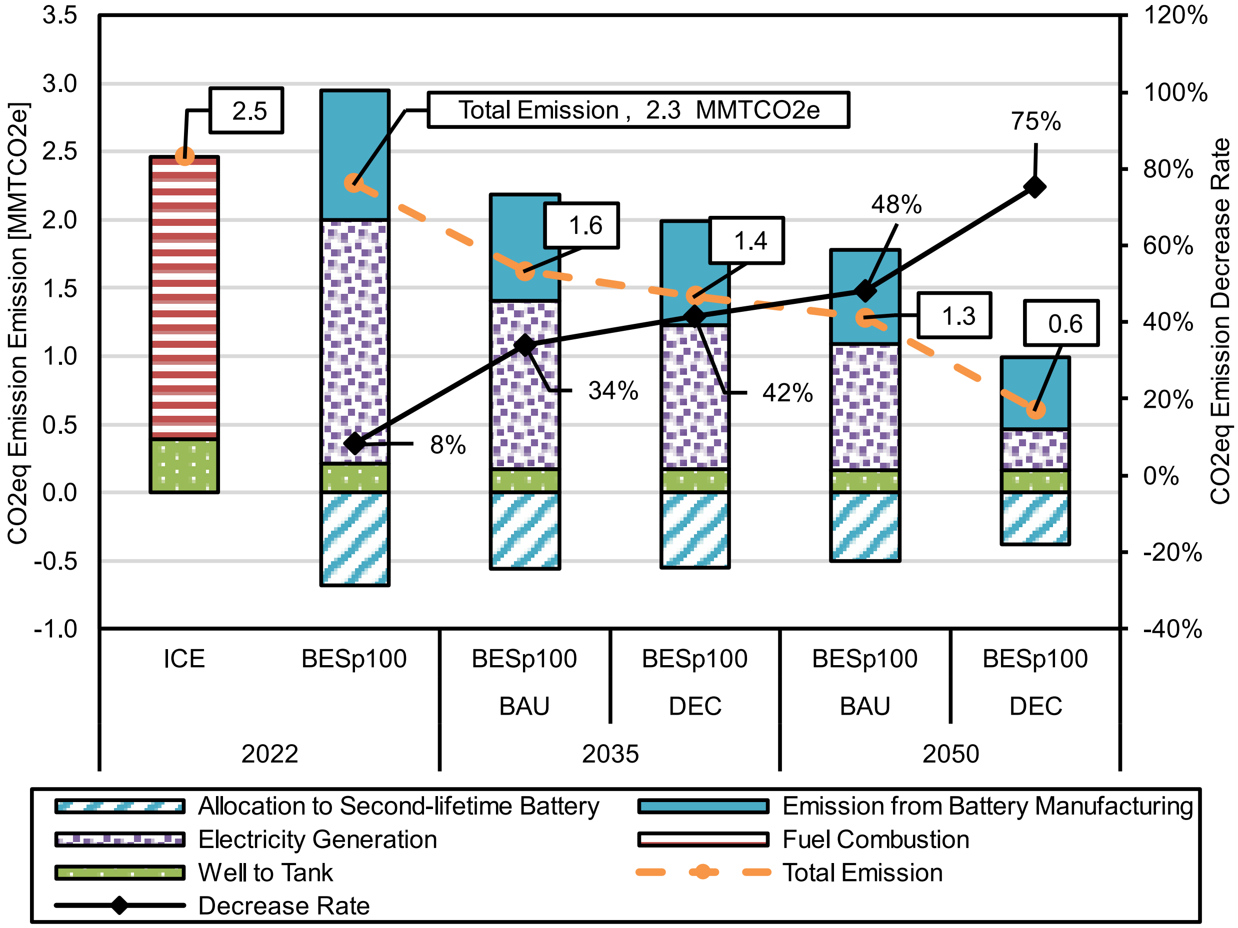


Figure 4-7. Annual CO_2e Emissions from ICE Ships and BESs

Figure 4-8 presents detailed emission results for BESs based on their capacity tiers. Again, "BESpX" represents BES ships that perform only X% of total ICE trips. Since BESs with lower capacity tiers do not serve all ICE trips, direct comparison of their respective total CO_2e emissions can be misleading. To ensure an appropriate comparison, we have estimated per distance CO_2e by dividing total emissions by the annual traveled distance for each capacity tier.

The analysis reveals a clear trend: as the capacity tier decreases, CO_2e emissions also decrease. This reduction is attributed to smaller battery sizes in lower capacity tiers, leading to lower emissions from battery manufacturing. The percentage of CO_2e emissions from battery manufacturing decreases for lower capacity tiers, with values of 56.8%, 28.1%, 20.3%, and 16.8% for p100, p99, p95, and p90, respectively. Note that these calculations do not incorporate the emissions allocation to second-life batteries (SLBs), which decreases total CO_2e emissions from battery manufacturing by 72%. This allocation results in net CO_2e emissions from battery manufacturing decreasing to between 4.7% and 15.9% of total BES emissions.

The most cost-effective emission reduction scenario involves retrofitting ICEs to BESp90 under a 2050 DEC scenario, which achieves an 81% reduction in per distance CO_2e emissions compared to ICEs in

2022. While Well to Tank emissions show minimal change among scenarios, considering decarbonization across industries could lead to decreased emissions in the Well to Tank stage, resulting in even greater emission reductions beyond the 81% just described. Again, incorporating the Biden-Harris administration's goal of achieving 100% power sector decarbonization by 2035 could potentially accelerate to 2035 the BES emission decrease trend seen in 2050 (USEOP, 2021).

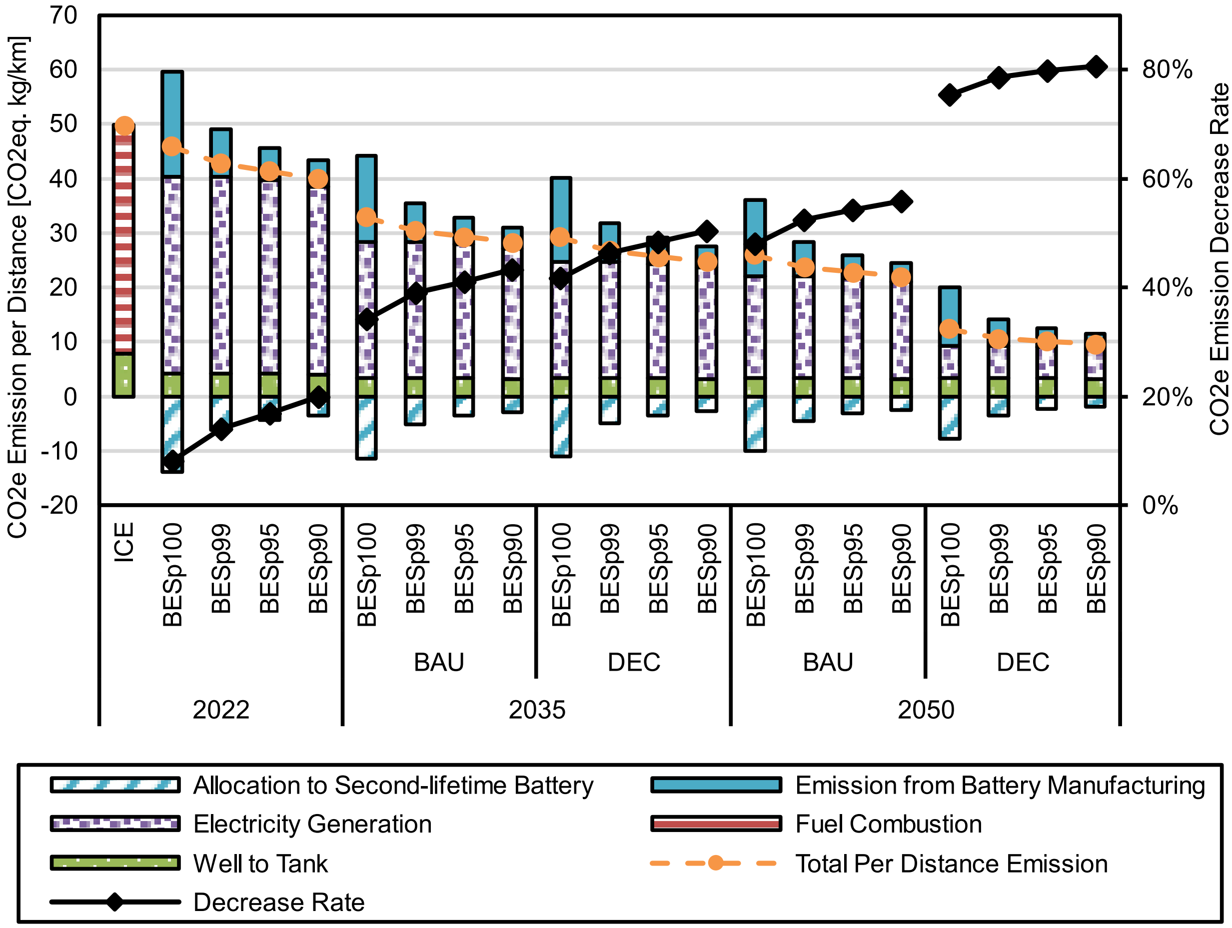


Figure 4-8. Per Distance CO_2e Emissions from ICE Ships and BESs of Various Capacity Tiers

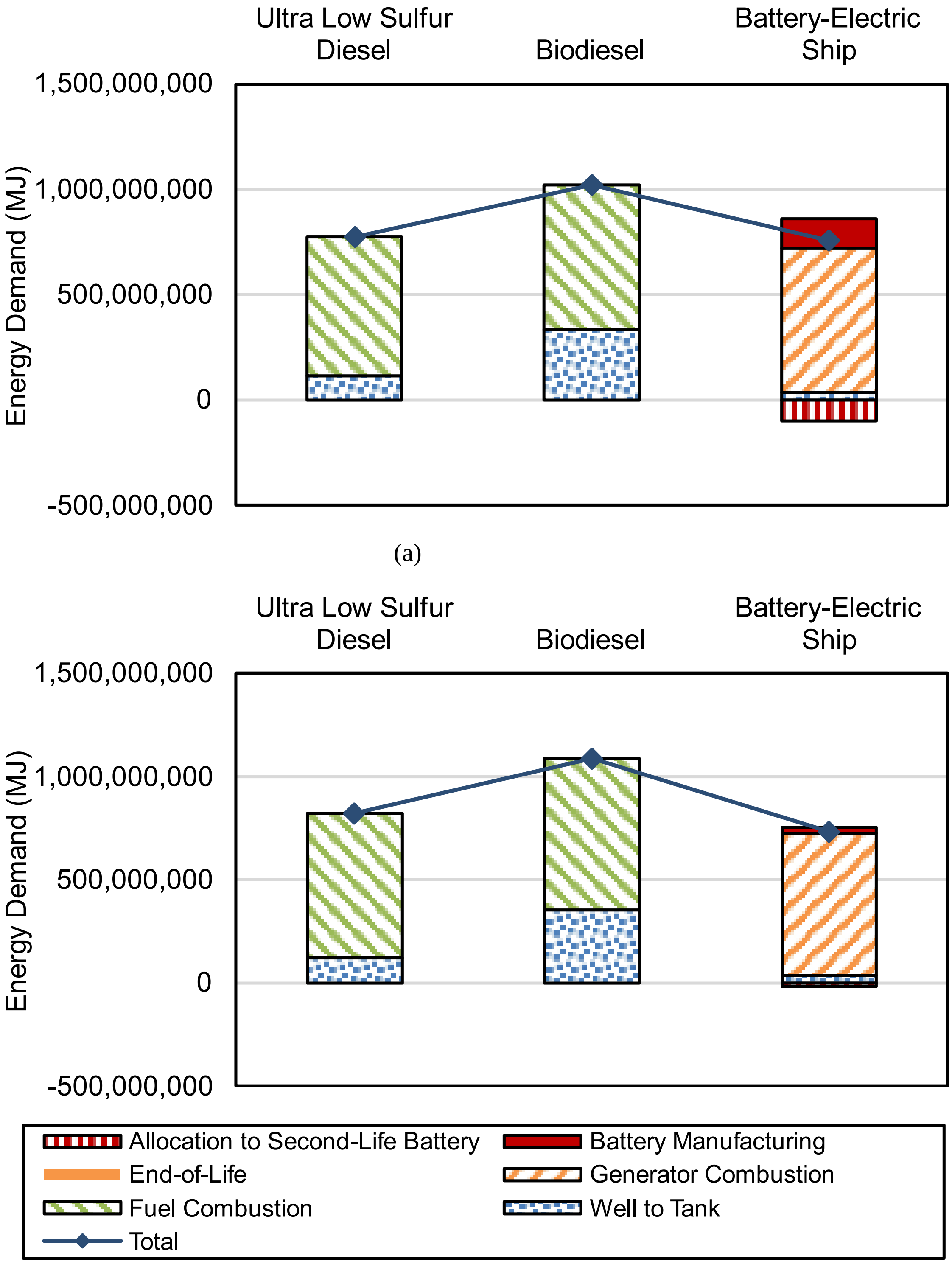
4.4 Life Cycle GHG Emissions

Although Louisiana has the highest charging energy requirement (see Figure 4-2), its lower decarbonization target limits the potential of BESs to reduce CO_2e emissions. To demonstrate the effects of rapid decarbonization, we conducted an LCA analysis on two vessels: a Tug (Coastal-Harbor) of 632 GT registered in Texas, and a Passenger vessel of 462 GT registered in California. The results, presented in Figure 4-9, were obtained from a comprehensive 30-year examination, considering an annual energy consumption of 4,161 MWh and 4,255 MWh, respectively. To explore an alternative energy resource for ICE ships, we selected biodiesel alongside ULSD, deriving emission factors from the GREET model (Want et al., 2021).

For the ICE ships, energy consumption is categorized into two stages: “Well to Tank,” covering all energy usage before combustion; and “Fuel Consumption,” encompassing energy consumed onboard or during electricity generation through combustion. Emission factors for the production, refining, and combustion of ULSD and biofuels are based on the GREET 2021 U.S. average fuel mixes.

For BESs, energy consumption is categorized into five stages: “Well to Tank,” covering all energy usage before generation; “Generator Combustion,” including emissions during electricity generation; “Battery Manufacturing,” representing the production of vessels’ Li-ion batteries from raw material extraction to final manufacturing; “Allocation to Second-Life Battery,” allocating energy consumption to SLBs considering the share of delivered energy during each life stage; and “End-of-Life,” accounting for any negligible energy utilized for battery recycling.

The BES modeled in Figure 4-9 uses the “95% Decarbonization by 2050 Scenario” (DEC) electricity mix projections for Texas and California derived from the NREL Cambium model (Gagnon et al., 2021). The analysis demonstrates that BESs consume less energy than ICE vessels in Texas and California, consuming 98% and 89% of the energy needed by an ICE with ULSD in each state, respectively. Energy demands for biodiesel are the highest in both states due to its higher energy consumption in the “Well to Tank” stage.



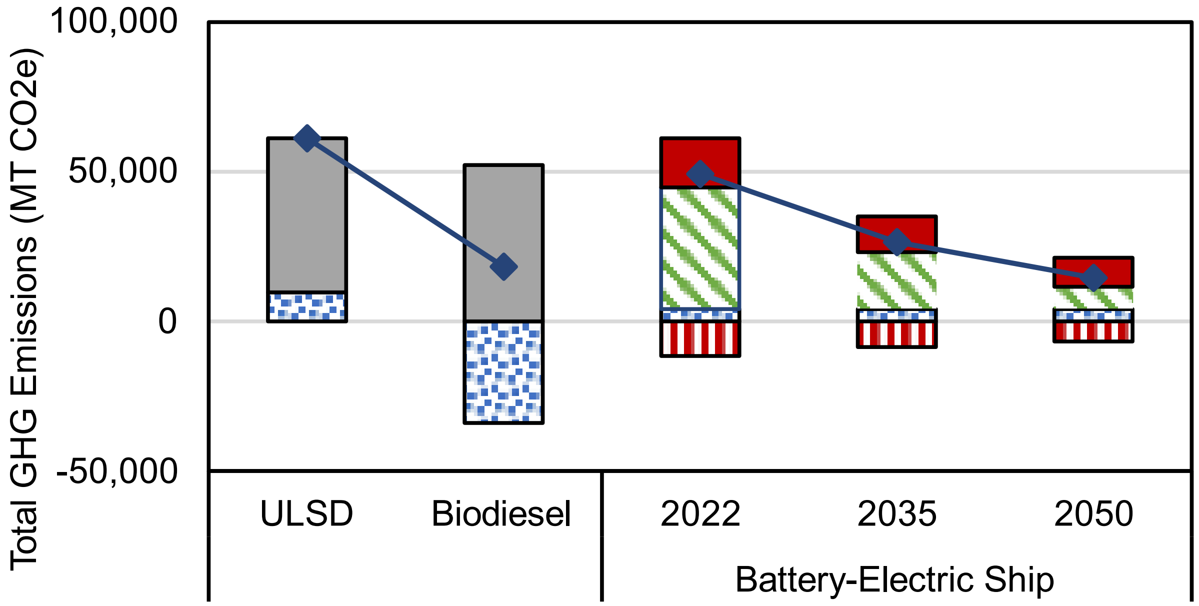
(a)

(b)

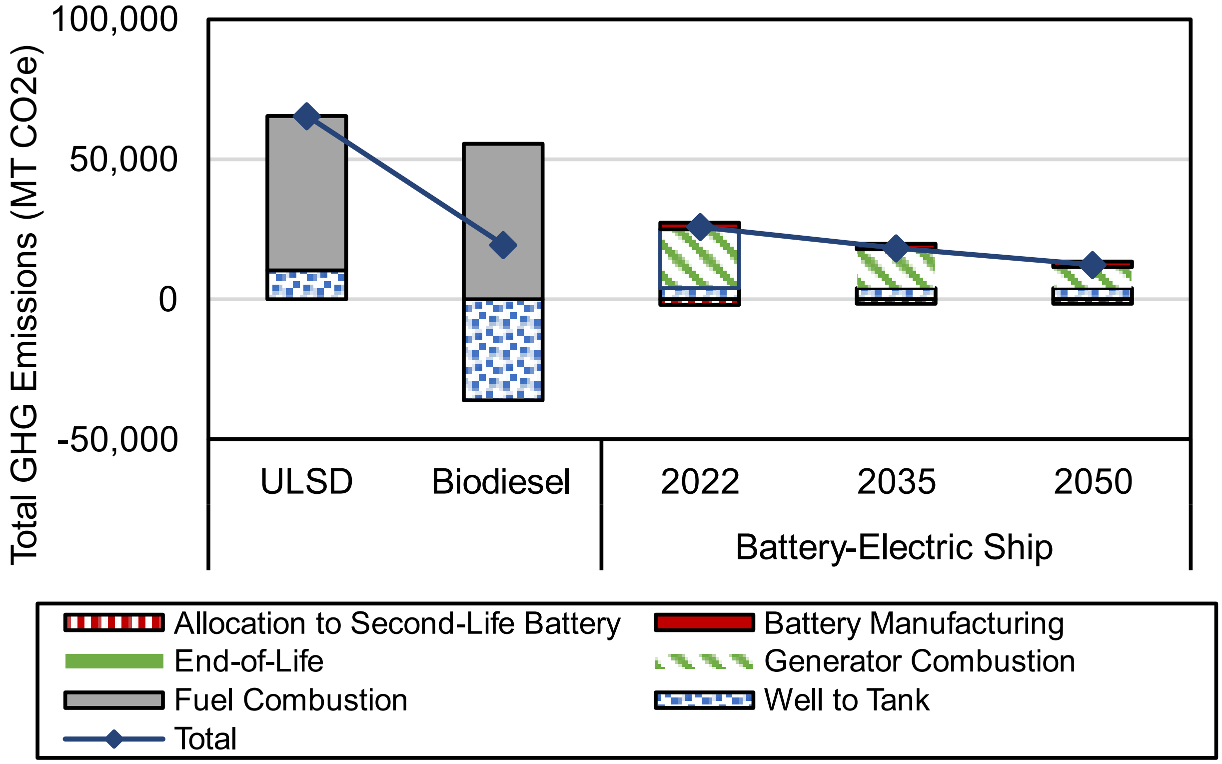
Ship details: (a) MMSI 368549000, Tug (Coastal-Harbor), Registered in Texas, 632 GT, BESp99; (b) MMSI 366857070, Passenger, Registered in California, 462 GT, BESp99.

Figure 4-9. Total Energy Demand of Selected Ships by Energy Source under a 95% Decarbonization by 2050 (DEC) Scenario

In Figure 4-10, BESs exhibit significant CO_2e emission reductions of 57% and 72% in 2035, and 77% and 81% in 2050 in Texas and California, respectively, when compared to ICE ships under the DEC scenario. Although biodiesel has a higher energy demand than ULSD, its net CO_2e emissions are lower, thanks to carbon credits from in the "Well to Tank" stage. In Texas, CO_2e emissions of BESs in 2035 are higher than those from biodiesel but become lower in 2050. In California, the CO_2e emissions of BESs are already lower than those from biodiesel in 2035. These findings demonstrate how state-level decarbonization efforts impact the emissions reduction potential of BESs and suggest that ships charging in ports with greener electricity can contribute to lowering carbon emissions.



(a)



(b)

Ship details: (a) MMSI 368549000, Tug (Coastal-Harbor), Registered in Texas, 632 GT, BESp99; (b) MMSI 366857070, Passenger, Registered in California, 462 GT, BESp99.

Figure 4-10. Total CO_2e Emissions of Selected Ships by Energy Source under a 95% Decarbonization by 2050 (DEC) Scenario

4.5 Economic Feasibility

Figure 4-11 presents the ratio of cost-effective BESs compared to ICEs considering the year, capacity tier, emission scenario, and cost scenario. The results show that when the capacity tier decreases, the ratio of cost-effective BESs compared to ICEs increases: average cost-effective ratios are 44%, 81%, 89%, and 92% for BESp100, BESp99, BESp95, and BESp90, respectively. Under the INT cost scenarios, these ratios increase by 7% for the Optimistic scenarios and decrease by 8% for the Challenging scenarios on average. In the DEC scenarios, the ratios increase by an average of 2% compared to those of BAU. Moreover, as the year increases to 2035 and 2050, these ratios also increase by an average of 28% and 38%, respectively. These results clearly indicate that changing the capacity tier has the most significant impact on BES cost-effectiveness, followed by extending the year, improving the cost scenario, and changing the emission scenario.

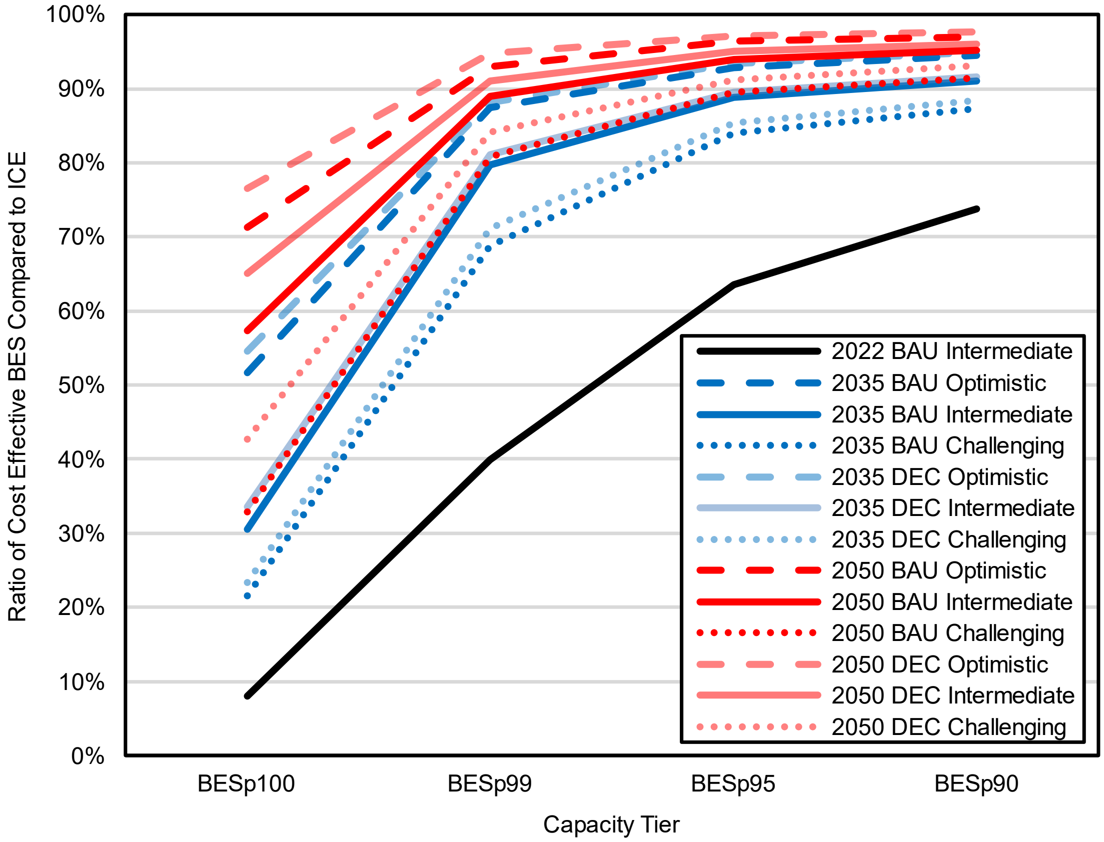


Figure 4-11. Ratio of Cost-Effective BESs Compared to ICE Ships

Figure 4-12 displays the median LCOT for both ICE ships and BESs with capacity tiers p100 and p99. For ICE ships, median LCOT increases from $25.5/km ($47.2/nautical mile (nm)) in 2022 to $29.6/km ($54.9/nm) in 2030 and $33.6/km ($62.2/nm) in 2050, driven by rising emissions and fuel unit costs.

Over time, BESs show a decreasing cost trend, which is primarily driven by reduced battery costs. In the INT cost scenarios, the unit cost of charging increases by 5.2% and 6.8% in 2035 and 2050, respectively, while the unit cost of the battery system decreases significantly by 33% and 46% during the same periods. Despite the increase in the unit cost of CO_2e emissions in 2035 and 2050, the overall CO_2e social cost of each BES declines due to reduced CO_2e emissions resulting from improvements in the emission factors of the electricity grid. The CO_2e social cost reductions are notably more significant in DEC scenarios. In the BAU scenario, the CO_2e social cost of a BESp100 decreases by 5% and 7% in 2035 and 2050, respectively. However, in the DEC scenario, the CO_2e social cost reduction is much more substantial, decreasing by 15% and 54% during the same periods.

When comparing ICEs and BESs in 2022, the ICE median LCOT falls between BESp99 and BESp90. However, in 2035 and 2050, ICEs are more expensive than BESp99 in all scenarios. In 2035, ICEs are even more costly than BESp100 under the Optimistic scenario. Notably, in 2050, BESs in all capacity tiers, except for the BAU Challenging scenario, appear to be more cost-effective than ICEs. These results demonstrate that over time, BESs are expected to gain a stronger competitive advantage over ICEs in terms of cost. The factors driving these cost variations are discussed in detail below.

Figure 4-12 shows the importance of emission costs to the median LCOT. When costs for CO_2e, NO_x, and SO_x emissions are not considered, LCOT for ICEs remains relatively stable at $9.4/km ($17.4/nm), $10.8/km ($19.9/nm), and $11.2/km ($20.8/nm) in 2022, 2035, and 2050, respectively, with only a slight increase attributable to rising fuel costs. Further, despite significant BES cost reductions resulting from lower battery system costs, BESs always show higher overall costs compared to ICEs in the absence of emission costs. These results underscore the significant impact of including emission costs as a crucial cost-effectiveness driver for retrofitting ICEs to BESs.

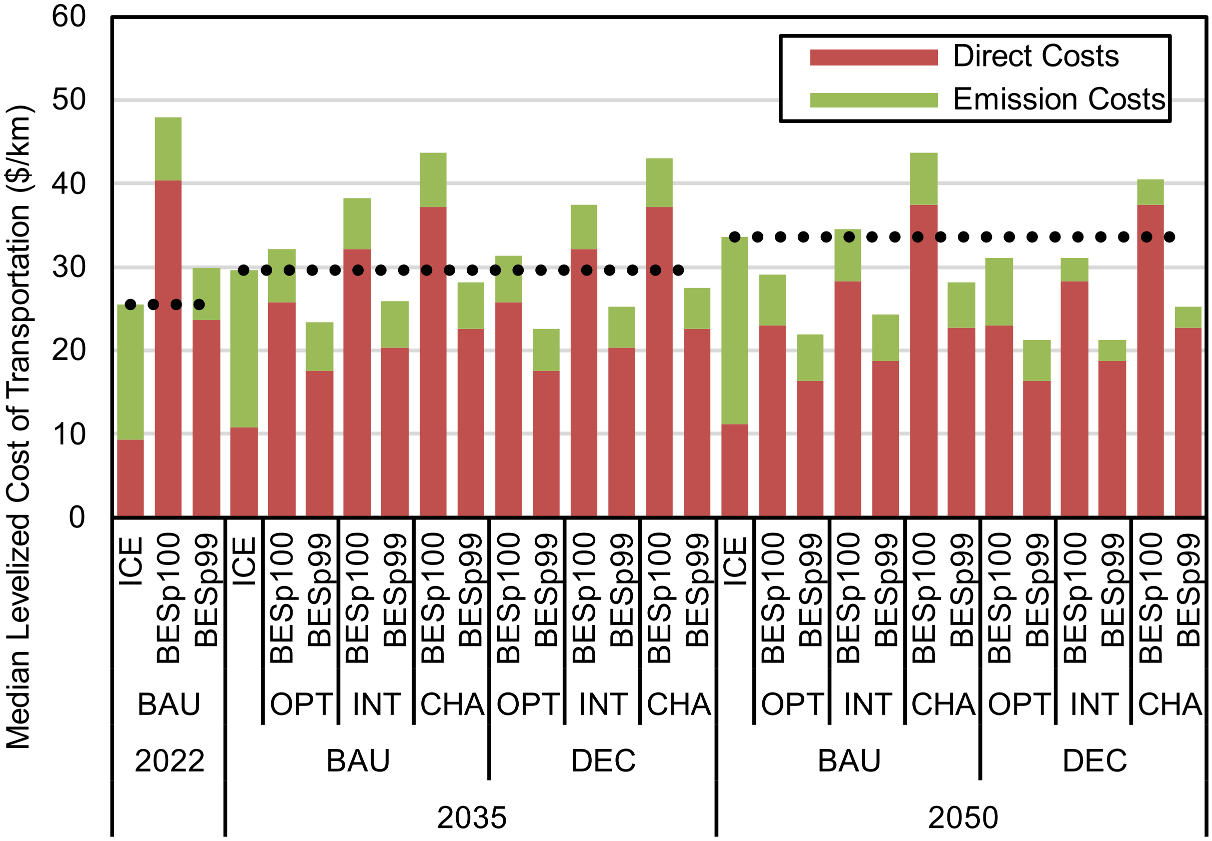


Figure 4-12. Median Levelized Cost of Transportation (LCOT), Excluding Emission Costs

Figure 4-13 shows the average LCOT breakdown for 2022. ICE ships have the lowest LCOT, followed by BESp90, BESp95, BESp99, and BESp100. For ICE ships, the emission cost accounts for 63% of the total LCOT, with 54% attributed to CO_2e social cost and 9% to air pollution cost (NO_x and SO_x). Direct costs, excluding emissions, make up only 36% of the total LCOT.

BESs exhibit a clear decreasing cost trend as the capacity tier decreases, while average cost in every tier is still more expensive than that of ICE. This trend is primarily driven by battery cost reductions resulting from smaller battery sizes. For instance, for BESp100, the combined battery cost and net battery cost after SLB reimbursements are $51.5/km ($95.5/nm) – 64% of BESp100 costs – whereas for BESp90 this cost is significantly lower at $12.3/km ($22.8/nm). Reimbursements from SLBs substantially alleviate the burden of battery cost, making BESs more economically viable. Initially, battery cost represented a substantial portion of the total LCOT, ranging from 123% to 70%. However, after factoring in SLB reimbursements, this proportion decreases to a range of 71% to 38%, where SLB values account for approximately 42% to 46% of the battery system cost. The variation in the proportion of SLB values to battery cost is attributed to the fact that lower capacity tiers tend to have shorter lifespans, resulting in less of a decrease in battery system costs (and higher SLB values). As the capacity tier decreases, other costs such as CO_2e social cost, electricity cost, and O&M cost do not vary significantly since they are proportional to energy consumption, which remains relatively constant on a per-kilometer basis. Further, as the capacity tier decreases, overall BES costs decline, and the above-mentioned costs represent an increasingly larger proportion of total LCOT.

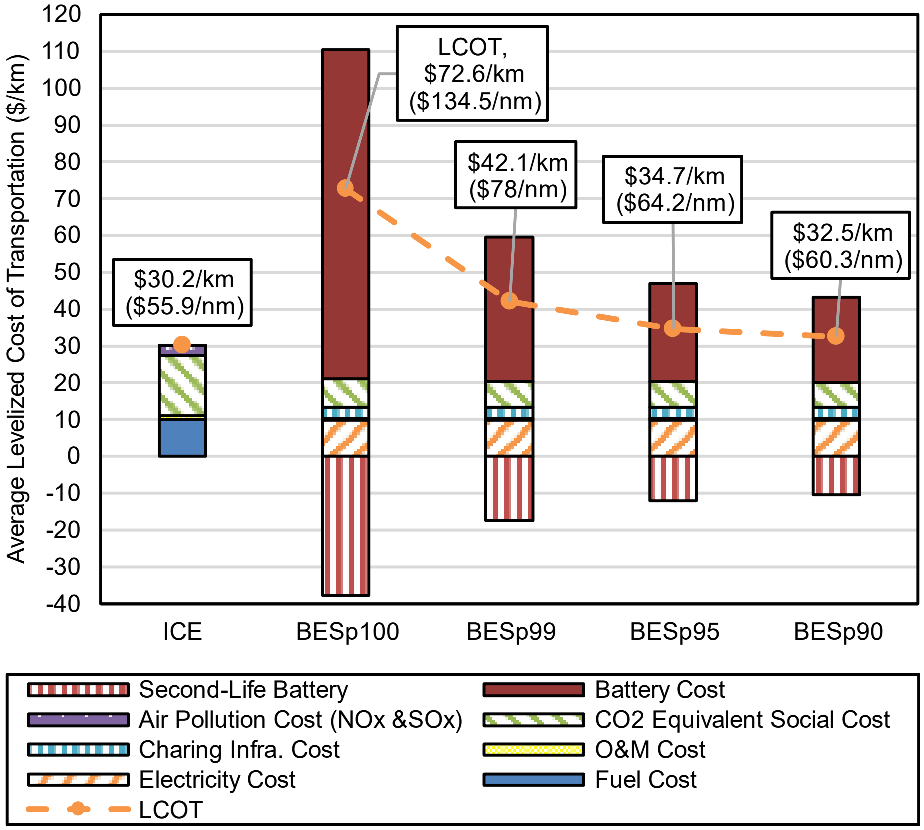


Figure 4-13. Average LCOT of ICE Ships and BESs in 2022 under an INT Cost Scenario

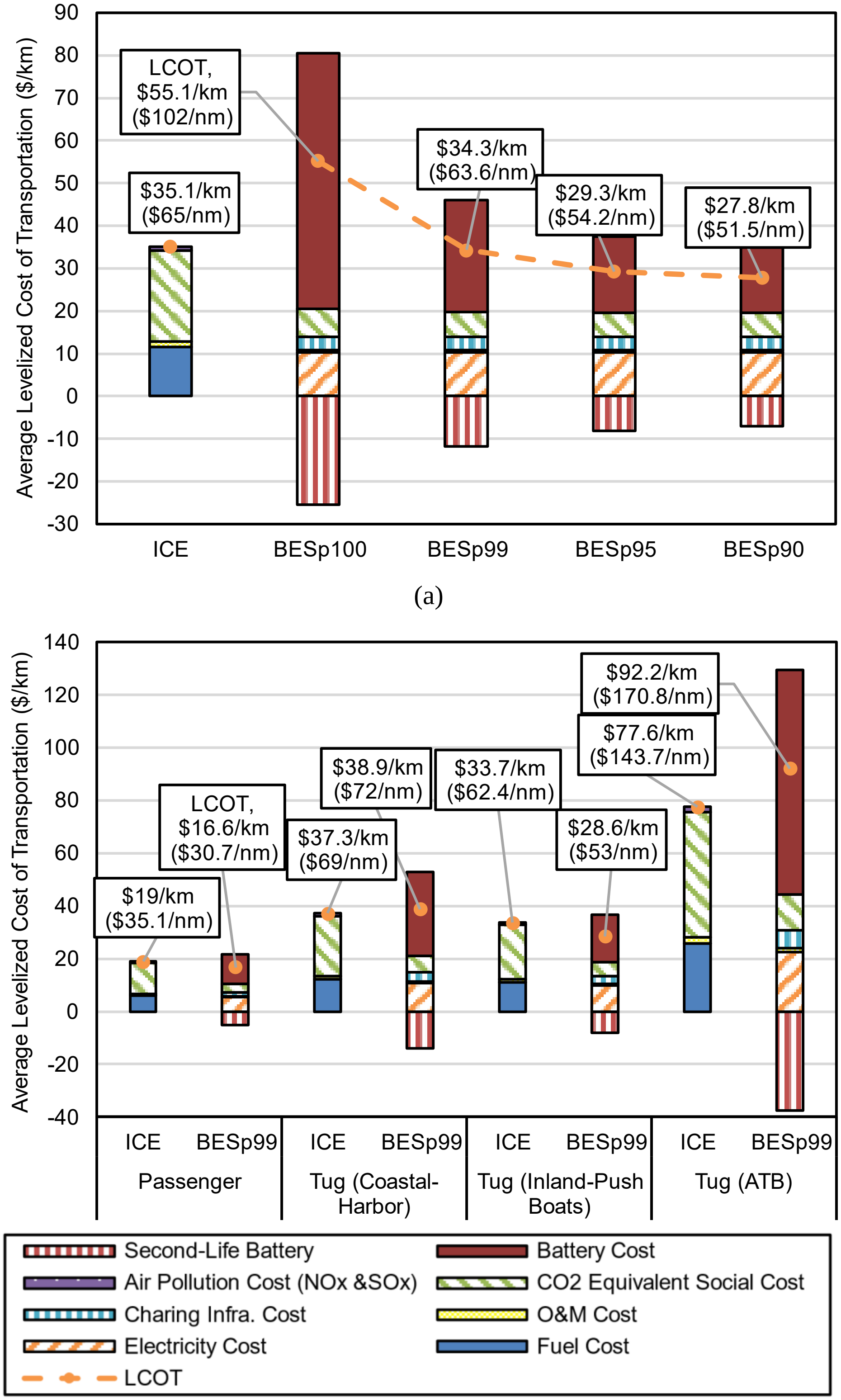
Figure 4-14 (a) illustrates the LCOT comparison between ICEs and BESs in 2035 under the INT cost scenario and the 95% Electricity Decarbonization by 2050 scenario. In 2035, all BES capacity tiers, except for BESp100, showed lower costs than ICEs in average. Compared to 2022, ICE average costs increased by $4.9/km ($9.1/nm), with the most significant driver being CO_2e social costs. However, air pollution costs decreased due to an assumed 65% reduction in NO_x emissions and zero SO_x emissions in 2035. On the other hand, BES costs decreased across the board, with BESp100, BESp99, BESp95, and BESp90 cost reductions of $17.5/km ($32.5/nm), $7.8/km ($14.4/nm), $5.4/km ($10.0/nm), and $4.7/km ($8.7/nm), respectively.

Interestingly, other costs, excluding the battery cost, remained stable at around $20/km ($37/nm), indicating minimal variation across different BES capacity tiers and no significant deviation from the 2022 scenario by 2035. Despite a 30% increase in CO_2e social costs, the overall impact was modest due to a substantial 59% reduction in the emission factor in the 2035 DEC scenario, compared to 2022. Notably, even under BAU, the emission factor decreased by 69% in 2035 compared to 2022, suggesting that BESs can offset increasing social costs of carbon through improvements in grid carbon emissions intensity.

In 2035, different cost trends were observed among ship types in Figure 4-14 (b). ICE costs were lowest for Passenger ships, followed by Tug (Inland-Push Boats), Tug (Coastal-Harbor), and Tug (ATB). Tug (ATB) had the highest costs at $77.6/km ($143.7/nm), which were four times higher than the $19.0/km ($35.1/nm) for Passenger ICEs. This difference can be attributed to larger ships consuming more energy per traveled distance. Despite variations among ship types, emission costs accounted for approximately 65% of total costs for all ship types, while fuel costs represented 33% of total costs. This is because most cost items are proportional to energy consumption, except in cases of low load factors.

Comparing BESp99s to ICEs for each ship type, Tug (ATB) and Tug (Coastal-Harbor) showed 19% and 4% increases in LCOT, respectively. On the other hand, Passenger and Tug (Inland-Push Boats) experienced reductions of 13% and 15%, respectively, below the LCOT of ICE ships. Based on ship-to-ship comparisons, 90%, 76%, 89%, and 45% of BESp99s in Passenger, Tug (Coastal-Harbor), Tug (Inland-Push Boats), and Tug (ATB), respectively, are cost-effective compared to ICEs. Notably, despite higher average costs compared to ICEs, 45% of BESp99 of Tug (ATB) are considered cost-effective. This highlights the importance of finding ships with higher BES potential through ship-to-ship comparisons.

When comparing BESs with capacity tier p99, cost shares varied among ship types. Tug (Inland-Push Boats) had the lowest average battery system cost share at 63%, followed by Passenger with 69%, Tug (Coastal-Harbor) with 82%, and Tug (ATB) with 92%. Conversely, electricity cost shares were lowest for Tug (ATB) at 25%, followed by Tug (Coastal-Harbor), Passenger, and Tug (Inland-Push Boats). This indicates that Tug (ATB) in capacity tier p99 had relatively lower electricity usage compared to its significant battery size. Conversely, this also implies that Passenger and Tug (Inland-Push Boats) have higher battery utilization rates. The variation in battery usage across different ship types is discussed in more detail in Section 5.1.



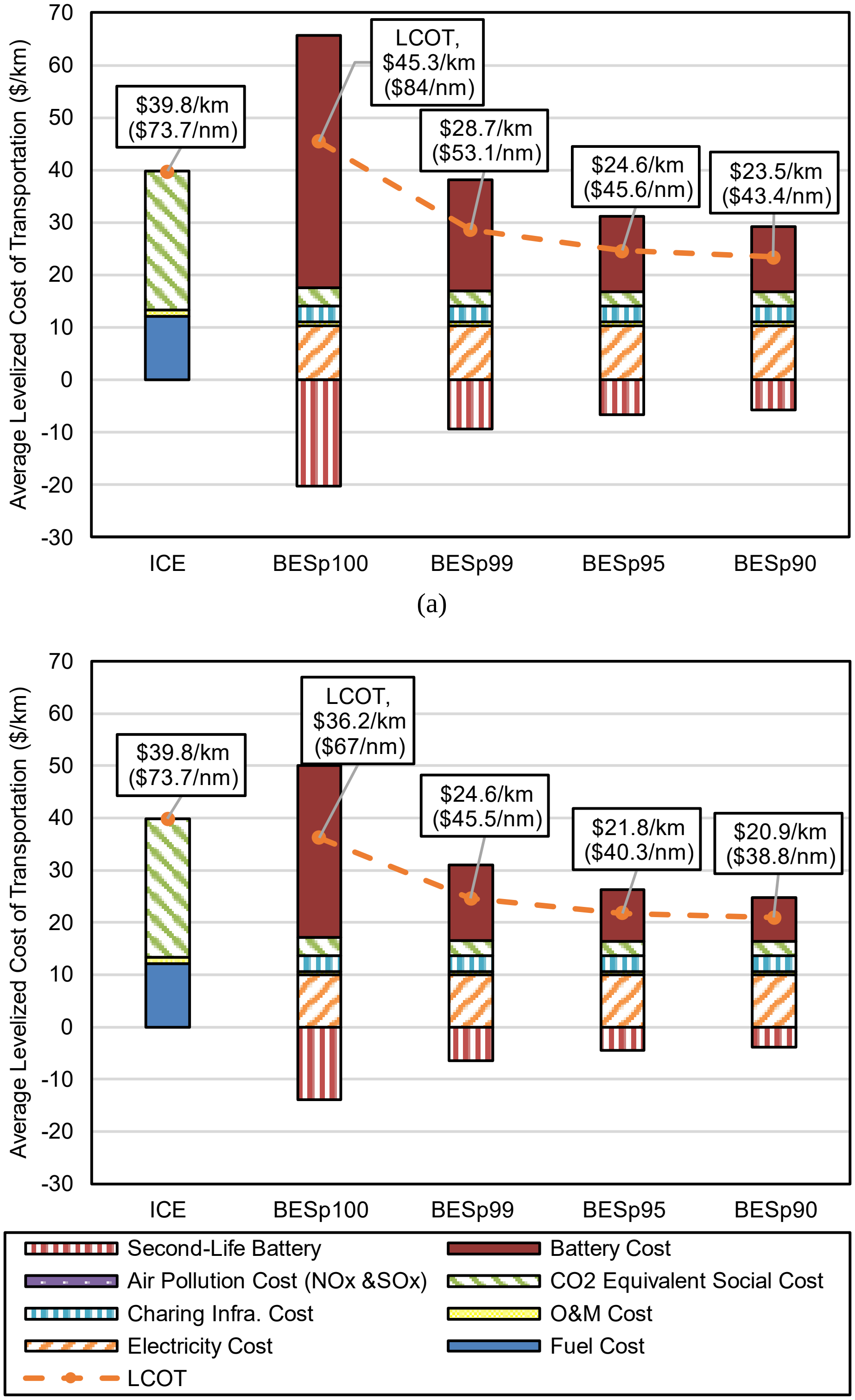
(a)

(b)

Figure 4-14. Average LCOT for ICE Ships and BESs in 2035 under a 95% Electricity Decarbonization by 2050 (DEC) Emission Scenario and INT Cost Scenario: (a) By Capacity Tier, (b) By Ship Type for BESs with Capacity Tier p99 (BESp99)

Figure 4-15 (a) and (b) illustrate the trends in average costs for ICEs and BESs under a 95% Electricity Decarbonization by 2050 (DEC) Scenario and both Intermediate (INT) and Optimistic (OPT) cost assumptions. Average costs for ICEs increase from $35.1/km ($65/nm) to $39.8/km ($73.7/nm), a 13.4% increase from 2035 levels. This can be attributed to a 24% increase in the per CO_2e emission cost between 2035 and 2050.

In 2050, the average cost of BESp100 is still higher than ICEs under the INT scenario, but it falls below ICE costs under the OPT scenario. Specifically, the average cost for BESp100 under the OPT scenario is $36.2/km ($67.0/nm), or 9% below the average cost for ICEs. This highlights the improved cost-effectiveness of BES in Optimistic scenario, making BESp100 potentially cost-competitive with ICEs without needing to lower the capacity tier. It is essential to consider the reimbursement from the value of SLB in this context, as it plays a vital role in making BES more economically viable. If this value is not factored in, the average cost of BESp100 would be significantly higher under the Optimistic scenario – $50.1/km ($92.8/nm) more expensive than ICEs – while BESp99 or lower capacity tiers would demonstrate lower costs than ICE. Hence, capturing the value of SLBs after their initial use in BESs is crucial for enhancing BES cost-competitiveness.



(a)

(b)

Figure 4-15. Average LCOT of ICE Ships and BESs in 2050 under a 95% Electricity Decarbonization by 2050 (DEC) Emission Scenario with (a) Intermediate (INT) and (b) Optimistic (OPT) Cost Assumptions

4.6 Weight Comparison Between BESs and ICEs

As shown in Figure 4-16, the weight increase of BESs relative to their ICE counterparts tends to exhibit variations among different capacity tiers, with a decreasing trend observed for lower capacity tiers. The median BES weight increases are 137%, 30%, 8%, and 2% for capacity tiers p100, p99, p95, and p90, respectively. For BESp100, 41% of vessels had a weight increase of over 100% (i.e., were more than twice as heavy as their ICE counterparts), highlighting significant weight increases for a considerable portion of these ships. In contrast, BESp99 showed more modest weight impacts, with 65% of vessels having a weight increase of 50% or less relative to ICEs. For BESp95, 69% of vessels had a weight increase of 20% or less, while BESp90 had a striking 91% of vessels with a weight increase of 20% or less, highlighting the weight reduction trend seen in lower capacity tiers. This suggests that adopting battery-electric propulsion systems in these lower capacity tiers can lead to more favorable weight outcomes, potentially making them attractive options from a weight perspective.

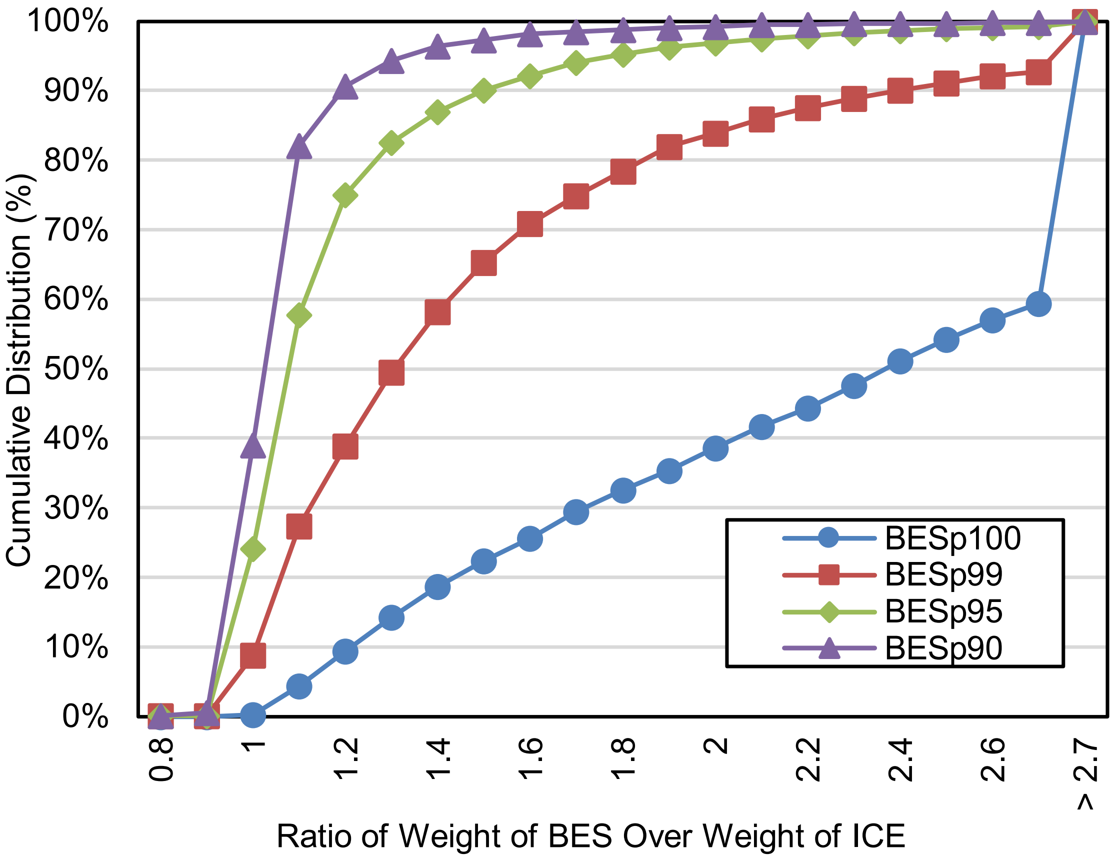


Figure 4-16. Ratio of BES Weight to ICE Weight by BES Capacity Tier

Beyond capacity tiers, the analysis also reveals significant variations in weight increase trends depending on ship type (Figure 4-17). Specifically, for BESp99, we found that passenger ships displayed the least weight increase, with 94% having a weight ratio of 1.5 or less compared to ICEs. In contrast, for two types of tugs, coastal-harbor and inland-push boats, 60% and 69% experienced a weight ratio of 1.5 or less, respectively, compared to ICE ships. ATB tugs exhibited the largest weight increase, with only 10%

of ships experiencing a weight ratio of 1.5 or less. Given the patterns of weight increase based on ship types, it is crucial to consider the specific ship type when contemplating retrofitting ICE to BES.

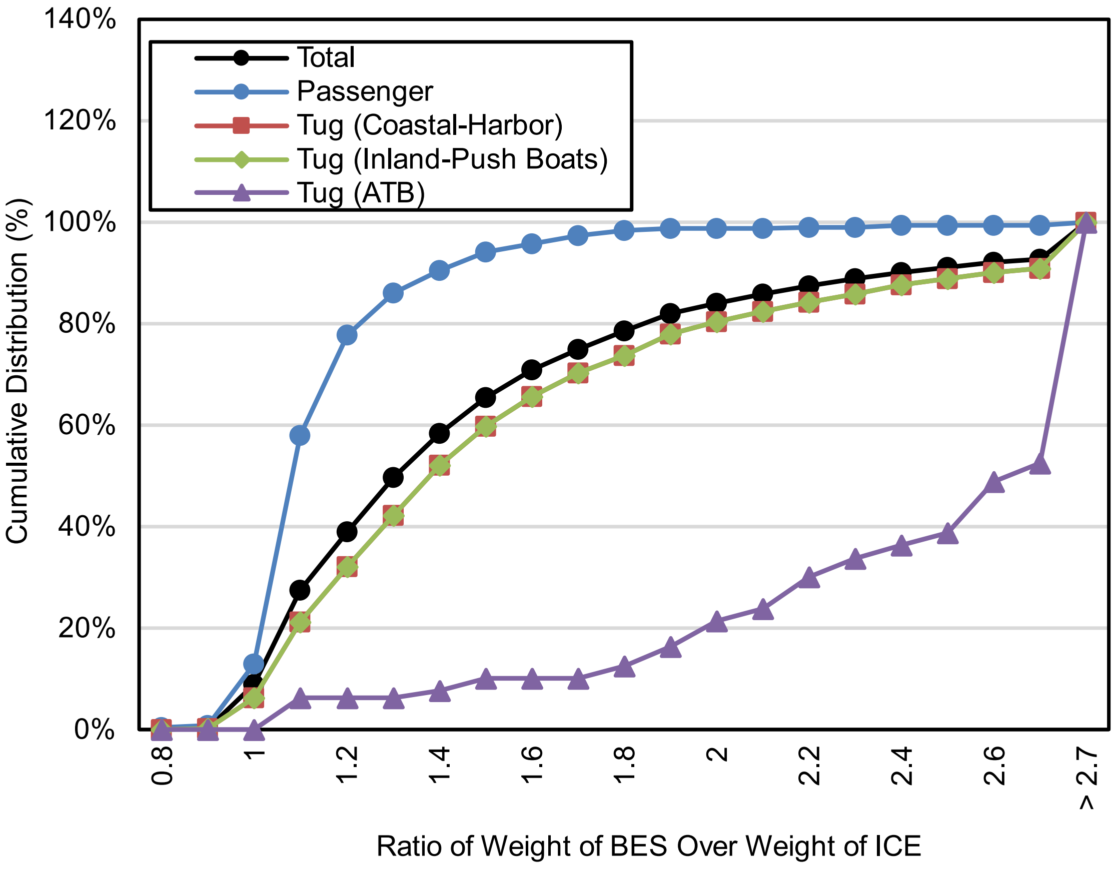


Figure 4-17. Ratio of BES p99 Weight to ICE Weight by Ship Type

Figure 4-18 shows that improvements in battery system weight can reduce the BES-to-ICE weight ratio. The figure shows this ratio using the BESp99 capacity tier. Using the assumed 20.4 kg/kWh battery weight as baseline, BES-to-ICE weight ratios are calculated for per kWh battery system weight reductions of 0% (baseline), 25%, 50%, and 75%. The median weight ratio for each battery weight reduction scenario are 1.30, 1.21, 1.13, and 1.04. Among all BESs, 39%, 48%, 63%, and 84%, respectively, have a weight ratio of 1.2 or less under each respective battery weight reduction scenario. Passenger vessels show the most significant weight improvements. For BESp99, the median weight ratio under each battery weight reduction scenario is 1.08, 1.04, 1.00, and 0.99, indicating that battery weight improvements lead to overall weight improvements, with potentially more significant effects in certain vessel types.

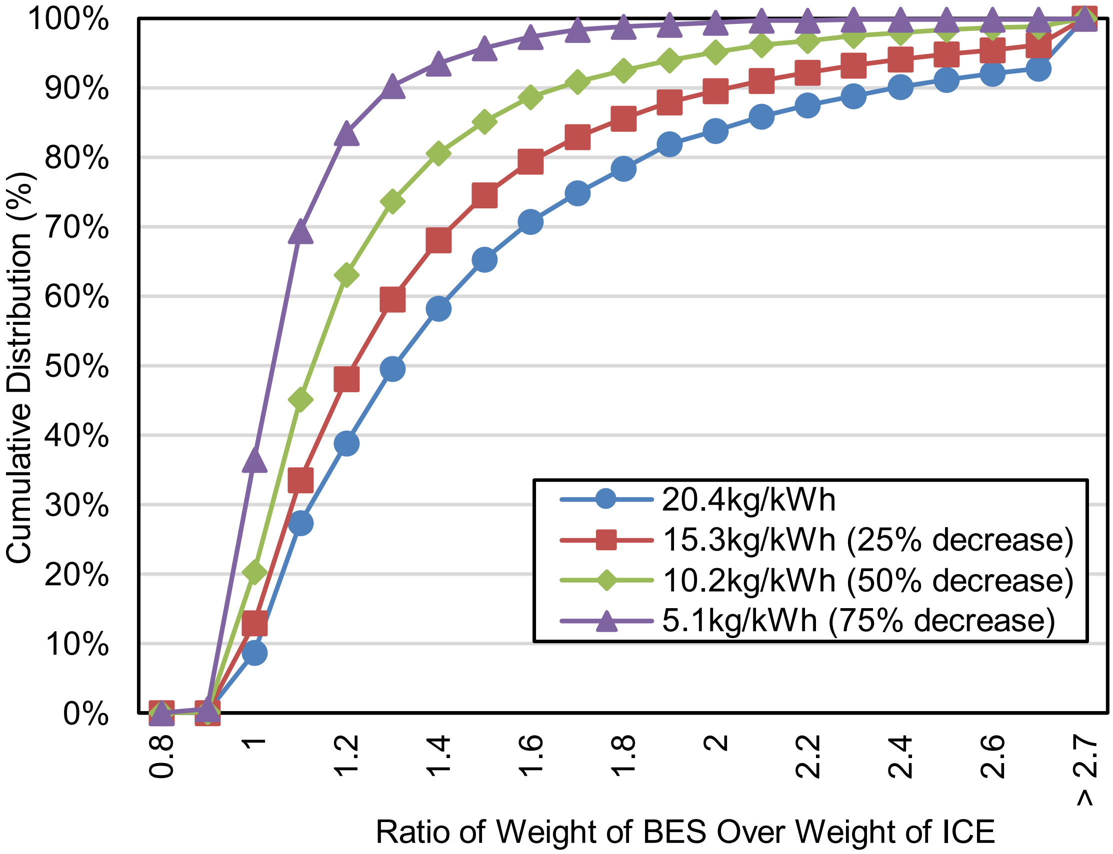


Figure 4-18. Ratio of BES p99 Weight to ICE Weight by Ship Type under Multiple Battery Weight Reduction Scenarios

5. Discussion and Policy Insights

5.1 Relationship Between Full Equivalent Cycle and Cost Effectiveness

The number of FECs until the battery's end of life (EoL) is calculated as the product of annual FECs and battery lifetime, as defined in equation (25) (see Technical Documentation). FEC until EoL serves as an indicator of how much the battery is utilized during its first lifetime to power a BES. Figure 5-1 illustrates the relationship between FEC until EoL and the ratio of BES cost over ICE cost for capacity tier p100; we call this figure the "Ratio-FEC graph." A ratio of BES cost over ICE cost greater than 1 indicates the BES is not cost-effective, while a ratio less than 1 signifies the BES is cost-effective. The graph confirms that a larger number of FECs until the battery's end of life leads to a lower BES-to-ICE cost ratio.

Moreover, as cost conditions for BESs improve (e.g., from lower battery system costs), the Ratio-FEC graph shifts downwards, indicating that BESs become cost-effective at lower FEC levels. Specifically, the FEC values at which BESs become cost-effective are around 1358, 671, and 385 in 2022, 2035, and 2050, respectively. This demonstrates that with better pricing conditions, BESs can achieve a competitive advantage over ICE ships in terms of cost-effectiveness while utilizing less battery capacity.

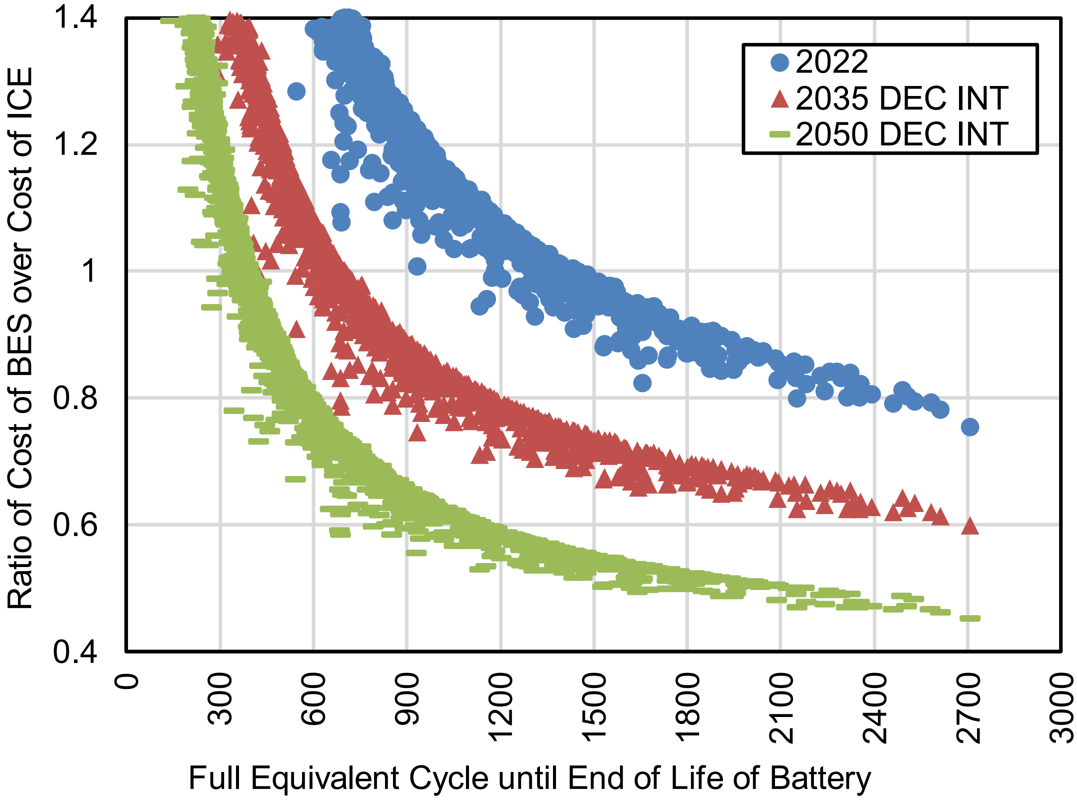
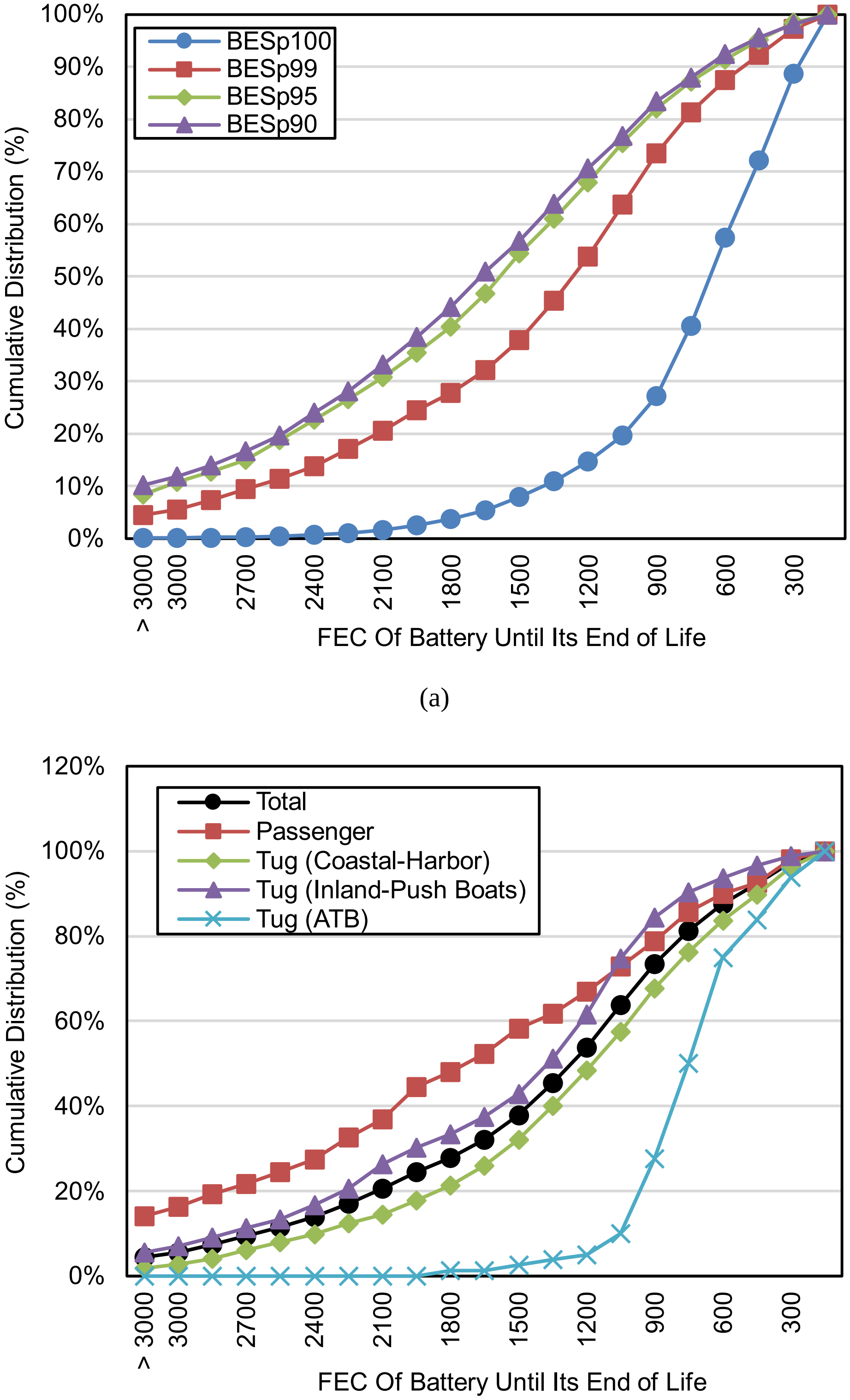


Figure 5-1. Relationship Between FEC and Battery EoL for BES p100 vs. ICE Cost-effectiveness ("Ratio-FEC Graph")

If improved pricing conditions shift the Ratio-FEC graph downwards, then lowering the capacity tier is another way of increasing FEC until EoL. The median FEC until EoL for each capacity tier is 512, 1105, 1440, and 1531 for p100, p99, p95, and p90, respectively (Figure 5-2). Lower capacity tiers have higher FEC values, contributing to higher cost-effectiveness. This trend also varies across ship types. For BESp99, the order of FEC from highest to lowest is as follows: Passenger, Tug (Inland-Push Boats), Tug (Coastal-Harbor), Tug (ATB). This implies that certain ship types can achieve greater cost-effectiveness by adopting lower capacity tiers with higher FEC values.



(a)

(b)

Figure 5-2. Cumulative Distribution of FEC until Battery EoL by (a) BES Capacity Tier and (b) Ship Type

5.2 Reference Trips and Unserved Trips

Figure 5-3 illustrates the cumulative distribution of the energy demand for the reference trip of each ship. The curves, such as the “100th Percentile Trip” and the “95th Percentile Trip,” represent the cumulative distribution of energy consumption for the largest trip and the 95th largest percentile trip, respectively, for each ship. As the percentile gets lower, the trip energy required by the selected reference trip gets smaller. This trend was also shown in our earlier observation that BESs with lower capacity tiers have smaller batteries, and that battery sizes are determined based on the size of reference trips.

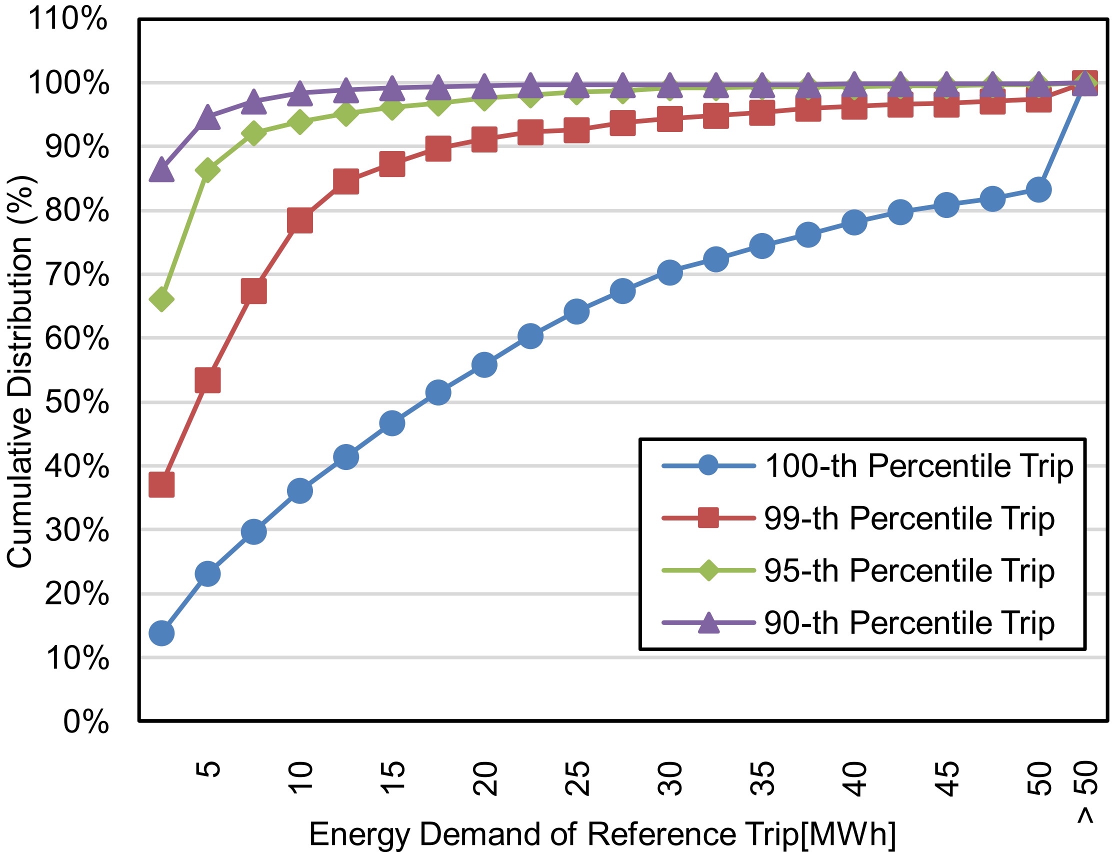
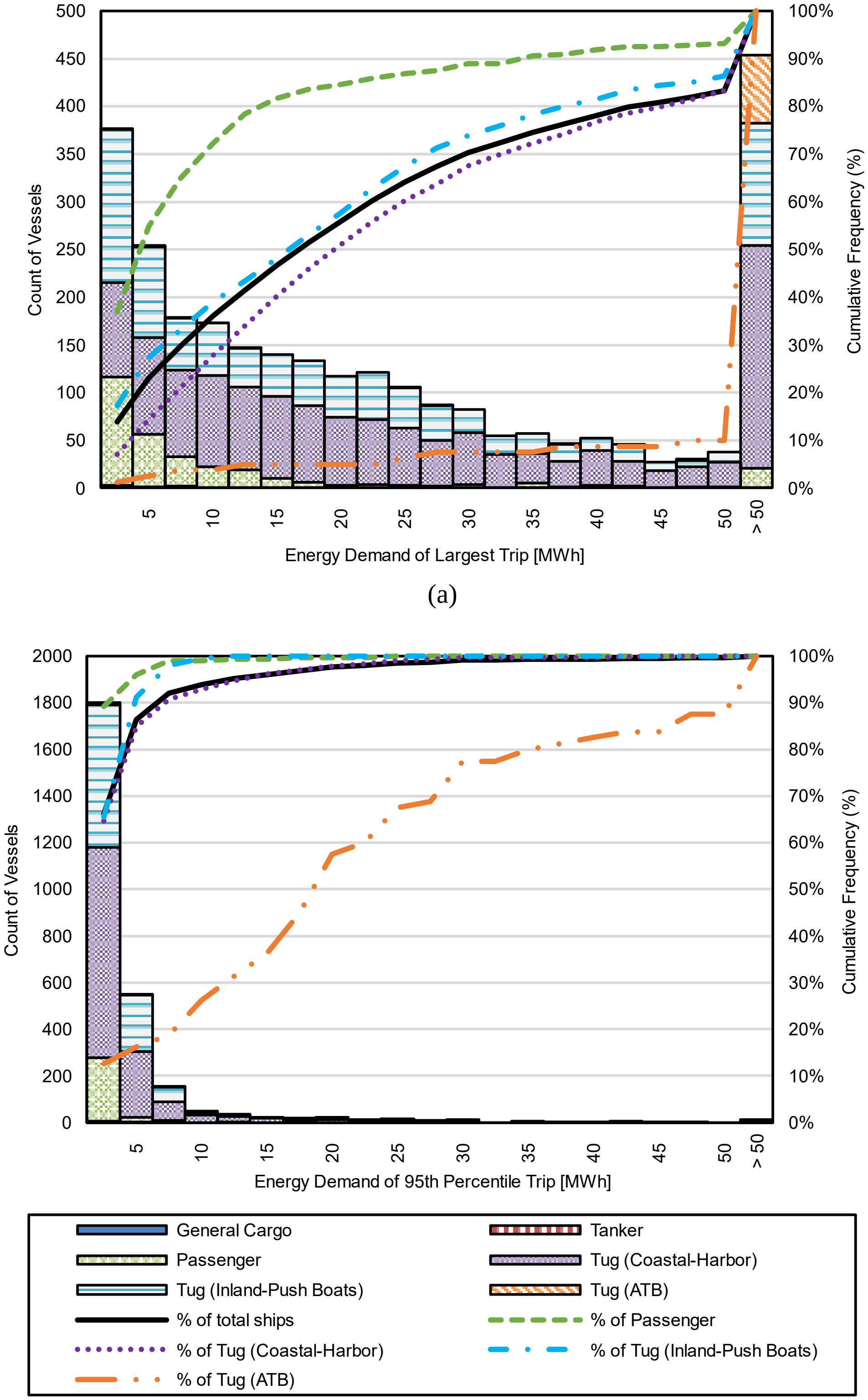


Figure 5-3. Cumulative Distribution of Reference Trip Energy Demand

The cumulative distribution of energy demand for reference trips varies depending on the ship type, as shown in Figure 5-4. The energy demand of the 95th percentile trip shows a distinct difference from that of the largest trip. When comparing the largest trips of different ship types, the order of energy demand from highest to lowest is as follows: Tug (ATB), Tug (Coastal-Harbor), Tug (Inland-Push Boats), Passenger. This pattern can be attributed to Tug (ATB) having larger engine sizes and, on average, longer annual travel distances. Passenger ships exhibit a trend of having less energy demand compared to Tug (Coastal-Harbor) and Tug (Inland-Push Boats) despite having similar travel distances. This can be attributed to Passenger ships having a smaller main engine capacity.

However, trip patterns may differ for each ship type, so merely relying on engine size and annual travel distance is insufficient to infer the reference trip. For instance, the average energy demand of the 99th percentile trip for Passenger ships is 2.0 MWh, while for Tug (ATB) it is 60.6 MWh, showing a 30X difference. However, when considering the product of trip size and engine size, the values for these two ships are 37,654 MW×km and 212,284 MW×km, respectively, showing only a 5.6X difference. This demonstrates the importance of considering the activity patterns of each vessel when determining the size of a battery, and it confirms that the AIS-based approach employed in this study is essential and provides the requisite foundation for determining battery size.



(a)

(b)

Figure 5-4. Distribution of Energy Demand: (a) Largest Trip, (b) 95th Percentile Trip

Despite the potential decrease in battery size associated with decreasing capacity tiers, BESp99, BESp95, and BESp90 exhibit a trade-off wherein the reduced battery capacity leads to an increase in the sum of energy from unserved trips. Figure 5-5 displays the distribution of unserved trip ratios for BES capacity tiers below p100. (The figure presents the distribution for BESp99, BESp95, and BESp90, as BESp100 covers all historical trips.) The unserved trip ratio is calculated by dividing the sum of energy for unserved trips by the sum of energy for all trips. As the capacity tier decreases from BESp99 to BESp90, the number of ships with higher unserved trip ratios increases. Specifically, for BESp99, approximately 78% of ships have an unserved ratio of less than 25%, whereas around 81% of BESp90s have a ratio of unserved trips exceeding 50%.

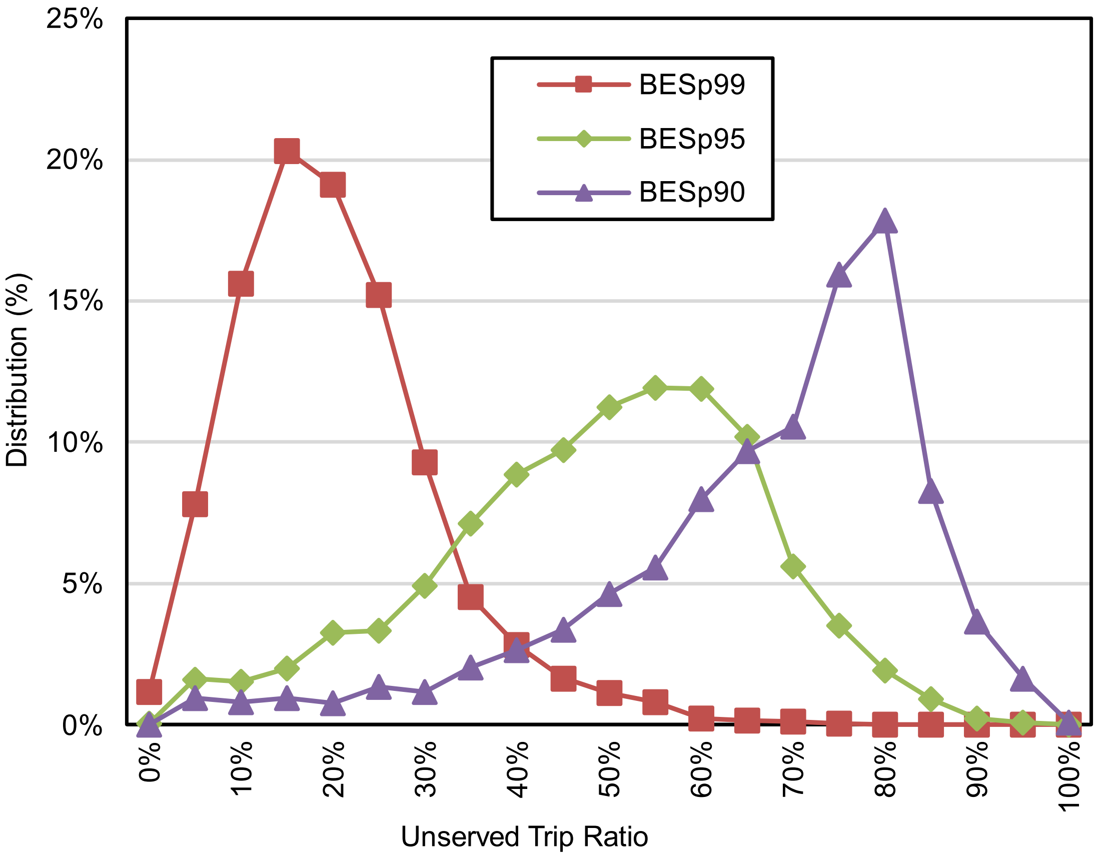


Figure 5-5. Distribution of Ratio of Unserved Trip Energy by BES Capacity Tier (p99, p99, and p90)

The unserved trip ratio exhibits different trends across different ship types. Figure 5-6 illustrates the unserved trip ratios of BESp95, demonstrating a clear disparity of the distribution among ship types. Passenger ships tend to display a smaller unserved energy ratio, with approximately 63% of ships having an unserved trip ratio below 25%. On the other hand, Tug (ATB) exhibits the highest unserved trip ratio compared to other vessel types, with around 66% of ships having an unserved trip ratio exceeding 50%. Tug (Coastal-Harbor) and Tug (Inland-Push Boats) types show similar distributions. Based on these results, it is appropriate to replace ICEs with BESs when the unserved trip ratio is lower. Thus, these findings indicate a highest to lowest suitability ranking for retrofitting ICEs to BESs as follows:

Passenger ships, Tug (Coastal-Harbor), Tug (Inland-Push Boats), and finally Tug (ATB).

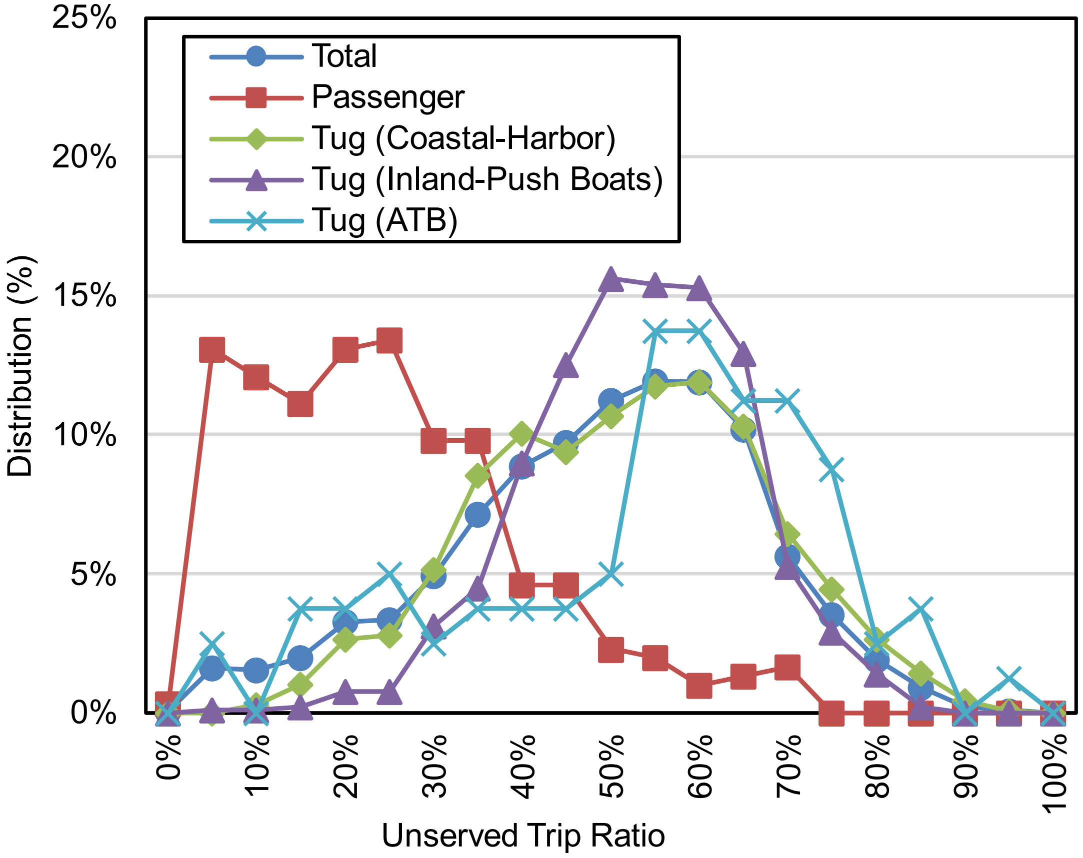


Figure 5-6. Distribution of Unserved Trip Ratio by Ship Type for Capacity Tier BES p95

5.3 Unserved Trips by Lower Tier BESs

As the capacity tier decreases and the battery size becomes smaller, more unserved trips occur. However, these unserved trips can be addressed by dividing them into smaller trips, which can be beneficial from an emissions perspective. To figure out this beneficial, we estimated emissions including the emissions from unserved trips that were not included in prior analysis. Assuming vessels with lower capacity tiers could perform the unserved trips with the factor of 2 to CO_2e emissions. Figure 5-7 shows the distribution of the ratio of CO_2e emission decrease by capacity tiers. Despite the applied factor, it is observed that almost all vessels with lower capacity tiers showed a decrease in CO_2e emissions compared to ICEs. The average reduction rates are 40%, 38%, 26%, and 18% for p100, p99, p95, and p90, respectively. Therefore, dividing longer trips into multiple shorter trips may offer CO_2e emission benefits compared to traditional ICE ships.

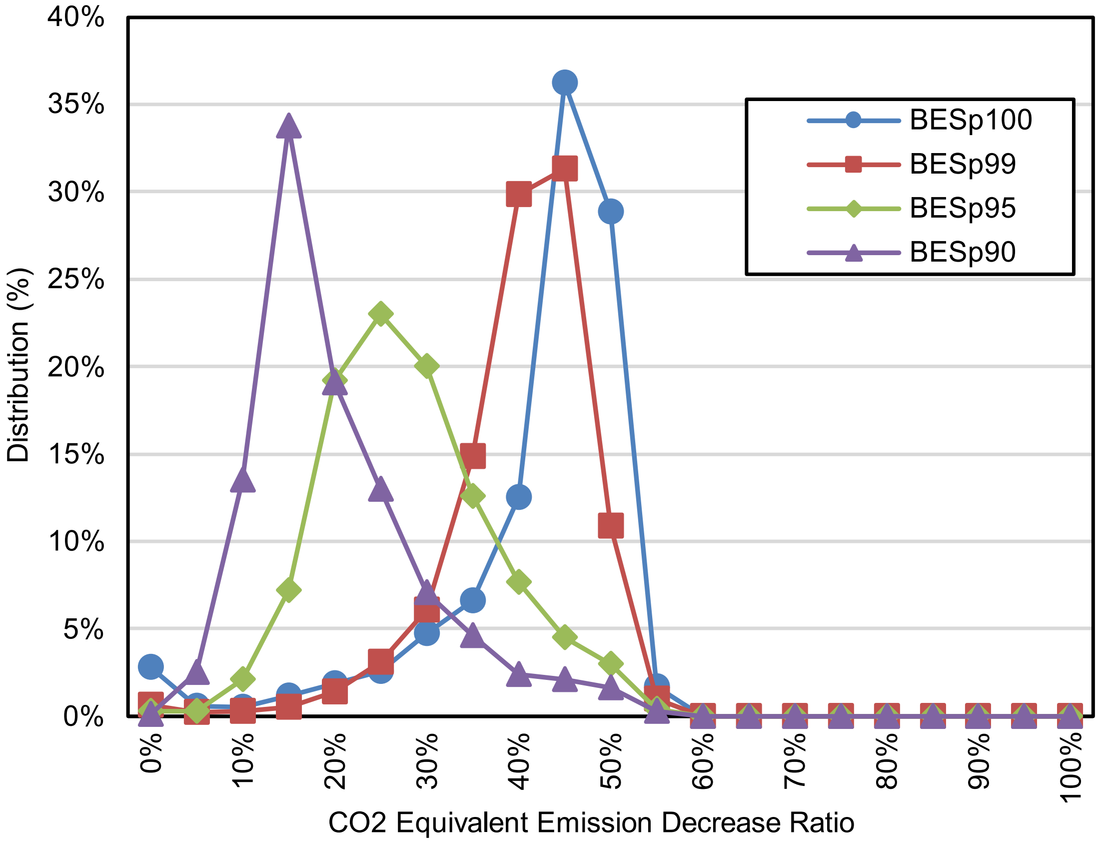


Figure 5-7. Distribution of the Ratio of CO_2e Emission Decrease vs. ICE Ships with a Factor of 2 for Unserved Trips in 2035 under a 95% Decarbonization by 2050 (DEC) Scenario

5.4 Managing Charging Power Requirements at Ports

Commercial shore power systems in the U.S. can be broadly classified into two categories (EPA, 2022c):

- High voltage shore connection (HVSC): 6,600 or 11,000 V, >1 MVA equipment primarily used to service large cruise, container, and reefer vessels.
- Low voltage shore connection (LVSC): 220-480 V, < 1 MVA equipment typically used to service smaller ships such as fishing, tug, workboat, ferry, and service vessels.

Shore power systems primarily cater to hotel loads; however, they can serve as an initial benchmark for comparing existing facilities with future requirements. Figure 5-8 illustrates the power requirements distribution per SPC under both Historical Activity-based Charging and Trip-Based Charging at the Illinois International Port. Again, Historical Activity-based Charging is a charging strategy that aligns with each ship's historical activity, while Trip-Based Charging involves charging for a longer duration than the ship actually stayed at port (see Section 3.1.2).

Trip-Based Charging enables greater coverage of charging demand with a lower power capacity requirement for SPCs. Specifically, with a maximum power capacity of 1 MW for the LVSC, Trip-Based Charging fulfills 96% of charging requirements, whereas Historical Activity-based Charging only satisfies 79%. This finding highlights the advantage of Trip-Based Charging compared to Historical

Activity-based Charging in relieving power requirements for SPCs.

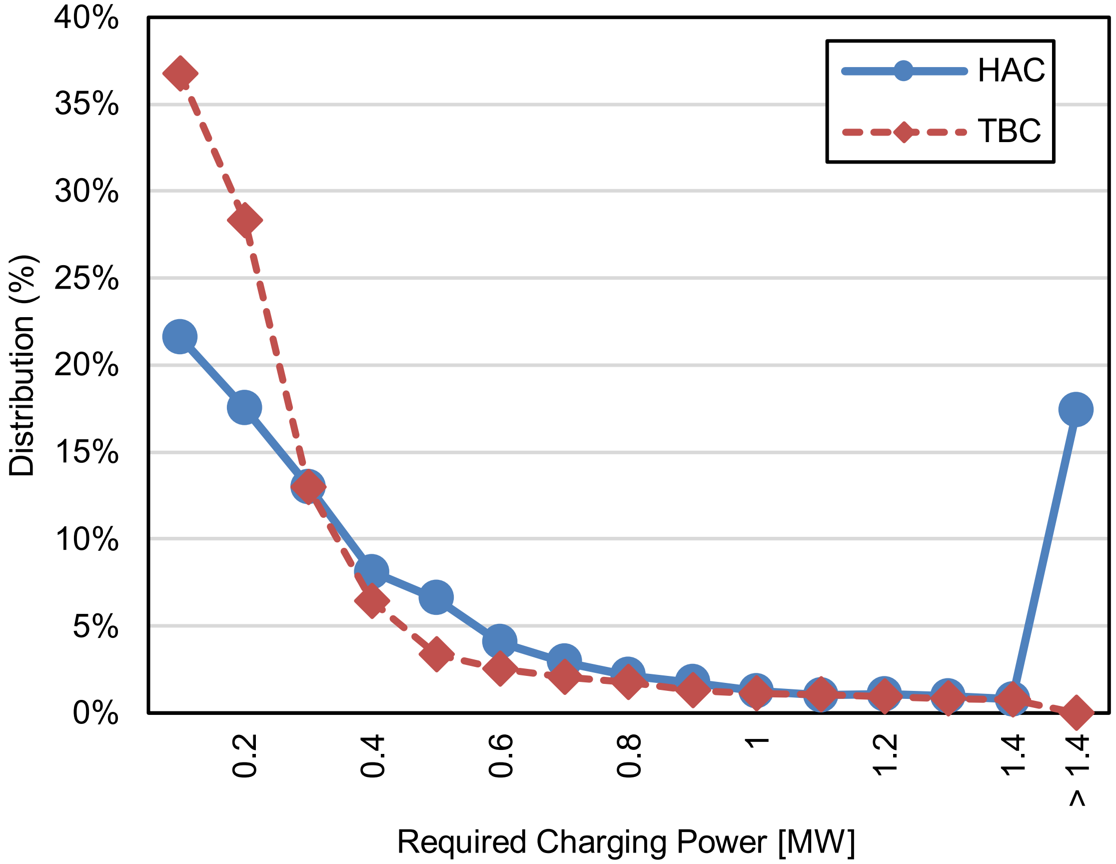


Figure 5-8. Distribution of Power Requirements for SPCs under Historical Activity-based Charging (HAC) and Trip-Based Charging (TBC) at the Illinois International Port

However, implementing Trip-Based Charging comes with a tradeoff. In Figure 5-9, the distribution of the number of charging ships shows how many SPCs will be required at the Illinois International Port. This distribution reveals that under Historical Activity-based Charging, only 2 SPCs could supply charging demand during 66% of the hours in a year; under Trip-Based Charging, 7 SPCs would be required for the same coverage. Furthermore, to satisfy charging requirements 95% of the time, 4 SPCs are needed under Historical Activity-based Charging, while Trip-Based Charging requires 12. The New York port, which has the highest charging demand, would require 46 SPCs to serve requirements 50% of the time under Historical Activity-based Charging, and 72 under Trip-Based Charging. The increased need for SPCs under Trip-Based Charging results from longer charging times compared to Historical Activity-based Charging.

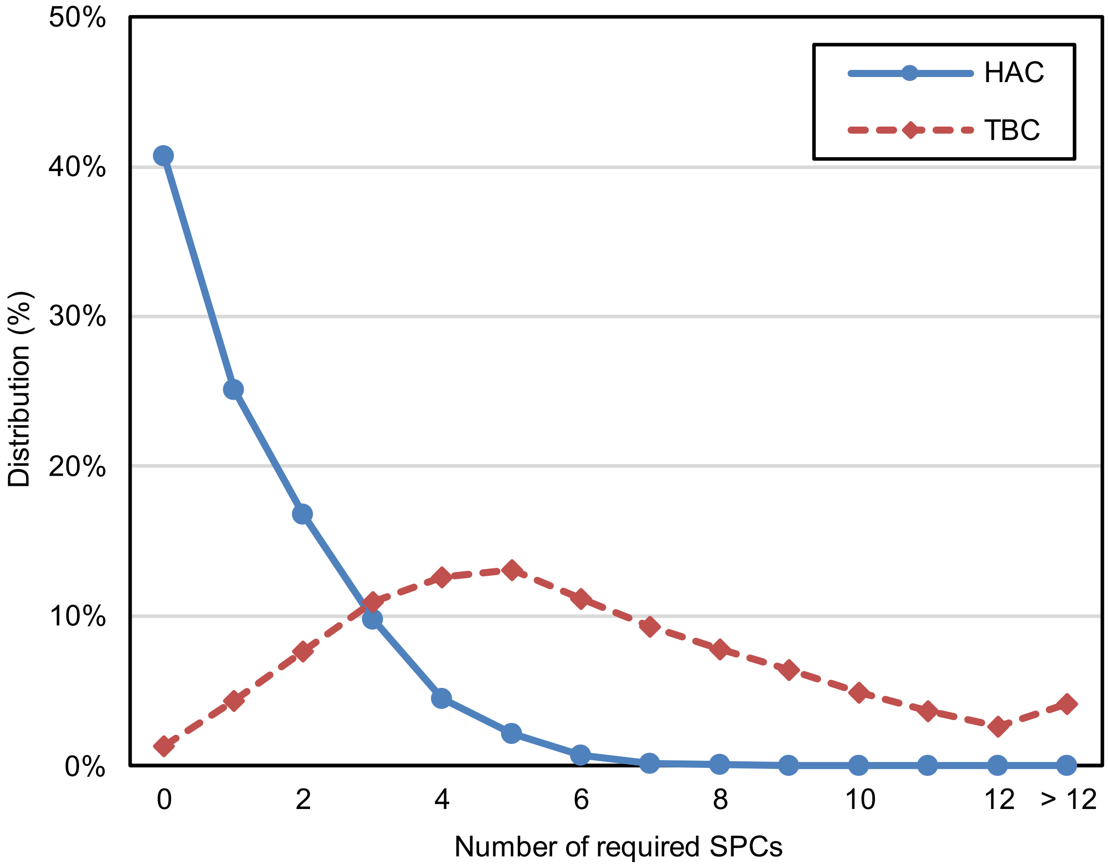


Figure 5-9. Distribution of Number of Required SPCs under Historical Activity-based Charging (HAC) and Trip-Based Charging (TBC) at the Illinois International Port

5.5 Battery Supply Chain

Based on our analysis, Figure 5-10 depicts total battery capacity categorized by capacity tiers, along with a comparison to the expected production capacity of North American battery plants in 2030. The demand for batteries varies depending on the capacity tier of the BESs, ranging from 7.9 GWh for BESp90 to 136 GWh for BESp100. The estimated annual production capacity of North American battery plants in 2030 is 998 GWh per year (Gohlke et al., 2022). Consequently, the ratio of batteries needed by BESs in 2030 to total North American production capacity at that time ranges from a minimum of 0.8% to a maximum of 13.6%. Note that the battery demand depicted in the figure solely encompasses domestic vessels within the 50-1000 GT range. As shown in Figure 4-1, larger vessels necessitate larger battery capacities. Considering that the total sum of GT for the ships represented in the figure accounts for a mere 4.8% of the 11,687 ships in the Integrated Ship Database, there is clearly potential for very significant battery demand from the maritime transportation sector.

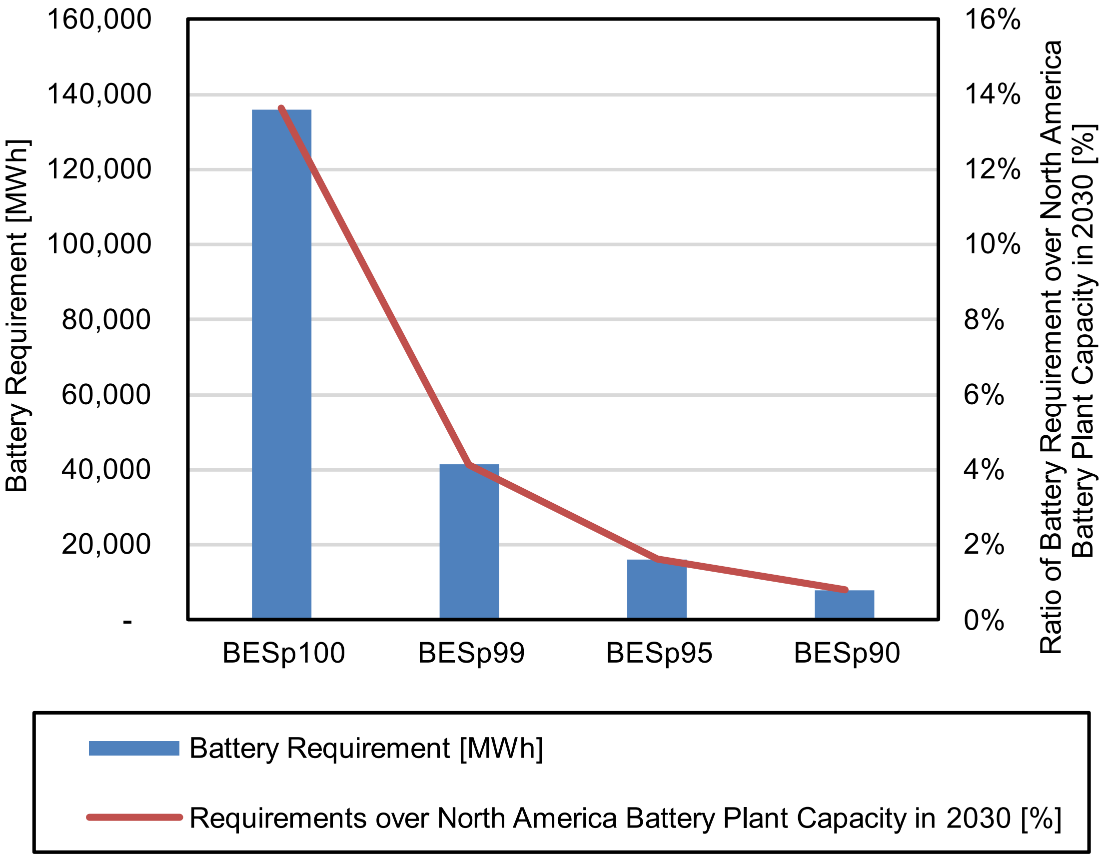


Figure 5-10. BES Battery Capacity Requirements by Capacity Tier Compared to North American Battery Manufacturing Capacity in 2030

5.6 Caveats and Further Research

While we evaluated the potential of BESs in the U.S. through exhaustive data analysis, further research is needed to deepen our understanding of other aspects of BES potential. We offer the following caveats about our research to clarify our approach and assist with future research efforts.

In cases where AIS data is unavailable, our default assumption was that the ship was inactive. However, the ship may have been operational during these missing data periods. While methods to estimate and fill in missing data exist (IMO, 2020), we chose not to employ them due to the uncertainty about whether missing data truly means that no operations occurred. The use of supplementary data – like each ship's operational days per year, or its annual fuel consumption – would provide a more solid basis for making such estimations.

The analysis in this study relies on AIS data from 2021. Ship activity can fluctuate due to changes in shipments and economic conditions, and future activity may vary significantly. As a result, key findings from our analysis, such as energy requirements for the grid, could also change. Similarly, the economic feasibility of retrofitting individual ships could vary annually based on each ship's operational activities.

When determining whether a BES was in a suitable condition to charge, we only considered the ship's speed over ground and did not account for its distance from land. This assumption was made to reduce computational demands and to allow for the possibility that BESs may change their activities from historical ICE operations. As a result, there are two cases where we assumed charging could occur even though it may be impractical. First, in cases where a ship is anchored far offshore for extended periods, it realistically would not be able to charge due to its distance from land-based charging stations; but if the vessel were a BES instead of an ICE ship, it might have changed its stay to remain closer to shore, making charging possible. The second case involves instances where a single long trip is divided into two shorter trips by a stop of more than 10 minutes in distant waters. If this split trip served as the reference trip for battery sizing, it could lead to an underestimation of battery size requirements. However, the impact of this would likely be minimal if such stops are not a regular occurrence, as the next longer trip still could serve as the reference for battery sizing.

When scheduling charging, we did not account for power limitations, which could potentially lead to excessive power charging and discharging. Future research can address this by utilizing advanced charging scheduling methods or by modifying BES activity patterns.

The increase in each ship's weight due to the addition of batteries could necessitate higher power and energy consumption for movement, a factor that was not factored into our analysis but could be considered in future study.

When sizing the battery of each ship, various factors were considered. Specifically, we incorporated a 5% safety factor into calculations. Additionally, the sizing accounts for a 20% degradation in the state of health of the battery, ensuring that ships can still complete the reference trip even after such degradation. As a result, the battery size in its first year of use would be 25% larger than what is strictly needed for the reference trip.

When considering retrofitting, we focused primarily on the cost of the battery system and did not account for other expenses related to ship power systems. Future studies could conduct a more detailed and comprehensive total cost of ownership (TCO) analysis. This study also did not thoroughly examine the cost components associated with charging infrastructure, which could be addressed more comprehensively in future research. The social cost of carbon has varied across different U.S. administrations: it was $43 per ton during the Obama administration, reduced to $3 and $5 per ton under the Trump administration, and officially estimated at $51 per ton by the Biden-Harris administration (Asdourian and Wessel, 2023). For this study, we used the most recent values updated by the EPA, which are $190, $250, and $310 per ton for 2022, 2035, and 2050, respectively. Fluctuations in this parameter can significantly impact the study's overall economic feasibility.

The DC ship power system is assumed, but in actual operation it may have distinct configurations and efficiencies compared to AC ship power systems. Because we examined steady-state conditions at a 5-minute time interval, the dynamics of ship power systems are beyond the scope of this study.

Regarding spatial and temporal granularity, the carbon intensity of the electrical grid may vary depending on the time and location where the BES is charged. We used the national average grid carbon intensity to calculate emissions; in practice, charging strategies could vary based on regional grid carbon intensity, something future research could explore. Similarly, while charging costs can change based on time and location, we used a nationwide average electricity cost for our calculations. This is a generalization; in practice, BESs could minimize charging costs by strategically choosing when and where to charge, a dynamic future studies could examine.

To find optimal battery charging schedules, it is useful to develop a method that effectively manages the charging and discharging cycles of batteries. Such a method can help reduce peak power requirements for battery charging and optimize overall battery performance. By implementing a sophisticated management system, BES operators can strategically schedule the charging and discharging processes to align with favorable energy conditions. This involves accounting for factors such as grid demand, electricity tariffs, renewable energy availability, and BES operational requirements. The method may need to employ algorithms that consider real-time data, battery characteristics, and operational constraints to determine the most efficient charging schedules. Such a method can also prioritize charging during periods of low demand and/or when renewable energy generation is high, thereby reducing reliance on fossil fuel power plants, optimizing energy utilization, and reducing GHG emissions.

The charge management system can also incorporate smart charging techniques that balance charging and discharging cycles to minimize stress on the batteries and prolong their useful lives. By avoiding excessive charging or discharging rates, the system can enhance battery health and efficiency.

Designing a port microgrid system that explores optimal sizes for solar and wind power systems, along with batteries for charging BES batteries, can be beneficial. By integrating renewable energy sources such as solar and wind into the port microgrid, ports can leverage clean and sustainable power generation to meet the energy demands of charging ships' batteries. Optimal sizing of these renewable energy systems involves assessing factors such as the available space, solar irradiance, wind resources, and energy consumption patterns of the port and ships. Determining the optimal size of the solar and wind power systems ensures that they can generate sufficient energy to meet the charging requirements of the BESs, considering factors like battery capacities and charging rates. This helps maximize the utilization of renewable energy, reduce dependence on conventional grid electricity, and lower GHG emissions.

Additionally, integrating battery energy storage systems within the microgrid provides several advantages. Batteries can store excess energy generated by solar and wind systems during periods of high production and supply. Proper sizing and management of the battery storage systems contributes to the stability of the microgrid, enables load balancing, and enhances grid resiliency. Advanced energy management and control systems can also be employed to optimize the operation of the port microgrid, considering various parameters like real-time energy generation, load demand, and battery charging requirements. These systems can incorporate intelligent algorithms to prioritize renewable energy utilization, minimize peak demand, and ensure the efficient charging of ship batteries.

A comprehensive ship specifications database is crucial, but data availability varies. GT and length data are widely available (100% and 96%, respectively), while main engine data are limited to 75% of ships, mainly from the USACE dataset. Auxiliary engine capacity (7%) and reference speed (17%) data are even scarcer. Imputation is conducted for missing data, potentially affecting analytical accuracy. Ship type classifications differ among databases, necessitating reclassification into harmonized types. To improve database management, covering a wide range of ships in terms of GT and using unique identifiers like MMSI is recommended. Comprehensive ship specifications, including GT, main engine, auxiliary engine power capacity, and reference speed, are necessary. Harmonized ship type classifications will ensure consistency and accuracy across databases.

Furthermore, several important topics must be explored to gain a comprehensive understanding of the potential of BESs in the maritime industry. Firstly, investigating the operational efficiency gains achieved through the implementation of battery power is essential to identify opportunities for optimized energy utilization and cost-effectiveness. Secondly, assessing the impact of BESs on maintenance requirements and offline time for vessels will provide valuable insights into potential reductions and operational advantages. Additionally, exploring the feasibility of modularizing large ships or energy-intensive trips using smaller BES vessels as a cost-effective alternative to replacing one large ICE vessel, as proposed by Fleetzero’s business model, is vital (Coldewey, 2022). Moreover, thorough research on the data needs for accurately analyzing current fuel and electricity consumption at each port is crucial for making informed decisions regarding BES adoption. Lastly, projecting changes in vessel traffic patterns and evaluating the accuracy of 2021 AIS data in representing future vessel trips, particularly for the year 2030, will be fundamental in shaping the future of sustainable maritime transportation.

In summary, developing a comprehensive method for managing battery charging and discharging cycles is useful for reducing peak power requirements, optimizing energy utilization, and ensuring the longevity of BESs. Along with this, designing port microgrid systems that deploy optimally sized solar and wind generation will offer significant advantages in terms of utilizing renewable energy, reducing emissions, and optimizing the charging of BES batteries. Finally, continuing research and analysis in several important topic areas is crucial to gaining a comprehensive understanding of the potential of BESs in the maritime industry.

6. Conclusion

In this study, we assessed the battery electrification potential of U.S. domestic ships in terms of emissions, economic feasibility, and physical feasibility, based on historical AIS data from 2021. The analysis involved integrating data from four comprehensive ship databases and examining ships’ real-world activity data at 5-minute intervals. It encompassed an evaluation of the effects on lifetime GHG emissions, as well as the technical and economic feasibility.

Our study reveals that by 2035, the battery electrification of 6,323 vessels in the Domestic Fleet could lead to a significant reduction in lifetime GHG emissions, ranging from 34% to 42%, depending on the emission factor of the power system. Moreover, under a 95% decarbonization by 2050 scenario, this reduction can be further accelerated, reaching 75% or more compared to emissions from ICE ships by 2050. Considering the Biden-Harris administration’s commitment to achieve 100% power system decarbonization by 2035, the emission reduction rate this study projected for 2050 could occur in 2035 (USEOP, 2021).

The estimated annual electricity requirement for these 6,323 BESs is approximately 7.7 TWh, which represents less than 1% of total annual electricity demand in the U.S. However, meeting this demand necessitates a significant expansion of charging infrastructure at U.S. ports. Notably, about 46% of this requirement is concentrated at just 20 of 150 major ports nationwide.

We categorized BES capacity tiers as p100, p99, p95, and p90 based on the percentage of historical ICE trips a BES can perform. This allowed us to decrease the required battery size for BESs in lower capacity tiers. As capacity tiers decrease and the required battery size becomes smaller, cost advantages occur but the number of unserved trips increases. Using a BESp99 with high utilization rates as a reference for comparison, we observed that in 2022, only 40% of BESs were cost-effective, whereas in 2035, this percentage increased to a range of 69% to 88% depending on the scenario. By 2050, 81% to 95% of BESp99 vessels were cost-effective. This is attributed to the decreasing costs of batteries and the availability of power from a cleaner grid. Notably, incorporating emission costs and SLBs' value significantly enhances the cost-effectiveness of BESs compared to ICEs.

This study also compared the weight of BESs with that of ICEs. While there was a weight increase trend due to heavy batteries, if the battery system's weight ratio can be reduced to around 50% at a level of 10.2 kg/kWh, then 63% of BES vessels would experience a weight increase of only 20% or less compared to ICE ships.

Among all ship types, passenger ships emerged as the most favorable choice for retrofitting to BES. They proved to be the most cost-effective compared to other ship types, and their unserved trip ratio increased the least as their capacity tier decreased. Additionally, the weight increase resulting from the BES conversion was also the lowest for passenger ships. Among the three tug types, inland-push boats appear to be the most attractive option for BES retrofitting due to more favorable costs, which are attributed to their higher battery utilization rates. Conversely, ATB tugs face challenges with high costs, excessive weight increase, and a high unserved trip ratio when considering battery retrofitting.

The decarbonization of the maritime industry presents challenges, particularly concerning unserved trip energy in lower capacity BESs. However, dividing long unserved trips into multiple smaller trips can lead to greater GHG reductions compared to ICEs – particularly if CO_2e emissions from battery manufacturing are also reduced. Moreover, lower capacity BESs demonstrate minimal weight increase, highlighting their advantages from both emissions and weight perspectives.

The large-scale implementation of BESs requires substantial investments in power infrastructure at ports. Nevertheless, these infrastructure requirements can be mitigated through advanced scheduling of ship activity and charging, as well as the adoption of battery swapping-based charging systems. Furthermore, the demand for batteries in maritime transportation is expected to soar, particularly with the potential electrification of ocean-going vessels and large domestic containers.

In conclusion, this study emphasizes the potential for electrification in domestic U.S. ships and the benefits it entails. Further research is recommended to explore operational approaches for effectively managing energy demanding trips and to develop microgrid plans for ports serving as charging stations.

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