Electric tugboat deployment in maritime transportation: detailed analysis of advantages and disadvantages

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Abstract

Purpose – This study aims to provide a comprehensive review of electric tugboat deployment in maritime transportation, including an in-depth assessment of its advantages and disadvantages. Along with the identification of advantages and disadvantages of electric tugboat deployment, the present research also aims to provide managerial insights into the economic viability of different tugboat alternatives that can guide future investments in the following years.

Design/methodology/approach – A detailed literature review was conducted, aiming to gain broad insights into tugboat operations and focusing on different aspects, including tugboat accidents and safety issues, scheduling and berthing of tugboats, life cycle assessment of diesel tugboats and their alternatives, operations of electric and hybrid tugboats, environmental impacts and others. Moreover, a set of interviews was conducted with the leading experts in the electric tugboat industry, including DAMEN Shipyards and the Port of Auckland. Econometric analyses were performed as well to evaluate the financial viability and economic performance of electric tugboats and their alternatives (i.e. conventional tugboats and hybrid tugboats).

Findings – The advantages of electric tugboats encompass decreased emissions, reduced operating expenses, improved energy efficiency, lower noise levels and potential for digital transformation through automation and data analytics. However, high initial costs, infrastructure limitations, training requirements and restricted range need to be addressed. The electric tugboat alternative seems to be the best option for scenarios with low interest rate values as increasing interest values negatively impact the salvage value of electric tugboats. It is expected that for long-term planning, the electric and hybrid tugboat alternatives will become preferential since they have lower annual costs than conventional diesel tugboats.

Practical implications – The outcomes of this research provide managerial insights into the practical deployment of electric tugboats and point to future research needs, including battery improvements, cost reduction, infrastructure development, legislative and regulatory changes and alternative energy sources. The advancement of battery technology has the potential to significantly impact the cost dynamics associated with electric tugboats. It is essential to do further research to monitor the advancements in battery technology and analyze their corresponding financial ramifications. It is essential to closely monitor the industry's shift toward electric tugboats as their prices become more affordable.

Originality/value – The maritime industry is rapidly transforming and facing pressing challenges related to sustainability and digitization. Electric tugboats represent a promising and innovative solution that could address some of these challenges through zero-emission operations, enhanced energy efficiency and integration of digital technologies. Considering the potential of electric tugboats, the present study provides a comprehensive review of the advantages and disadvantages of electric tugboats in maritime transportation, extensive evaluation of the relevant literature, interviews with industry experts and supporting econometric

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analyses. The outcomes of this research will benefit governmental agencies, policymakers and other relevant maritime transportation stakeholders.

Keywords Cost analysis, Digital transformation, Maritime transportation, Electric tugboats, Emissions reduction

Paper type Research paper

1. Background

Maritime transportation plays a vital role in the development of different countries around the world (Elmi *et al.*, 2023a; Jeevan *et al.*, 2023; Vemuri and Munim, 2023). The demand for international seaborne trade has been showing an increasing trend over the past few years. One of the reasons for such a trend is the growing population and the existing global market needs. Seaports serve as the major maritime hubs and handle more than 80% of international seaborne trade (Li *et al.*, 2023a). The arriving ships must be berthed for cargo loading and unloading operations before they can sail to the next port of call. Ship service should be completed in a timely manner, as service delays can incur substantial costs for liner shipping companies (Abou Kasm *et al.*, 2023; Dulebenets, 2023). In the meantime, ship service delays can cause congestion at seaports and negatively affect cargo deliveries to the final destinations. Ship berthing processes, especially port area maneuvering and mooring, are often considered challenging (Shipping News, 2019). Port area maneuvering and mooring involve human interactions. Human interactions always create a possibility of human errors that may cause not only damage to berthing positions and cargo handling equipment but also injuries to ship crews and onshore personnel as well.

Towboats or tugboats are crucial to seaports for several reasons. Modern tugs can guide moorings, combat fires, respond to oil spills and break ice. Tugboats have been used for many centuries. At the early stages of the development of human civilization, in medieval ports and harbors, rowing boats or smaller ships, termed “towboats” or “tugboats,” moved bigger ships, which were run by human labor, oars and rudimentary watercraft employed by the Egyptians, Greeks and Romans. Since over two centuries ago, tugboats have eased marine traffic as they can tow ships between ports and handle bigger ships in tight places. Initially, rowers or sailors operated watercraft, and then steam-powered tugboats were developed in the early 19th century (Anon, 2023). Steam power revolutionized tugboats with their greater pulling force and maneuverability. William Symington constructed the first steam tugboat, “Charlotte Dundas,” in Scotland in 1802. The first steam-powered tugboat, “Aaron Manby,” was launched on England’s River Severn in 1819. Global ports had several steam-powered tugboats in the mid-19th century. Since the early 19th-century, tugboats had a rich history, and steam-powered tugboats helped huge ships enter and depart ports. Later, tugboats with diesel engine generators became popular due to their cost-effectiveness (Anon, 2023).

Nowadays, tugboats swarm ports, push, pull and guide big ships during docking and undocking, and help them cruise slowly in confined areas. Tugboat crews may include three to 10 people, including deckhands, seamen, engineers, a mate and a master (Reid and Williams, 2017). Tugs must follow heavy tankers in specific places to respond quickly to calls for help. When a marine platform goes aground, capsizes or sinks, tugboats are crucial for performing rescue efforts. Equipped with powerful propulsion systems, tugboats are designed to operate in both inland and open ocean waters, using innovative Kort nozzles to enhance propeller power and enable the towing of larger ships. As indicated earlier, their diverse range of applications stems from docking ships and moving barges to rescue operations, pipeline construction, salvage missions, firefighting, patrolling and icebreaking (Vicenzutti *et al.*, 2015). Despite their importance, tugboat operations still have not been researched to the same extent as operations of larger ships (Balakrishnan and Sasi, 2016). More information regarding different types of tugboats and their functions is provided in Table 1 (Weve, 2022).

a/a	Type of tugboats	Definition
1	Harbor tugboats	Harbor tugs move ships and barges at ports and harbors in restricted locations by taking advantage of their tiny size and mobility
2	Terminal tugboats	Same as the harbor but specialized in hauling enormous cargo ships
3	Escort tugboats	Mainly work on tankers and cruise ships for escorting crowded areas
4	Ocean- or seagoing tugboats	Towing massive boats and construction equipment over long distances and open seas
5	Salvage tugboats	These tugboats are equipped and trained for salvage and rescue operations. They combat, refloat stranded boats, and carry underwater repair and salvage equipment
6	Anchor-handling tugs/ supply tugboats	These tugboats play a vital role in placing heavy ships and oil rigs in the ocean from the harbor. They also stabilize oil rig ships
7	River tugboats	These tugboats are small and shallow draft to handle barges and push boats in confined waterways
8	Icebreaking tugboats	These tugboats sail and clear frozen rivers using strengthened hulls to keep the rigs steady

Source(s): Table by authors

Table 1.
Types of tugboats and their functions

Burning diesel in marine ships generates black carbon (BC), which increases particulate matter (PM) emissions that affect air quality and health of living organisms, with most PM emissions occurring within 400 kilometers of coastlines and ports globally. Even with the global adoption of low-sulfur marine fuels (0.5% sulfur by weight), it is anticipated that marine ship emissions will result in 250,000 cardiovascular and lung cancer deaths and 6.4 million juvenile asthma cases every year (Sofiev *et al.*, 2018). Tugboats are viewed as a significant source of emissions in port areas. Most transoceanic ships need two tugboats to enter and navigate harbors. Even though tugboats are small, their massive engines use a lot of fuel to guide ships in port access channels. Standard tugboat engines generate 5,000 horsepower. Air pollution increases when performing maneuvers due to high engine power. Even while not in operation and at a reduced power level, engine pollutes the air. Tugboats spend up to 50% of their operational time idling, meaning their main engines are running while the ship is not moving. Many agencies currently introduce certain mechanisms to control port ship pollution (CARB, 2021).

Towing, pilot, passenger, fishing, personnel and supply ships generate emissions that pollute coastal areas, with Southern California having one of the busiest ports in North America, where harbor ship pollution is viewed as a major concern. Commercial harbor ship emissions are mostly generated by tugboats, and by 2023, towing boats are expected to generate 19% of PM and 23% of NOx emissions of commercial harbors (CARB, 2021). In-service performance standards help California-registered towing boats reduce emissions by requiring them to use Tier 4 diesel particulate filter (DPF) engines or Tier 3 engines with DPFs if Tier 4 engines are unavailable for power categories under 600 kW. Tier 4 diesel engines for off-road construction, agriculture, locomotives and maritime usage must meet the regulations set by the Environmental Protection Agency and cut PM and NOx emissions dramatically. Tier 4 engines include DPFs, selective catalytic reduction and enhanced exhaust gas recirculation. On the other hand, Tier 3 engines have catalytic converters and better engine controls to meet stricter pollution rules. Compliance costs for escort and ship support towing boats may increase the cost of transporting a twenty-foot equivalent unit (TEU) of cargo by $0.48 per TEU, which are expected to fall on customers.

Tugboats may need cleaner fuel or pollution control technology to decrease emissions, but they are also perfect for new propulsion systems and alternative fuels. In certain countries, natural gas powers ferry boats, but not tugboats yet. Plans to use hybrid electric tugboats at the Port of Los Angeles, which are powered by diesel generators and batteries, have existed for many years (Cannon, 2008). Over the past decade, the United States (US) and other countries have increased efforts to promote electric vehicles as a solution to fossil fuel pollution and the need to reduce oil imports, defining hybrid electric vehicles as the most popular personal transportation alternative to internal combustion engine cars (Jenn *et al.*, 2013; Pasha *et al.*, 2024). To reduce fuel usage and emissions, researchers are developing innovative methods to generate, transport, store and utilize electric power in automobiles, where the hybrid electric vehicle solution utilizing two power sources is viewed as a promising one. In the maritime sector, hybrid tugboats are becoming increasingly popular as an ecologically responsible solution, since these boats employ gas engines and electric power to reduce fuel consumption and pollution. Power control, battery technology and design are being studied to make hybrid tugboats more economical and sustainable (Kassakian *et al.*, 2000).

Electric tugboats are equipped with innovative digital tools and customized solutions for their operations (Crowley, 2021). Crowley Engineering Services offered the design of the first electric tugboats in the US that relied on autonomous technology. The electric tugboat design can be fully customized based on customer needs. Modular batteries can be upgraded due to changes in electric technology. Intelligent control and maneuvering systems enable more effective operation of electric tugboats. Such systems are viewed as critical, especially in busy coastal areas. Digital platforms and technology installed in new electric tugboats allow timely service of ships and reduce environmental impacts (Crowley, 2021). In addition to electric tugboats, Crowley designed onshore charging stations to support the reliable performance of electric tugboats at the designated port locations.

Considering the promising potential of electric tugboats, the present study provides a comprehensive review of electric tugboat deployment in maritime transportation, including an in-depth assessment of its advantages and disadvantages. An extensive literature review and interviews with industry experts were conducted to synthesize the current state of knowledge. Moreover, a set of econometric analyses is also conducted as a part of this study to quantitatively evaluate the economic viability of electric tugboats. The outcomes of this research are expected to provide managerial insights into the practical deployment of electric tugboats and point to future research needs. The remainder of this manuscript is arranged as follows. Section 2 reviews the relevant literature on tugboat operations. Section 3 discusses the interviews that were conducted with the leading experts in the electric tugboat industry. Section 4 performs econometric analyses for different tugboat alternatives. Section 5 provides a holistic discussion of the study findings. Section 6 summarizes the present research and provides the key concluding remarks along with the future research opportunities.

2. Literature review

As a part of this study, a detailed literature review was conducted, aiming to gain broad insights into tugboat operations. The search of the relevant literature was performed by means of the well-established content analysis method (Krippendorff, 2018). Web of Science and Scopus were considered the main literature databases during the search. Studies from a large variety of publishers were evaluated, including IEEE, Elsevier, Springer, Wiley, Emerald, Sage and others. The following keywords and their combinations were used to guide the process of the relevant literature search: tugboats, towboats, electric tugboats, conventional tugboats, diesel tugboats, hybrid tugboats, tugboat emissions, tugboat safety, tugboat scheduling, tugboat life cycle assessment, tugboat cost and tugboat operations. Only studies written in the English language were considered during the literature search. Hundreds of studies were detected based on the initial literature search, and only the most relevant studies were selected for a detailed evaluation and analysis. The selected studies were further categorized based on different themes, including tugboat accidents and safety issues, scheduling and berthing of tugboats, life cycle assessment of diesel tugboats and their alternatives, operations of electric and hybrid tugboats, environmental impacts and others. Each study group is discussed in the following sections of the manuscript.

2.1 Tugboat accidents and safety issues

Çakır *et al.* (2021) analyzed 477 tugboat accidents using data mining techniques. They found that older single-propeller tugboats over 20 feet long caused more serious accidents, likely due to poor maintenance and training. Most of the accidents occurred during tugboat maneuvering. The study pointed out that weather conditions could influence accident severity. It was also underlined that future studies could examine accident causes and incorporate human factors. Fiskin *et al.* (2021) used decision tree algorithms for 496 tugboat accidents for the 2008–2019 time period. The analysis results indicated that propulsion type was the main factor influencing the tugboat accident severity based on the collected data. The statistical models developed as a part of this study and the managerial insights revealed could assist the relevant stakeholders with a better understanding of factors that may cause the occurrence of tugboat accidents. Kim and Kang (2021) conducted a study aiming to improve tugboat safety and decrease the number of grounding accidents. A total of 63 locations with previous grounding accidents were identified and included on GPS plotters, which were provided to 61 tugboats. Such an approach was found to be efficient, as no grounding accidents were reported for more than 20 months. The majority of tugboat captains indicated that they noticed substantial safety improvements and more effective navigation. It was highlighted that the information on previous locations of grounding accidents and locations of unknown reefs could be helpful to tugboat crews.

2.2 Scheduling and berthing of tugboats

Zhen *et al.* (2018) formulated the tug scheduling problem as a mixed-integer program and developed an exact Branch-and-Price algorithm, which directly incorporated a number of acceleration techniques in order to obtain solutions in a timely manner. The presented approach outperformed CPLEX in large instances. Chen *et al.* (2020) tracked tugboat activities based on the automatic identification system (AIS) data collected for the Port of Tianjin (China). A temporal and spatial analysis was performed to investigate the assignment of tugboats for different tasks, locations of berthing operations, utilization of tugboats and service time. Du *et al.* (2020) developed a multi-layer optimal control technique for cooperative autonomous tugboats to efficiently berth unpowered ships. The proposed methodology demonstrated promising results, and reference trajectories of autonomous tugboats could be obtained online. Kang *et al.* (2020) developed proactive and reactive scheduling strategies for tugboat scheduling under uncertainties. A mixed-integer formulation was developed for the problem, aiming to minimize the total weighted service time along with the expected value associated with the recovery cost. The problem was solved using an ad-hoc optimization algorithm.

Koznowski and Łebkowski (2021) presented an agent system that can be used to control the formation of unmanned seaport tugboats responsible for towing services. The developed multi-agent system allowed synergistic cooperation among the available tugboats and improved the effectiveness of various port activities, including ship maneuvering, precise tugboat movements, monitoring of port areas and performing ice operations. Hao *et al.* (2023) developed an integer programming model and variable neighborhood search algorithm to minimize the cargo transfer time in a river-sea network by jointly scheduling barges and tugboats. The computational experiments conducted using the real data showed significant efficiency improvements with the integrated scheduling scheme. Li *et al.* (2023b) proposed an optimization model for tugboat scheduling with multiple berthing bases under operational uncertainties. A customized Gray Wolf Optimizer was developed to solve this problem. The proposed algorithm demonstrated its efficiency when compared to alternative exact and metaheuristic methods. Nikghadam *et al.* (2023) modeled cooperation between pilot and tugboat services using simulations, and the results showed that information exchange improved resource utilization and reduced ship waiting times. Further research could focus on examining the effects of weather, service heterogeneity, pilot specialization and tug characteristics.

2.3 Diesel tugboats and alternative options

Kumar *et al.* (2019) optimized the scheduling of variable-speed diesel-electric generators to minimize fuel consumption. The computational experiments indicated that the proposed approach could offer 29.9% in fuel savings when compared to the diesel-mechanical-propelled system. Wang *et al.* (2020) conducted a life cycle assessment to compare five engine configurations for a tugboat using an in-house analytical tool. The findings showed that medium-sized engines had the lowest emissions over the tugboat lifespan, demonstrating the value of life cycle assessment for evaluating marine emission reduction technologies. Karaçay and Ozsoysal (2021) conducted a techno-economic analysis of four tugboat propulsion systems, including diesel, diesel-electric, gas and dual-fuel propulsion systems. A 20-year lifecycle cost analysis was performed for the considered propulsion system alternatives. It was found that alternative propulsion systems could yield annual operational cost savings ranging from 5% to 55%. These cost savings were primarily caused by lower fuel consumption, less lubrication, reduced running hours of the main engines, higher efficiency of gas engines and cheaper unit price of gas.

Viran and Mentes (2021) provided a comprehensive overview of developments in tugboat propulsion systems for diverse operational contexts. The study emphasized the importance of sea-keeping, stability and maneuverability, especially for open-water escort tugboats and offered different perspectives on propulsion system impacts on the overall tugboat performance. Bouhouta *et al.* (2022) proposed a solar and wind energy backup system for tugboats, which could provide emergency power in order for them to function continuously without any interruptions. The suggested alternative allowed tugboats to remain operational for up to 1 h by using a storage battery in case of emergency situations. The study indicated that the presented solar and wind energy backup system could substantially reduce CO_2 emissions and yield fuel cost savings. Chen and Lam (2022) performed a life cycle assessment of hydrogen- and diesel-powered tugboats. The results of the conducted analysis indicated that hydrogen fuel cells would be able to decrease the impact of global warming by approximately 85%. Moreover, the overall environmental burden for both power options could be significantly decreased by means of recycling at the decommissioning stage.

2.4 Electric and hybrid tugboats

Jayaram *et al.* (2010) examined hybrid tugboat emissions and compared them with regular tugboats. The results of experiments showed that the hybrid tugboat alternative with batteries produced less PM, NOx and CO_2 emissions when compared to the conventional tugboat alternative with an average reduction of 73%, 51% and 27%, respectively. Shiraishi *et al.* (2015) discussed the development of a hybrid propulsion system for tugboats. The actual size of the considered hybrid tugboat alternative was assumed to be the same as that of the conventional tugboat. The battery capacity, main engine capacity and motor/generator capacity were determined based on simulation runs that involved different conditions observed during the actual operations. The proposed hybrid system achieved a 20%

reduction in fuel consumption and CO_2 emissions compared to conventional systems. It was underlined that the hybrid propulsion system could be also applicable to other ships (not just tugboats), such as small ferries, supply boats and sightseeing ships.

Kifune and Nishio (2017) examined the relationship between the control method and the efficiency of hybrid propulsion systems in tugboats. The researchers used a simulation model to study the correlation between the control method and efficiency when the tugboat was not in service. They found that a wide range of propulsion power is required in service, while in transit and waiting situations, the demanded propulsion power was less than 20%. The study highlighted the importance of controlling energy flow in hybrid propulsion systems and the need for a balance between controllability, redundancy and efficiency. The simulation results also underlined the importance of decreasing energy loss in a slipping clutch for improving hybrid propulsion system efficiency. Kumar *et al.* (2020) proposed a coordinated diesel-electric tugboat control system to optimize generator and battery usage for fuel efficiency based on load profiles. Simulations and experiments showcased 26.4% fuel savings compared to traditional diesel tugboats and reduced costs and emissions, thereby demonstrating the value of control systems for marine fuel efficiency.

2.5 Emissions and environmental impacts

Yapici and Koldemir (2016) discussed propulsion technologies for tugboats, noting that newer liquefied natural gas (LNG) and hybrid tugboats offer reduced emissions but face infrastructure limitations at ports. They estimated that hybrid tugs emit 25% less CO_2 and 50% less NOx than conventional tugs. Digital emission monitoring could help identify deviations and improve operations. Van *et al.* (2019) reviewed the effects of the International Maritime Organization (IMO) sulfur limits on refining, fuels, and ship emissions. It was noted that the newly implemented IMO regulations expect a substantial reduction in emissions from all types of ships. The alternative types of fuel might be required in order to meet the imposed regulations. Ni *et al.* (2020) reviewed emission regulations, ship emission factors and control technologies, highlighting the presence of stricter standards, emission control areas and variable emission factors based on the load. The study suggested that switching fuels, improving engine technologies and combining after-treatment methods could help meet increasingly strict standards, with further research needed to address emerging fuels, catalyst deactivation and integrated controls.

Perčić *et al.* (2021) performed a techno-economic assessment of five alternative fuels for inland ships, including methanol, electricity, LNG, ammonia, hydrogen and biodiesel. It was found that electric-powered ships would be the most environment-friendly alternative. Methanol could be the most cost-effective alternative for cargo ships, whereas full electrification would be the most economical option for passenger ships. Koznowski and Łebkowski (2022) applied a Particle Swarm Optimization algorithm to optimize the shape of a hull for electric tugboats. Based on the results from conducted experiments, it was found that the optimized hull of electric tugboats could substantially reduce energy consumption by up to 6.59% in some scenarios. Li *et al.* (2022) developed models for optimizing tugboat fuel consumption through route planning and speed control. An Evolutionary Algorithm was developed for tugboat route planning and speed optimization. The numerical experiments demonstrated that the selection of optimized speed suggested by the proposed solution algorithm could substantially decrease the overall fuel consumption, emissions produced and associated monetary losses for tugboat companies.

2.6 Miscellaneous

Several studies have discussed the applications of tugboats in salvage operations. As an example, Azofra *et al.* (2007) proposed a methodology to optimize sea rescue asset allocation, which was based on the gravitational and zonal distribution models. The distribution of rescue tugboats was performed based on several factors, including the number of accidents, their severity, accident location and required resources (e.g. medical care might be needed). An illustrative example for the assignment of rescue tugboats was presented to showcase the potential of the developed approach. Valmas (2020) differentiated salvage and towage operations that are performed by tugboats. Salvage was defined as a voluntary rescue from danger without a contract, whereas towage was described as a paid non-voluntary contracted service, noting that towage is generally not associated with any danger. The study also mentioned that it is quite difficult to determine "danger" in some instances. Furthermore, it could be also viewed as acceptable to provide a monetary award to a salver. Ptakh *et al.* (2014) overviewed switched reluctance drive usage in the Russian Navy and its application for a rescue tugboat. The operation of switched reluctance electric motors and their applications demonstrated a high level of reliability, efficiency and survivability. Furthermore, all the requirements for noise and vibration characteristics were met as well. Loisel (2023) described the Abeille Bourbon, an emergency response and salvage tugboat for the French Navy equipped with a high-speed internet system, emphasizing the tugboat innovations in communications at sea and the importance of rapid response capabilities. This tugboat operates 365 days every year with two navy crews that normally rotate every month.

A number of studies focused on bollard pull testing and its effects on tugboat operations. Yang *et al.* (2010) identified the effects of propeller speed, thrust direction, water depth and ship wake on bollard pull and braking force using scale model tests. The study results indicated that fluctuations caused by tugboat motions reduced the efficiency by up to 35%, highlighting the potential for further research on ship interactions to enhance tugboat stability and risk assessment. Dan and Khairul (2012) computationally modeled a bollard pull tugboat using computer-aided design and finite element analysis to evaluate the hull configuration. It was found that the shape of the tugboat hull could potentially influence the water flow and/or airflow, which could lead to some operational issues. Therefore, a detailed fluid flow analysis is required to ensure the adequate design of hulls for bollard pull tugboats and the safety of tugboat operations. Menon (2021) overviewed bollard pull principles, measurement and applications, noting that bollard pull quantifies static towing capacity, which is critical for managing large ships. Clear conditions, tight towline connections and reinforced ropes could improve the accuracy. The bollard pull value is generally required for tugs to ensure that they would be able to provide towage services for a given type of ship.

Several studies have investigated the operations of push boats and barge systems. Bui *et al.* (2011) developed a mathematical model for a four-tugboat system, which directly incorporated ship draft uncertainty. A pseudo-inverse algorithm was designed to determine the direction and thrust of each tugboat considered. Numerical simulations demonstrated the potential of the presented methodology. However, the feasibility of the proposed approach should be further investigated under actual operational conditions. Konings *et al.* (2013) modeled a container barge hub-and-spoke system to improve transport activities near the Port of Rotterdam. A cost model was developed to compare the performance of the existing services and the services that could be provided under different settings. It was found that the hub-and-spoke alternative has the potential to yield adequate cost performance. Yuba and Tannuri (2013) analyzed azimuth thrusters for pusher-barge maneuverability, noting that azimuth thrusters improved low-speed control, while rudders performed better at higher speeds. Moreover, it was found that the additional bow azimuth thruster might enhance maneuverability as well since the turning moment can be increased by the force imposed at the bow.

Bucci *et al.* (2016) proposed an electric hybrid pusher-barge concept for the Rhine-Danube corridor, balancing technical, regulatory and economic feasibility. The conducted research encouraged modernizing inland fleets to meet new standards although further design improvements are needed. Abramowicz *et al.* (2017) introduced a new steering system that can be installed on river push barges navigating in inland waterways that are environmentally sensitive. The proposed system included the auxiliary steering devices placed at the bow, the main steering devices placed at the stern, as well as the mechanical coupling system. Asmara (2018) simulated barge maneuvers using a mathematical model, revealing the risk of collision and the need for more tugs than mandated by the port authority. It was also highlighted that simulation modeling could assist the relevant stakeholders with the evaluation of maneuvering risks in confined ports. Lee *et al.* (2022) developed a tug-barge control system model using sliding mode control theory. Computational simulations verified the robustness and utility of the proposed system for precisely maneuvering barges. The presented sliding mode controller proved its effectiveness even under disruptive conditions.

3. Interviews with the industry representatives

To complement the literature review, a set of comprehensive interviews was conducted with the leading experts in the electric tugboat industry, including DAMEN Shipyards and the Port of Auckland (New Zealand). The interviews were performed in a structured manner using a questionnaire. The questionnaire covered a wide range of aspects, including basic features of electric tugboats, the total cost of ownership, charging infrastructure, battery selection, operational challenges, environmental benefits, technological advancements and sales strategies related to electric tugs. A full version of the questionnaire is provided in the Appendix, which accompanies this manuscript. The main insights, discovered during the interviews with the representatives from DAMEN Shipyards and the Port of Auckland, are further discussed in this section of the manuscript.

Based on the conducted interviews, it was discovered that electric tugboats have a higher total cost of ownership than their diesel-powered counterparts. However, electric tugboats operate more cost-effectively. The initial cost includes the purchase of the tugboat and dock charging equipment. Annual costs include crew training, with power, maintenance, repair and insurance costs that vary depending on regional rates. Electric tugboats offer significant cost savings in regions with higher energy costs, such as New Zealand. Their reduced maintenance costs also contribute to long-term financial advantages, making their total cost of ownership more favorable over time. Additionally, the expenses associated with shorecharging infrastructure can be substantial and vary between $1m and $2m. Governmental subsidies, particularly in countries like New Zealand, can help cover these costs. DAMEN's mobile charging arm offers a cost-effective solution for ports lacking space for permanent charging stations. The cost of charging energy, which averages $0.30 per kilowatt-hour in New Zealand, can also impact operational expenses. Charging arms can harness wave and tidal energy to reduce the environmental impact of electric tugboats. Wave and tidal energies hold the potential to revolutionize the marine sector. Solar panels are expected to offer potential cost reductions over time as well.

DAMEN recommends Lithium Titanate Oxide (LTO) batteries for their electric tugboats. Safety considerations mainly drove this decision, as LTO batteries possess a higher thermal runaway threshold, making them ideal for maritime conditions. The 1,500 kW charge capability of the LTO batteries aligns with DAMEN's goals of increasing power capacity and facilitating rapid port recharging. Battery technologies are dynamic, with ongoing improvements and potential cost reductions. The electric tugboat charging time poses a challenge, especially for smaller enterprises operating multiple tugboats simultaneously. Potential solutions include mobile charging stations and shore charging infrastructure near ports. Additionally, the limited 20-mile range of electric tugboats may complicate long-distance operations. Hybrid electric tugboats or battery swap systems are viable alternatives to address this issue. Despite these limitations, electric tugboats offer advantages in terms of reduced noise, lower operational costs and environmental friendliness. As technology evolves, electric tugboats are becoming more versatile and practical for various applications. Electricity expenses, maintenance tasks, crew training, battery replacement, motor repairs and general maintenance affect these costs. While there are certain costs involved, electric tugboats still have lower operational and maintenance costs than their diesel-powered counterparts.

DAMEN has a global support strategy for marketing and deploying electric tugboats, shedding light on the complex factors influencing the adoption of marine tugboats. The strategy is refined to meet port power demands. Solutions should be customized based on the needs of each port, including charging infrastructure readiness. Sustainable growth requires flexibility. Cutting-edge technology and bespoke solutions demonstrate DAMEN's environmental responsibility. The economic value of electric tugboats is currently explored in New Zealand and the United States. Although these two countries have varying electricity and labor costs, the overall economic value of electric tugboats is comparable. Government incentives in New Zealand, such as tax rebates, reduced registration fees and financing schemes, make electric tugboats more appealing. In contrast, the United States offers tax benefits but no specific incentives for electric tugboat purchases. Based on the conducted interviews and available literature, information on the main cost components associated with conventional, electric and hybrid tugboats was obtained (see Table 2).

4. Econometric analyses

A set of econometric analyses was performed as a part of this study to evaluate the financial viability and economic performance of electric tugboats and their alternatives (i.e. conventional tugboats and hybrid tugboats). The analyses captured the key attributes that have to be considered when assessing the viability of tugboats, including initial costs, operational costs, interest rates and machine lifetimes. The data collected during the review of the relevant literature and interviews with the leading experts in the electric tugboat industry were directly used throughout the econometric analyses. The key background information on the econometric relationships used in the conducted analyses and the analysis results are further discussed in the following sections.

4.1 Background information for the econometric analyses

This study utilized present worth analysis as the primary econometric methodology to evaluate and compare the financial costs associated with conventional diesel, electric and hybrid tugboats. Present worth analysis calculates the present value of all current and future costs related to an investment by discounting future cash flows back to the present using an assumed interest or discount rate (Panneerselvam, 2013). This allows the determination of a present value representing the total investment cost in the current dollar terms for analysis and comparison. Present worth analysis normally incorporates the initial capital investment cost, annual operating costs, salvage value at the end of asset life, interest or discount rate and asset lifetime. A total of three econometric analyses were conducted for conventional diesel, electric and hybrid tugboat alternatives, including the following: (1) analysis of the impacts of changing interest rates, (2) analysis of the impacts of changing initial investment costs and (3) analysis of the impacts of changing annual costs.

The following relationship was used to estimate the present worth in the first two analyses (Panneerselvam, 2013):

a/a	Description	Conventional diesel tugboat	Electric tugboat	Hybrid tugboat	Reference
1	Initial purchase price	$1,000,000	$2,000,000	$1,500,000	Professional Mariner (2019), Kane (2019), Karaçay and Özsoysal (2021)
2	Annual operating costs	Fuel: $200,000 (assuming fuel price of $2 per gallon)	Electricity: $100,000 (assuming electricity price of $0.1 per kilowatt-hour)	Fuel + Electricity: $150,000 (assuming fuel price of $2 per gallon)	Miller (2022)
3	Cost of electricity	$0.1 per kilowatt-hour	$0.1 per kilowatt-hour	$0.1 per kilowatt-hour	Electric Choice (2023)
4	Annual maintenance and repairs	$10,000	$5,000	$10,000	Interviews
5	Insurance	$10,000	$12,500	$10,000	Interviews
6	Crew training	$5,000	$10,000	$10,000	Interviews
7	Onshore charging infrastructure	$10,000	$50,000	$50,000	Interviews
8	Salvage value	$500,000	$1,000,000	$750,000	Interviews

Note(s):• The data presented in rows 4 to 8 of Table 2 are based on the interviews that were conducted with the representatives from DAMEN and the Port of Auckland

• The cost of onshore charging infrastructure is included in the initial purchase price. The onshore charging infrastructure was included in the cost estimations for the conventional tugboat alternative as well since conventional tugboats also use electricity when docked at the port

• The cost components presented in this table will be used in the estimation of the initial cost and total annual cost

✓ Initial cost = Initial purchase price (includes Onshore charging infrastructure)

✓ Total annual cost = Annual operating costs + Annual maintenance and repairs + Insurance + Crew training

Source(s): Table by authors

Table 2. The main cost components associated with conventional, electric and hybrid tugboats

$$PW = I + TA \cdot (P/A, i, n) - SV \cdot (P/F, i, n) \tag{1}$$

where PW = present worth value for a given tugboat alternative;

I = initial investment for a given tugboat alternative;

TA = total annual cost for a given tugboat alternative;

SV = salvage value for a given tugboat alternative;

i = interest value (uniform period-by-period increase);

n = number of years considered in the analysis;

$(P/A, i, n)$ = present worth factor that is fixed for a given time period and interest rate value and can be determined based on the end-of-period compound interest tables (Oxford University Press, 2023);

$(P/F, i, n)$ = present worth factor that is fixed for a given time period and interest rate value and can be determined based on the end-of-period compound interest tables (Oxford University Press, 2023).

The following relationship was used to estimate the present worth in the third analysis (Panneerselvam, 2013):

$$PW = I + TA \cdot (P/A, i, n) + G \cdot (P/G, i, n) - SV \cdot (P/F, i, n) \tag{2}$$

where PW = present worth value for a given tugboat alternative;

I = initial investment for a given tugboat alternative;

TA = total annual cost for a given tugboat alternative;

G = subsequent annual cost increase in the following years for a given tugboat alternative;

SV = salvage value for a given tugboat alternative;

i = interest value (uniform period-by-period increase);

n = number of years considered in the analysis;

$(P/A, i, n)$ = present worth factor that is fixed for a given time period and interest rate value and can be determined based on the end-of-period compound interest tables (Oxford University Press, 2023);

$(P/G, i, n)$ = present worth factor that is fixed for a given time period and interest rate value and can be determined based on the end-of-period compound interest tables (Oxford University Press, 2023);

$(P/F, i, n)$ = present worth factor that is fixed for a given time period and interest rate value and can be determined based on the end-of-period compound interest tables (Oxford University Press, 2023).

4.2 Analysis results

The first econometric analysis was conducted by changing the interest rate values for the considered tugboat alternatives. In particular, a total of 11 interest rate scenarios were developed by increasing the interest rate from 5% to 15% with an increment of 1%. The analysis time period was assumed to be 10 years, and the main cost components were adopted from Table 2. The results of the conducted analysis are reported in Table 3 which includes the following information: (1) scenario number for interest rates, (2) initial investment cost for a given tugboat alternative, (3) total annual cost for a given tugboat alternative, (4) interest rate considered, (5) P/A factor value for a given time period and interest rate value, (6) P/F factor value for a given time period and interest rate value, (7) analysis time period considered, (8) salvage value for a given tugboat alternative and (9) estimated present worth for a given tugboat alternative. Furthermore, Figure 1 illustrates the impacts of changing interest rates on the present worth of all the considered tugboat alternatives.

It can be observed that, for the considered interest rate scenarios, the present worth pattern showed a decreasing trend for the conventional diesel and hybrid tugboat alternatives. However, an increasing trend in the present worth values was identified for the electric tugboat alternative. Such a pattern can be explained by the increasing value of $[TA \cdot (P/A, i, n) - SV \cdot (P/F, i, n)]$ from one scenario to another. The analysis results demonstrate that the electric tugboat alternative would be the best option for scenarios with low interest rate values. Increasing interest values negatively impact the salvage value of

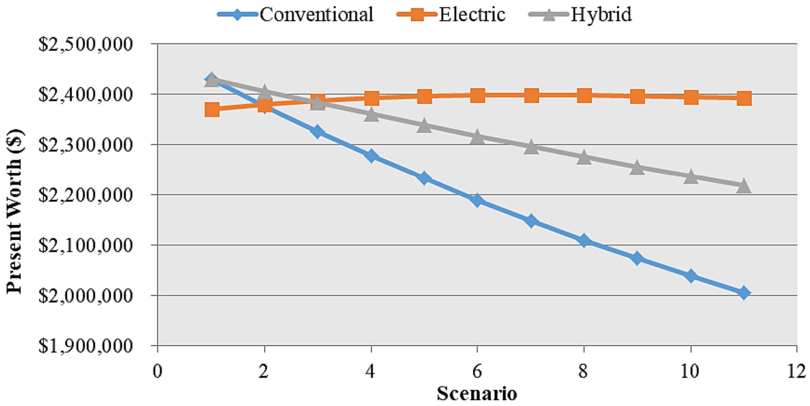
Table 3. Present worth values for the considered tugboat alternatives and interest rate scenarios

Scenario	Initial cost ($)	Annual cost ($)	Interest (%)	*P/A* factor	*P/F* factor	Period (years)	Salvage value ($)	Present worth ($)
Conventional tugboat								
1	$ 1,000,000	$ 225,000	5%	7.722	0.6139	10	$ 500,000	$ 2,430,500
2	$ 1,000,000	$ 225,000	6%	7.360	0.5584	10	$ 500,000	$ 2,376,800
3	$ 1,000,000	$ 225,000	7%	7.024	0.5083	10	$ 500,000	$ 2,326,250
4	$ 1,000,000	$ 225,000	8%	6.710	0.4632	10	$ 500,000	$ 2,278,150
5	$ 1,000,000	$ 225,000	9%	6.418	0.4224	10	$ 500,000	$ 2,232,850
6	$ 1,000,000	$ 225,000	10%	6.145	0.3855	10	$ 500,000	$ 2,189,875
7	$ 1,000,000	$ 225,000	11%	5.889	0.3522	10	$ 500,000	$ 2,148,925
8	$ 1,000,000	$ 225,000	12%	5.650	0.3220	10	$ 500,000	$ 2,110,250
9	$ 1,000,000	$ 225,000	13%	5.426	0.2946	10	$ 500,000	$ 2,073,550
10	$ 1,000,000	$ 225,000	14%	5.216	0.2697	10	$ 500,000	$ 2,038,750
11	$ 1,000,000	$ 225,000	15%	5.019	0.2472	10	$ 500,000	$ 2,005,675
Electric tugboat								
1	$ 2,000,000	$ 127,500	5%	7.722	0.6139	10	$ 1,000,000	$ 2,370,655
2	$ 2,000,000	$ 127,500	6%	7.360	0.5584	10	$ 1,000,000	$ 2,380,000
3	$ 2,000,000	$ 127,500	7%	7.024	0.5083	10	$ 1,000,000	$ 2,387,260
4	$ 2,000,000	$ 127,500	8%	6.710	0.4632	10	$ 1,000,000	$ 2,392,325
5	$ 2,000,000	$ 127,500	9%	6.418	0.4224	10	$ 1,000,000	$ 2,395,895
6	$ 2,000,000	$ 127,500	10%	6.145	0.3855	10	$ 1,000,000	$ 2,397,988
7	$ 2,000,000	$ 127,500	11%	5.889	0.3522	10	$ 1,000,000	$ 2,398,648
8	$ 2,000,000	$ 127,500	12%	5.650	0.3220	10	$ 1,000,000	$ 2,398,375
9	$ 2,000,000	$ 127,500	13%	5.426	0.2946	10	$ 1,000,000	$ 2,397,215
10	$ 2,000,000	$ 127,500	14%	5.216	0.2697	10	$ 1,000,000	$ 2,395,340
11	$ 2,000,000	$ 127,500	15%	5.019	0.2472	10	$ 1,000,000	$ 2,392,723
Hybrid tugboat								
1	$ 1,500,000	$ 180,000	5%	7.722	0.6139	10	$ 750,000	$ 2,429,535
2	$ 1,500,000	$ 180,000	6%	7.360	0.5584	10	$ 750,000	$ 2,406,000
3	$ 1,500,000	$ 180,000	7%	7.024	0.5083	10	$ 750,000	$ 2,383,095
4	$ 1,500,000	$ 180,000	8%	6.710	0.4632	10	$ 750,000	$ 2,360,400
5	$ 1,500,000	$ 180,000	9%	6.418	0.4224	10	$ 750,000	$ 2,338,440
6	$ 1,500,000	$ 180,000	10%	6.145	0.3855	10	$ 750,000	$ 2,316,975
7	$ 1,500,000	$ 180,000	11%	5.889	0.3522	10	$ 750,000	$ 2,295,870
8	$ 1,500,000	$ 180,000	12%	5.650	0.3220	10	$ 750,000	$ 2,275,500
9	$ 1,500,000	$ 180,000	13%	5.426	0.2946	10	$ 750,000	$ 2,255,730
10	$ 1,500,000	$ 180,000	14%	5.216	0.2697	10	$ 750,000	$ 2,236,605
11	$ 1,500,000	$ 180,000	15%	5.019	0.2472	10	$ 750,000	$ 2,218,020

Source(s): Table by authors

electric tugboats, which is the highest among all the considered tugboat alternatives. The conventional tugboat alternative would be the most promising for scenarios with high interest rate values, assuming that the total annual cost does not change from one year to another before applying the P/A factor. It is also expected that for long-term planning (i.e. with a time horizon exceeding 10 years), the electric and hybrid tugboat alternatives will become preferential since they have lower annual costs when compared to the conventional diesel tugboat alternative.

The second econometric analysis was conducted by changing the initial investment values for the considered tugboat alternatives. In particular, a total of 11 initial investment scenarios were developed by increasing the base initial investment values (assumed to be $1,000,000, $2,000,000 and $1,500,000 for the conventional diesel, electric and hybrid tugboat alternatives, respectively) by $100,000 from one scenario to another. The analysis time period



Source(s): Figure by authors

Figure 1.
Analysis of the impacts of changing interest rates

was assumed to be 10 years, and the main cost components were adopted from Table 2. The results of the conducted analysis are reported in Table 4 which includes the following information: (1) scenario number for the initial investment value, (2) initial investment cost for a given tugboat alternative, (3) total annual cost for a given tugboat alternative, (4) interest rate considered, (5) P/A factor value for a given time period and interest rate value, (6) P/F factor value for a given time period and interest rate value, (7) analysis time period considered, (8) salvage value for a given tugboat alternative and (9) estimated present worth for a given tugboat alternative. Furthermore, Figure 2 illustrates the impacts of changing initial investment values on the present worth for all the considered tugboat alternatives.

It can be observed that, for the considered initial investment scenarios, the present worth pattern showed an increasing trend for the conventional diesel, electric and hybrid tugboat alternatives. The conventional tugboat alternative seemed to be the most promising alternative for all the considered initial investment scenarios. Such a pattern can be explained by uniform changes in the initial investment (i.e. the base initial investment was increased by the same amount from one scenario to another for all the considered tugboat alternatives). However, the findings from the conducted analysis can be still used to confirm that the initial investment costs are much more significant for electric tugboats when compared to conventional diesel tugboats. New options should be investigated in the following years to reduce the initial investment costs for electric tugboats (e.g. more cost-effective alternatives for onshore charging infrastructure and exploration of renewable energy sources). The hybrid tugboat alternative could also benefit from reduced initial investment costs; so, this alternative could become more affordable for different stakeholders.

The third econometric analysis was conducted by changing the annual cost values for the considered tugboat alternatives. In particular, a total of 11 annual cost scenarios were developed by increasing the base annual cost values (assumed to be $225,000, $127,500 and $180,000 for the conventional diesel, electric and hybrid tugboat alternatives, respectively) by $10,000 from one scenario to another. Moreover, a subsequent increase of $10,000 every year in the annual cost was modeled for each scenario (i.e. application of the arithmetic gradient). The analysis time period was assumed to be 10 years, and the main cost components were adopted from Table 2. The results of the conducted analysis are reported in Table 5 which includes the following information: (1) scenario number for the annual cost value, (2) initial investment cost for a given tugboat alternative, (3) total annual cost for a given tugboat alternative, (4) subsequent annual cost increase in the following years, (5) interest rate

Scenario	Initial cost ($)	Annual cost ($)	Interest (%)	*P*/*A* factor	*P*/*F* factor	Period (years)	Salvage value ($)	Present worth ($)
Conventional tugboat								
1	$ 1,000,000	$ 225,000	10%	6.145	0.3855	10	$ 500,000	$2,189,875
2	$ 1,100,000	$ 225,000	10%	6.145	0.3855	10	$ 500,000	$2,289,875
3	$ 1,200,000	$ 225,000	10%	6.145	0.3855	10	$ 500,000	$2,389,875
4	$ 1,300,000	$ 225,000	10%	6.145	0.3855	10	$ 500,000	$2,489,875
5	$ 1,400,000	$ 225,000	10%	6.145	0.3855	10	$ 500,000	$2,589,875
6	$ 1,500,000	$ 225,000	10%	6.145	0.3855	10	$ 500,000	$2,689,875
7	$ 1,600,000	$ 225,000	10%	6.145	0.3855	10	$ 500,000	$2,789,875
8	$ 1,700,000	$ 225,000	10%	6.145	0.3855	10	$ 500,000	$2,889,875
9	$ 1,800,000	$ 225,000	10%	6.145	0.3855	10	$ 500,000	$2,989,875
10	$ 1,900,000	$ 225,000	10%	6.145	0.3855	10	$ 500,000	$3,089,875
11	$ 2,000,000	$ 225,000	10%	6.145	0.3855	10	$ 500,000	$3,189,875
Electric tugboat								
1	$ 2,000,000	$ 127,500	10%	6.145	0.3855	10	$ 1,000,000	$2,397,988
2	$ 2,100,000	$ 127,500	10%	6.145	0.3855	10	$ 1,000,000	$2,497,988
3	$ 2,200,000	$ 127,500	10%	6.145	0.3855	10	$ 1,000,000	$2,597,988
4	$ 2,300,000	$ 127,500	10%	6.145	0.3855	10	$ 1,000,000	$2,697,988
5	$ 2,400,000	$ 127,500	10%	6.145	0.3855	10	$ 1,000,000	$2,797,988
6	$ 2,500,000	$ 127,500	10%	6.145	0.3855	10	$ 1,000,000	$2,897,988
7	$ 2,600,000	$ 127,500	10%	6.145	0.3855	10	$ 1,000,000	$2,997,988
8	$ 2,700,000	$ 127,500	10%	6.145	0.3855	10	$ 1,000,000	$3,097,988
9	$ 2,800,000	$ 127,500	10%	6.145	0.3855	10	$ 1,000,000	$3,197,988
10	$ 2,900,000	$ 127,500	10%	6.145	0.3855	10	$ 1,000,000	$3,297,988
11	$ 3,000,000	$ 127,500	10%	6.145	0.3855	10	$ 1,000,000	$3,397,988
Hybrid tugboat								
1	$ 1,500,000	$ 180,000	10%	6.145	0.3855	10	$ 750,000	$2,316,975
2	$ 1,600,000	$ 180,000	10%	6.145	0.3855	10	$ 750,000	$2,416,975
3	$ 1,700,000	$ 180,000	10%	6.145	0.3855	10	$ 750,000	$2,516,975
4	$ 1,800,000	$ 180,000	10%	6.145	0.3855	10	$ 750,000	$2,616,975
5	$ 1,900,000	$ 180,000	10%	6.145	0.3855	10	$ 750,000	$2,716,975
6	$ 2,000,000	$ 180,000	10%	6.145	0.3855	10	$ 750,000	$2,816,975
7	$ 2,100,000	$ 180,000	10%	6.145	0.3855	10	$ 750,000	$2,916,975
8	$ 2,200,000	$ 180,000	10%	6.145	0.3855	10	$ 750,000	$3,016,975
9	$ 2,300,000	$ 180,000	10%	6.145	0.3855	10	$ 750,000	$3,116,975
10	$ 2,400,000	$ 180,000	10%	6.145	0.3855	10	$ 750,000	$3,216,975
11	$ 2,500,000	$ 180,000	10%	6.145	0.3855	10	$ 750,000	$3,316,975

Source(s): Table by authors

Table 4.
Present worth values for the considered tugboat alternatives and initial investment scenarios

considered, (6) P/A factor value for a given time period and interest rate value, (7) P/F factor value for a given time period and interest rate value, (8) P/G factor value for a given time period and interest rate value, (9) analysis time period considered, (10) salvage value for a given tugboat alternative and (11) estimated present worth for a given tugboat alternative. Furthermore, Figure 3 illustrates the impacts of changing annual cost values on the present worth for all the considered tugboat alternatives.

It can be observed that, for the considered annual cost scenarios, the present worth pattern showed an increasing trend for the conventional diesel, electric and hybrid tugboat alternatives. The conventional tugboat alternative seemed to be the most promising alternative for all the considered annual cost scenarios. Such a pattern can be explained by uniform changes in the annual cost (i.e. the base annual cost was increased by the same amount from one scenario to another for all the considered tugboat alternatives, and the same

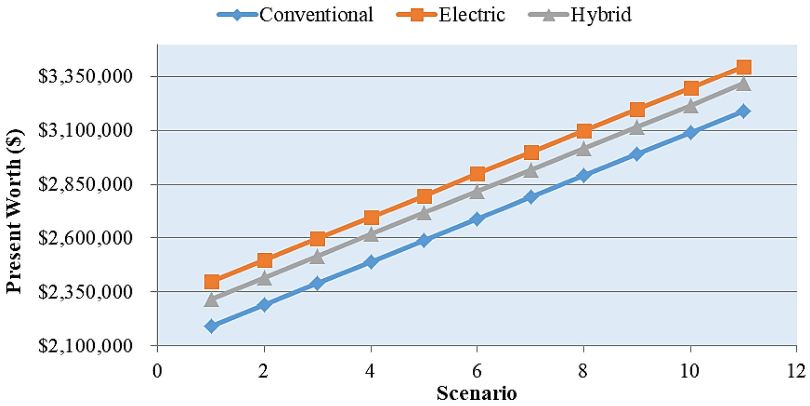


Figure 2.
Analysis of the impacts of changing initial investment values

Source(s): Figure by authors

values of subsequent annual cost increases were applied as well). Taking into account the existing uncertainties in the energy market, conventional diesel tugboats may be more susceptive than the electric and hybrid tugboat alternatives and experience greater annual cost increases from one year to another. Based on the results from the conducted analysis, the electric tugboat alternative with a total annual cost of $127,500 and subsequent annual cost increase of $10,000 in the following years would be a more promising option (the present worth value of $2,626,898) when compared to the conventional diesel tugboat alternative with the total annual cost of $265,000 and subsequent annual cost increase of $10,000 in the following years (the present worth value of $2,664,585). Furthermore, the hybrid tugboat alternative with a total annual cost of $180,000 and subsequent annual cost increase of $10,000 in the following years would be a more promising option (the present worth value of $2,545,885) when compared to the conventional diesel tugboat alternative with the total annual cost of $255,000 and subsequent annual cost increase of $10,000 in the following years (the present worth value of $2,603,135).

5. Discussion

5.1 Identified advantages of electric tugboat deployment in maritime transportation

The primary advantages of electric tugboats, which were identified as a result of the conducted literature review and interviews with the leading experts in the electric tugboat industry, include the following: (1) reduced emissions, (2) reduced operating costs, (3) improved energy efficiency and (4) reduced noise. One of the primary advantages associated with electric propulsion is a significant *decrease in atmospheric pollutants and emissions of greenhouse gases*. Tugboats equipped with diesel engines are known to generate significant quantities of pollutants, including nitrogen oxides (NOx), PM and carbon dioxide (CO_2). These emissions have been seen to have adverse effects on the air quality in the surrounding areas and contribute to the phenomenon of climate change. Research findings indicate that the use of electric propulsion systems may significantly reduce the emissions associated with tugboat operations. The study conducted by the International Council on Clean Transportation has approximated that the complete electrification of tugboats and other equipment operating at the Port of New York and New Jersey would result in a reduction of 69% in fine PM emissions, averting 16 premature deaths on a yearly basis (Gallucci, 2023). Moreover, cruise, container and other types of ships and tugboats at the Ports of Los Angeles

Table 5. Present worth values for the considered tugboat alternatives and annual cost scenarios

Scenario	Initial cost ($)	Annual cost ($)	Annual increase ($)	Interest (%)	P/A factor	P/F factor	P/G factor	Period (years)	Salvage value ($)	Present worth ($)
Conventional tugboat										
1	$ 1,000,000	$ 225,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 500,000	$ 2,418,785
2	$ 1,000,000	$ 235,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 500,000	$ 2,480,235
3	$ 1,000,000	$ 245,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 500,000	$ 2,541,685
4	$ 1,000,000	$ 255,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 500,000	$ 2,603,135
5	$ 1,000,000	$ 265,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 500,000	$ 2,664,585
6	$ 1,000,000	$ 275,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 500,000	$ 2,726,035
7	$ 1,000,000	$ 285,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 500,000	$ 2,787,485
8	$ 1,000,000	$ 295,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 500,000	$ 2,848,935
9	$ 1,000,000	$ 305,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 500,000	$ 2,910,385
10	$ 1,000,000	$ 315,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 500,000	$ 2,971,835
11	$ 1,000,000	$ 325,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 500,000	$ 3,033,285
Electric tugboat										
1	$ 2,000,000	$ 127,500	$ 10,000	10%	6.145	0.3855	22.891	10	$ 1,000,000	$ 2,626,898
2	$ 2,000,000	$ 137,500	$ 10,000	10%	6.145	0.3855	22.891	10	$ 1,000,000	$ 2,688,348
3	$ 2,000,000	$ 147,500	$ 10,000	10%	6.145	0.3855	22.891	10	$ 1,000,000	$ 2,749,798
4	$ 2,000,000	$ 157,500	$ 10,000	10%	6.145	0.3855	22.891	10	$ 1,000,000	$ 2,811,248
5	$ 2,000,000	$ 167,500	$ 10,000	10%	6.145	0.3855	22.891	10	$ 1,000,000	$ 2,872,698
6	$ 2,000,000	$ 177,500	$ 10,000	10%	6.145	0.3855	22.891	10	$ 1,000,000	$ 2,934,148
7	$ 2,000,000	$ 187,500	$ 10,000	10%	6.145	0.3855	22.891	10	$ 1,000,000	$ 2,995,598
8	$ 2,000,000	$ 197,500	$ 10,000	10%	6.145	0.3855	22.891	10	$ 1,000,000	$ 3,057,048
9	$ 2,000,000	$ 207,500	$ 10,000	10%	6.145	0.3855	22.891	10	$ 1,000,000	$ 3,118,498
10	$ 2,000,000	$ 217,500	$ 10,000	10%	6.145	0.3855	22.891	10	$ 1,000,000	$ 3,179,948
11	$ 2,000,000	$ 227,500	$ 10,000	10%	6.145	0.3855	22.891	10	$ 1,000,000	$ 3,241,398
Hybrid tugboat										
1	$ 1,500,000	$ 180,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 750,000	$ 2,545,885
2	$ 1,500,000	$ 190,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 750,000	$ 2,607,335
3	$ 1,500,000	$ 200,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 750,000	$ 2,668,785
4	$ 1,500,000	$ 210,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 750,000	$ 2,730,235
5	$ 1,500,000	$ 220,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 750,000	$ 2,791,685
6	$ 1,500,000	$ 230,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 750,000	$ 2,853,135
7	$ 1,500,000	$ 240,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 750,000	$ 2,914,585
8	$ 1,500,000	$ 250,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 750,000	$ 2,976,035
9	$ 1,500,000	$ 260,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 750,000	$ 3,037,485
10	$ 1,500,000	$ 270,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 750,000	$ 3,098,935
11	$ 1,500,000	$ 280,000	$ 10,000	10%	6.145	0.3855	22.891	10	$ 750,000	$ 3,160,385

Source(s): Table by authors

and Long Beach are expected to use onshore electricity during the docking periods in order to reduce emissions produced in the vicinity of ports. It is anticipated that these requirements would decrease the potential risk of cancer for the associated coastal communities by 55% (Gallucci, 2023). Therefore, there are significant advantages in air quality and public health that electric tugs may provide to port towns.

The elimination of on-site emissions also aids ports and carriers in complying with ever-stringent environmental rules. The International Maritime Organization (IMO, 2023) has established objectives to achieve a minimum reduction of 50% in greenhouse gas emissions from maritime ships by the year 2050. Moreover, a number of emissions control areas have been designated around the world with the objective of improving environmental sustainability and reducing pollution from maritime transportation in the vicinity of busy

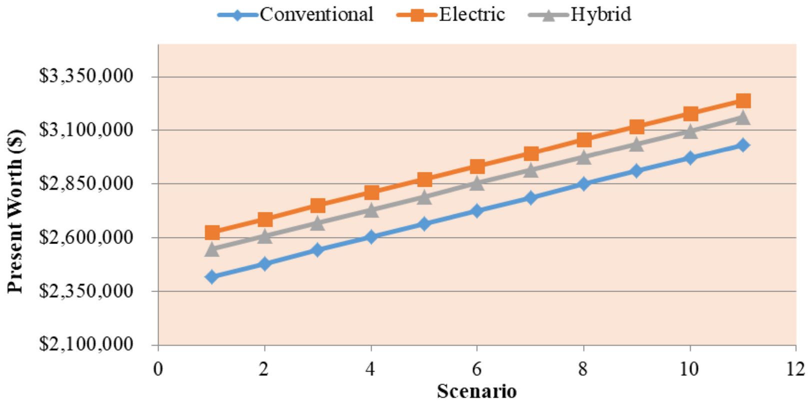


Figure 3.
Analysis of the impacts of changing annual cost values

Source(s): Figure by authors

ports. The emission control areas have been established in the North Sea, the Baltic Sea, the English Channel and along the North American coastal zone (Dulebenets, 2022; Elmi *et al.*, 2023b). Ships sailing within the boundaries of emission control areas are expected to use low-sulfur fuel that has no more than 0.10% sulfur (which is also called "ultra-low-sulfur fuel oil"). Consequently, these developments have led to a need for more environment-friendly solutions for oceangoing ships and tugboats as well. Electric propulsion plays a pivotal role in facilitating significant advancements toward the existing sustainability objectives.

In addition to their environmental benefits, electric and hybrid tugboats have the potential to substantially *decrease fuel and maintenance expenditures* in comparison to their diesel counterparts. The cost of electricity per unit of energy provided is much cheaper compared to the cost of diesel fuel. According to the recent study conducted by WorkBoat (2022), it has been shown that the expense associated with fueling a hybrid tugboat is about one-third of the cost incurred by its diesel-powered equivalent. Given the current high and unpredictable global fuel costs, the use of electric propulsion offers a significant fuel cost reduction. Electric motors have a reduced maintenance demand compared to diesel engines, necessitating regular oil changes, filter replacements, engine repairs and other services. According to the research conducted by Prinssen and Weg (2023), the yearly maintenance expenses associated with an electric tug could be thousands of dollars less when compared to a diesel tug of similar specifications. In addition, the streamlined propulsion systems enable electric tugs to be operated with reduced crew sizes, hence, leading to decreased labor expenses. Electric tugs provide a more cost-effective operational solution in the long term due to their potential for fuel and maintenance savings.

Electric propulsion offers much *superior energy efficiency* compared to diesel engines, thus constituting an additional substantial advantage for tugboat operations. According to the US Environmental Protection Agency and other credible sources (Renault Group, 2023), electric motors have a conversion efficiency of over 90% in terms of energy utilization for productive labor. In contrast, diesel combustion engines exhibit a far lower efficiency, using just 30–40% of the energy derived from fuel burning. Electric motors have the advantageous capability of delivering the maximum torque even at 0 revolutions per minute (rpm), making them very suitable for tasks that involve towing at low speeds. The research conducted by several port authorities has shown the potential for energy savings. According to a study conducted by the Port of Los Angeles, the electric tugs used at the port showed a significant reduction of around 70% in energy consumption per ship aided when compared to their diesel-powered counterparts. Since 2018, Corvus Energy and Navtek Naval Technologies have been working on new energy storage systems and software for NV-712 ZeeTug, which stands for a "zero emissions electric tug" (Pessa, 2020). The new digital elements and energy management systems are expected to improve the electric tugboat performance even further. Therefore, numerous studies performed to date have elucidated the inherent energy efficiency benefits that could be realized with applications of electric propulsion systems.

Electric tugboats also offer the advantage of reducing or mitigating unwanted and disruptive sounds in each environment. The electric motors used for propulsion on tugboats exhibit much *reduced noise levels* during operations in comparison to the loud and vibrating diesel engines, particularly during acceleration. The reduction of noise pollution is a substantial advantage for ports located in metropolitan regions or near vulnerable marine habitats. Electric and hybrid tugboats have been used at the Port of San Diego (Gallucci, 2023), and the relevant studies demonstrated that electric tugboats had noise levels that were 50–70% lower compared to those of traditional harbor tugs. The mitigation of noise pollution enhances the operational conditions for tug crews and minimizes the disruption to marine ecosystems. The use of a quiet operating strategy may potentially enhance the level of community acceptability toward port operations.

5.2 Identified disadvantages of electric tugboat deployment in maritime transportation

The primary disadvantages of electric tugboats, which were identified as a result of the conducted literature review and interviews with the leading experts in the electric tugboat industry, include the following (1) high upfront cost, (2) infrastructure requirements, (3) training requirements and (4) range limitations. One notable drawback associated with electric tugs is their *elevated initial investment cost* when compared to traditional diesel tugs. A considerable proportion of the increased expenses may be ascribed to the need to use extensive battery banks. According to Sezler (2023), the cost of lithium-ion batteries remains over $150 per kilowatt-hour (kWh) of capacity. Despite the declining costs of batteries, they still contribute significantly to overall expenses. The practice of distributing battery expenses across the whole operational lifetime of the ship contributes to enhancing the cost-competitiveness of electric tugs. Nevertheless, the substantial initial capital required may cause a barrier for businesses with limited financial resources. The provision of financial resources and government incentives may serve as effective means to mitigate the initial cost differential.

One other obstacle that hinders the widespread use of electric tugs is the need to establish *complementary onshore infrastructure* (WorkBoat, 2022). The process of port electrification necessitates substantial investments in grid enhancements, the establishment of onshore power supply systems, the installation of charging stations and the development of other related infrastructure. Most ports now exhibit insufficient infrastructure to accommodate the charging requirements of electric ships on a big scale. The absence of a well-developed charging infrastructure now presents a significant obstacle to the practicality of electric tugboats unless comprehensive charging networks are effectively implemented. Based on the interviews that were conducted with the leading experts in the electric tugboat industry, the necessary qualifications and skills are required for the key personnel; so, they can effectively perform their tasks during the operations and maintenance of electric tugboats. The inherent complexity of electric propulsion systems mandates the provision of supplementary *training for personnel operating electric tugboats*. It is essential to design novel procedures to control high-voltage systems effectively and safely. Different types of hazards, such as electric shock, require heightened safety consciousness. To acquire proficiency in the distinctive maneuvering techniques associated with electric tugs, pilots must undergo specialized training. The implementation of effective training is crucial for facilitating seamless adoption.

Electric tugs encounter *range constraints* due to their reliance on battery charging, which is viewed as a significant drawback when compared to the substantial fuel capacity of diesel tugs. To prevent periods of inactivity, it is essential to engage in meticulous route planning, coordinate charging activities and provide reliable backup power systems. While the management of short-range port tasks may be feasible, offshore and coastal tugs would encounter more significant obstacles. The ongoing progress in battery densities is expected to contribute to the expansion of range capabilities.

5.3 Tugboat idle time considerations

Tugboats spend a large portion of their operating time idling while not actively engaged in towing or maneuvering operations. This can be caused by late ship arrivals, port congestion and other port disruptions. The average waiting time of container ships at European ports may exceed several hours (Lind *et al.*, 2018), and this number can be even larger for ferry and cruise ships. Other parties involved in ship service, including tugboats, are also affected by excessive ship waiting times. Studies have shown that tugboats are often operated at low engine loads despite being equipped with large diesel engines sized for the maximum bollard pull capacity. There are various reasons for tugboat idle time, including waiting for task assignments at ports, being on standby for emergency response, delays in ship berthing/unberthing due to congestion or operational issues, and a mismatch between the main engine capacity and average load profile. Excessive idling has a number of disadvantages, such as wasted fuel, increasing emissions, engine wear and tear over time, generating air and noise pollution at ports, and leading to higher operating costs for tug owners.

The study conducted by Boyd and Macpherson (2014) analyzed typical tugboat duty cycles for different modes, such as transit, assist and barge moving. The results showed that tugs operate at full-rated power less than 10% of the time and at low power 80–90% of the time. With a power threshold of 360 kW, tugs operate below this threshold 87% of the time. The highest energy modes occur briefly while low power modes are prolonged. Harbor duty tugboats generally spend more time in the idling mode when compared to ocean duty tugs. This indicates significant potential for optimization and alternate power sources. Strategies to reduce tugboat idling and improve efficiency include the use of variable-speed diesel drives to optimize engine speed for power demand, installation of batteries/hybrid systems for low load operations, use of scheduling tools for just-in-time operations planning and providing shore power charging infrastructure for electric tugs. With new technologies and smarter practices, tugboat idle time can be substantially reduced to cut fuel use, emissions and electricity. Hybrid tugboats can substantially reduce their fuel consumption when powered by onshore charging stations during the idling time periods.

5.4 Econometric insights

A total of three econometric analyses were conducted as a part of this study for conventional diesel, electric and hybrid tugboat alternatives, including the following (1) analysis of the impacts of changing interest rates, (2) analysis of the impacts of changing initial investment costs and (3) analysis of the impacts of changing annual costs. The analysis conducted for changing interest rate values showed that the electric tugboat alternative would be the best option for scenarios with low interest rate values. Increasing interest values negatively impact the salvage value of electric tugboats, which is the highest among all the considered tugboat alternatives. The conventional tugboat alternative would be the most promising for scenarios with high interest rate values. It is also expected that for long-term planning (i.e. with a time horizon exceeding 10 years), the electric and hybrid tugboat alternatives will become preferential since they have lower annual costs when compared to the conventional diesel tugboat alternative.

Furthermore, the conventional tugboat alternative seemed to be the most promising alternative for all the considered initial investment scenarios. The findings from the conducted analysis confirm that the initial investment costs are much more significant for electric tugboats when compared to conventional diesel tugboats. New options should be investigated in the following years to reduce the initial investment costs for electric tugboats (e.g. more cost-effective alternatives for onshore charging infrastructure and exploration of renewable energy sources). The hybrid tugboat alternative could also benefit from reduced initial investment costs; so, this alternative could become more affordable for different stakeholders. Moreover, the conventional tugboat alternative seemed to be the most promising alternative for all the considered annual cost scenarios. Such a pattern can be explained by uniform changes in the annual cost (i.e. the base annual cost was increased by the same amount from one scenario to another for all the considered tugboat alternatives, and the same values of subsequent annual cost increases were applied as well). Taking into account the existing uncertainties in the energy market, conventional diesel tugboats may be more susceptive than the electric and hybrid tugboat alternatives and experience greater annual cost increases from one year to another. Therefore, as indicated earlier, electric and hybrid tugboats could be a more promising option for the long term.

5.5 Impacts on digitalization

The present research contributes to the digitalization of maritime transportation in several ways. The data collection process relied heavily on digital sources, including industry reports, databases and expert interviews conducted via digital platforms. Data analytics and econometric modeling techniques were applied using the latest software tools for financial scenario analysis. Furthermore, the findings of this study can be used to develop digital tools and dashboards to help maritime stakeholders make informed decisions about financial investments in electric tugboats. For example, a digital tool could be developed to calculate the total cost of ownership of electric tugboats over their lifetime, considering different interest rates, initial investment costs, annual cost growth rates and other factors. This would enable stakeholders to compare the financial viability of electric tugboats with conventional and hybrid alternatives. Additionally, the findings of the present study can be used to facilitate the development of digital platforms for asset management and predictive maintenance of electric tugboats. Such digital platforms would help stakeholders to optimize the performance and lifespan of their electric tugboats while minimizing operating costs. Overall, this study contributes to the digitalization of maritime transportation by providing data-driven insights into the financial viability and cost dynamics of electric tugboats. The outcomes of this research can be used to design new-generation decision support systems for the planning and management of tugboat investment decisions for different planning periods.

6. Concluding remarks and future research directions

Maritime transportation plays a vital role in the development of different countries around the world. Timely ship berthing processes, including port area maneuvering and mooring, are critical for effective cargo loading and offloading but are often challenging, especially at busy ports. Towboats or tugboats are crucial to seaports for several reasons. Modern tugs can guide moorings, combat fires, respond to oil spills and break the ice. Hybrid tugboats along with electric tugboats are becoming increasingly popular as an ecologically responsible solution since these boats employ gas engines and electric power to reduce fuel consumption and pollution. Power control, battery technology and design are being studied to make hybrid and electric tugboats more economical and sustainable. Considering the promising potential of electric tugboats, the present study provides a comprehensive review of electric tugboat deployment in maritime transportation, including an in-depth assessment of its advantages and disadvantages. An extensive literature review and interviews with industry experts were conducted to synthesize the current state of knowledge.

As a result of the conducted literature review and interviews with the leading experts in the electric tugboat industry, the primary advantages of electric tugboats were found to be (1) reduced emissions, (2) reduced operating costs, (3) improved energy efficiency and (4) reduced noise. The major disadvantages of electric tugboats were identified as follows: (1) high upfront cost, (2) infrastructure requirements, (3) training requirements and (4) range limitations. Moreover, a set of econometric analyses was conducted as a part of this study to quantitatively evaluate the economic viability of electric tugboats. It was found that the electric tugboat alternative would be the best option for scenarios with low interest rate values. Increasing interest values negatively impact the salvage value of electric tugboats, which is higher than that of conventional diesel and hybrid tugboats. It is also expected that for long-term planning, the electric and hybrid tugboat alternatives will become preferential since they have lower annual costs when compared to the conventional diesel tugboat alternative. The findings from the conducted analysis confirm that the initial investment costs are much more significant for electric tugboats when compared to conventional diesel tugboats. New options should be investigated in the following years to reduce the initial investment costs for electric tugboats (e.g. more cost-effective alternatives for onshore charging infrastructure and exploration of renewable energy sources). Last but not least, the present research contributes to the digitalization of maritime transportation. In particular, the findings of this study can be used to develop digital tools and dashboards to help maritime stakeholders make informed decisions about financial investments in electric tugboats. New digital platforms can be designed for asset management and predictive maintenance of electric tugboats.

Although the present study offers important managerial insights and provides useful information related to electric tugboats, there are several areas for further investigation. First, the conducted econometric analyses mostly focused on the costs associated with electric tugboat deployment. Future research could also quantify the environmental and social advantages that could be achieved from electric tugboats to make the analysis more thorough. Second, the presence of uncertainty in the cost components was not considered (e.g. uncertainty of fuel price). Explicit modeling of uncertain cost elements could be performed in the following years. Third, the advancement of battery technology has the potential to significantly impact the cost dynamics associated with electric tugboats. It is essential to do further research to monitor the advancements in battery technology and analyze their corresponding financial ramifications. Fourth, as the use of electric tugboats increases, it is imperative to investigate legislative and regulatory changes that might facilitate their deployment at a faster pace. Fifth, it is essential to closely monitor the industry's shift toward electric tugboats, as their prices become more affordable.

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Appendix

Questionnaire

The purpose of this questionnaire is to develop a broad understanding of advantages and disadvantages from electric tugboat deployment in maritime transportation. The questions outlined below cover the key aspects. However, additional information can be provided at the end of the questionnaire as well. Thank you for your participation in this important research activity.

1) Could you please provide an overview of the electric tugboats you construct and/or deploy? What are their key features and specifications?

2) What motivated your company to venture into the construction and/or deployment of electric tugboats? Was it driven by environmental concerns, cost savings, or other factors?

3) In terms of environmental impacts, what are the main advantages of electric tugboats compared to traditional diesel-powered tugboats?

4) Are there any specific technological advancements or innovations in your electric tugboats that contribute to their efficiency and performance?

5) How do electric tugboats perform in terms of power and maneuverability compared to their diesel counterparts?

6) What are the main challenges or limitations associated with the deployment of electric tugboats in maritime transportation?

7) Can you provide insights into the initial investment and operational costs of electric tugboats compared to traditional diesel-powered tugboats? Are there any significant cost savings? If possible, the research team would like to request a detailed document outlining the initial investment and operational costs of electric tugboats.

8) Are there any infrastructure requirements for charging or maintaining electric tugboats? How does the availability of charging infrastructure impact their deployment?

9) Have you conducted any studies or assessments on the lifecycle environmental impact of electric tugboats? If so, what were the findings?

10) What has been the market response and adoption rate of electric tugboats in the maritime industry? Are there any notable case studies or success stories you can share?

11) Are there any ongoing research and development efforts to further improve electric tugboat technology? What areas are being focused on?

12) Are there any governmental incentives or regulations in your country that promote the adoption of electric tugboats in maritime transportation?

13) Can you provide any projections or insights into the future of electric tugboats? How do you envision their role in shaping the maritime transportation industry?

14) How does the tax system affect the electric tugboat and the business as a whole?

15) Will the electrification boost or reduce employment opportunities?

16) Do particular qualifications need to be met in order to operate an electric tugboat, or is basic training adequate?

17) Standard electric tugboats can only accommodate ships of a certain size when used to tug or tow them. Do you have any large tugs designed for towing larger ships, and if so, what are their specifications?

18) Any other important notes about electric tugboats you are currently working with?

Source(s): Appendix by authors