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Advantages and Disadvantages of Using Electric Tugboats: A Systematic Review

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Abstract

The maritime industry is increasingly focusing on sustainability and reducing environmental impact, which has generated growing interest in adopting electric propulsion technologies for tugboats to reduce emissions in ports. This study analyses the advantages and disadvantages of electric tugboats through a systematic review conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysesmethodology, complemented by a focus group of industry representatives to validate the results. By synthesising information from forty-two carefully selected studies, the analysis highlights environmental benefits such as reduced greenhouse gas emissions, lower noise pollution, and decreased operational costs. However, the research also identifies significant challenges, such as high initial costs, limited range, and infrastructure requirements for port electrification. The focus group findings confirm these conclusions, providing practical insights into the operational feasibility and potential for large-scale adoption. The study underscores the need to align technological advances with policy incentives to facilitate the sustainable transition of the maritime industry.

Keywords: Electric tugboats, Sustainable maritime industry, Emission reduction, Green technology, Energy efficiency

1. Introduction

In recent years, electric propulsion for tugboats has gained popularity as the marine sector has placed a greater emphasis on sustainability and minimizing its adverse environmental effects. This change attempts to reduce emissions and encourage environmentally responsible port operations. Given the pressing need for more environmentally friendly options, the current study examines the benefits and drawbacks of electric tugboats, a crucial subject for the shift to greener marine transportation [1].

Around 80 per cent of global trade is conducted by sea. However, this business has a severe environmental cost due to its reliance on fossil fuels, noise pollution, and high greenhouse gas emissions. Despite making up a small fraction of the global fleet, tugboats are disproportionately liable for port pollution due to their frequent and intensive use in port operations. With over 21,000 units worldwide, the tugboat sector produces almost 40 million tonnes of CO_2 yearly, equivalent to the emissions of seven million cars. Although tugs only contribute 4% of all maritime pollutants, they have a substantial localised impact on air quality in coastal and port regions [2]. Notably, they are responsible for 14% of NO_2 emissions, 19% of CO_2 emissions, and 7.7% of SO_2 emissions in Europe annually, highlighting the need for immediate action to lessen their environmental impact [3].

Electric tugboats are becoming a viable substitute in light of tighter emission standards and the global shift to renewable energy. They have the potential to significantly lower port emissions while maintaining adherence to international environmental guidelines. Thus, this study aims to thoroughly examine electric tugboats, weighing the benefits and drawbacks of incorporating them into contemporary maritime operations, as well as assessing their environmental impact.

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2. Materials and Methods

2.1. Database and Search Strategy

This study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [4] standards to guarantee rigour and transparency in selecting and evaluating the scientific literature. The goal was to examine the benefits and drawbacks of electric tugboats as a potential green maritime transportation option.

The Web of Science, Scopus, ResearchGate, and Google Scholar were the primary databases used to find pertinent articles, focusing on English-language publications. Without regard to time constraints, the search covered studies published until November 7, 2024, guaranteeing that the most recent advancements in the discipline were included.

The researchers worked together to create a thorough search strategy, using the keywords "electric" and "tugboats"(see Table 1), to increase the relevance of the results that were returned.

2.2. Inclusion and Exclusion Criteria

Strict selection criteria were employed to guarantee a targeted analysis: only original, English-language papers from reputable scientific publications that specifically examine electric tugboats in a marine setting were included. Review articles, papers without full text, and research not focused explicitly on electric tugboats were disqualified to preserve relevance and prevent reliance on secondary sources.

2.3. Selection

Zotero was used to arrange the identified studies, thereby making reference and analysis easier. To guarantee unique references, duplicate articles were automatically eliminated. Full texts were checked as needed, and titles and abstracts were manually examined according to the inclusion criteria. The research team cooperated with the selection process, guaranteeing uniformity and relevance in the selected papers. Zotero was used to arrange the identified studies, thereby making reference and analysis easier. To ensure unique references, duplicate articles were automatically eliminated. Full texts were checked as needed, and titles and abstracts were manually examined following the inclusion criteria. The research team cooperated with the selection process, guaranteeing uniformity and relevance in the selected papers.

2.4. Results

A first search turned up 877 articles. One hundred and sixtyitems were left for examination after 113 duplicates were eliminated, and 539 articles were excluded using automated algorithms. After a full-text review, 81 articles were eliminated, and 65 more were eliminated based on a manual evaluation of the titles and abstracts. Sixty-eight items were left for consideration, after 11 of the 79 remaining articles were unavailable. Of these, 42 publications were selected for the final study after 7 were found to be incomplete and 19 were judged unrelated to electric tugboats. Two supplemental articles were added to bolster the PRISMA approach and the insights gathered from focus groups (see Figure 1).

3. Literature Review

3.1. The Role and Evolution of Tugboats

Compact and powerful, tugboats move big ships through narrow spaces like ports and waterways. They help with docking and undocking maneuvers, rescuing, moving heavy equipment like oil rigs, and putting out marine fires. In light of significant developments in propulsion technology, tugboats have evolved substantially over time, moving from human-powered systems to steam engines and then to contemporary diesel engines.

A significant turning point in tugboat history was reached in 1802, when the Charlotte Dundas, the first steam-powered tugboat, was built in Scotland. This vessel revolutionised the industry and paved the way for subsequent developments with its exceptional mobility and tractive force. Because of their advanced propulsion systems, modern tugboats can operate efficiently in both inland and open-water environments. They are also crucial in maritime disasters, including platform salvages, disaster relief, and assisting large ships in challenging conditions like high currents or winds [5,6].

3.2. The Environmental Impact of Tugboats and the Need for Greener Solutions

Although tugboats are essential to maritime activities, they have a substantial effect on the environment. The marine sector, adopting cutting-edge technology such as dual-fuel engines that can run on both conventional and greener fuels, and liquefied natural gas (LNG)-powered engines that emit

Table 1. *Search strings and results in four databases*

Database	Search string	Results
Web of Science	(((TS=(tugboats))) OR TS=(tugs)) AND TS=(electric)	118
SCOPUS	(TITLE-ABS-KEY (electric AND tugboat) OR TITLE-ABS-KEY (electric AND tugs))	407
Google Scholar	electric tugs OR electric tugboats	244
Research Gate	electric tugs OR electric tugboats	108

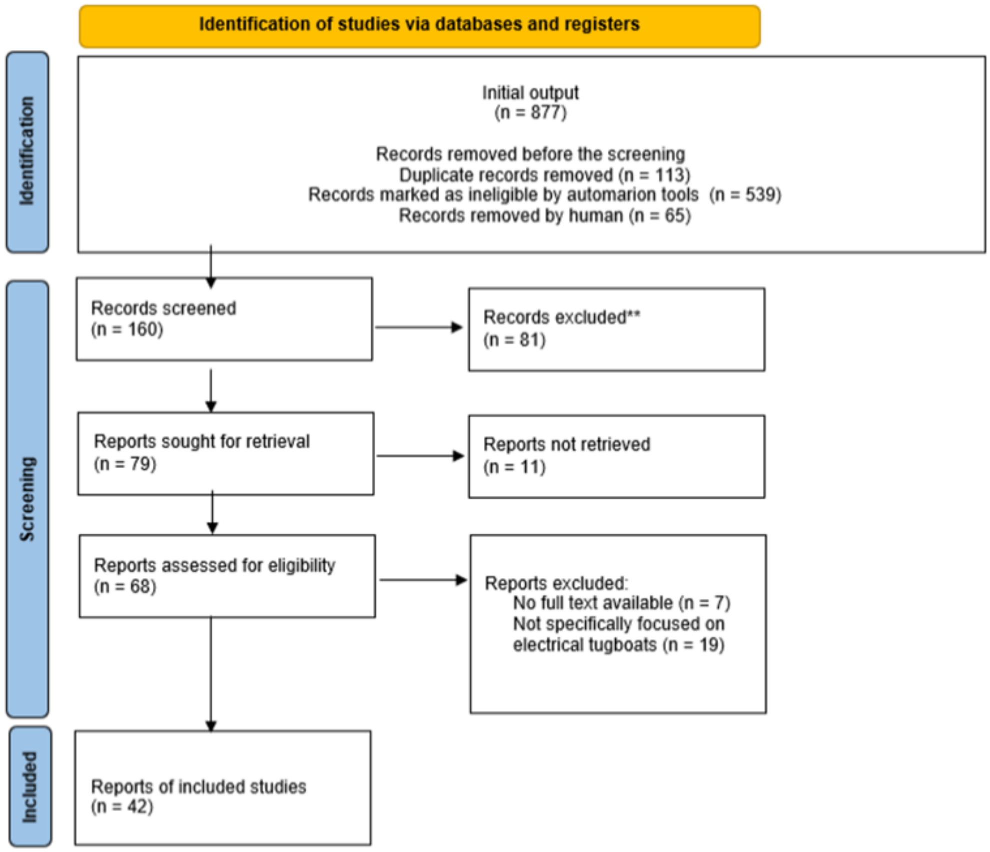

Figure 1. *Flow diagram of the included and excluded studies*

fewer pollutants, has acknowledged the pressing need to reduce emissions [7]. Combining electric and diesel power, hybrid propulsion systems provide a balanced method of increasing efficiency and lowering pollution. Additionally, alternative fuels like hydrogen and methanol are showing promise as long-term solutions. Additionally, by improving combustion, modern fuel injection technologies reduce pollution [6,8,9].

A baseline study conducted in the Gulf of İzmit, Türkiye, demonstrated the effect of tugboats on air pollution. Over three months in 2020, tugboats in this region generated 7,598.65 tons of pollutants, accounting for almost 10% of all ship emissions. This work laid a solid foundation for future research because it was the first to comprehensively analyse the pollution caused by port tugboats [3].

Tugboats contribute significantly to urban air pollution due to their high emissions of CO_2, NO_2, and SO_2. In ports, they are responsible for 14% of NO_2 emissions, a major contributor to urban smog. Adopting sustainable technology, creating emission control zones, and improving fuel quality are crucial in order to lessen these environmental effects. Furthermore, developing successful policies to limit port pollution depends on long-term monitoring of vessel traffic and emissions [10].

3.3. Research on Diesel-electric Systems for Tugboats

Numerous studies have explored ways to make tugboats' diesel-electric (DE) propulsion systems more sustainable and efficient. A mathematical model for DE systems utilising AC distribution was created by Guo et al. [11] (2005), who also examined aspects, including battery density, efficiency, and economic feasibility. A cost optimisation model for certified engines was presented by Solem et al. [12] (2015), who assessed NO_2 emissions, fuel consumption, and investment costs. Although a five-year payback period was impractical, their research revealed that profitability rose dramatically over time, offering a valuable tool for optimal diesel engine configurations [13].

In a different study, Kumar et al. [14] (2018) used MATLAB Simulink to compare diesel engines with fixed and variable speeds for an Indian tugboat. The results showed that fixed-speed engines performed better than conventional diesel systems, while variable-speed engines provided better fuel economy and reduced pollution. According to this study, DE systems can lower expenses, increase productivity, and lessen the systems' adverse environmental effects, making them an excellent option for contemporary tugboat design [15].

3.4. The Emergence of Electric and Hybrid Tugboats

Recent research on electric tugboats utilises cutting-edge technologies and energy management algorithms to maximise energy efficiency and lower carbon emissions. Predicting operational loads is a crucial research topic for effectively managing fuel and battery energy usage. Vu et al. [16] (2015) (suggested that energy management algorithms, based on known and unknown load profiles, consider factors such as energy consumption, battery state of charge, and energy losses. This method ensures effective resource allocation by dynamically adjusting the power distribution between generators and batteries through linear programming [16,17].

With techniques based on the Equivalent Consumption Minimization Strategy (ECMS) showing potential fuel savings of up to 10%, depending on load conditions, diesel-electric hybrid systems are also attracting more attention. While adaptive ECMS works better in low-load situations, constant ECMS is most effective under regular loads. Another viable way to cut emissions is to include LNG in hybrid or all-electric tugs. The Borgøy tugboat serves as the prime example of the invention, as it is the first LNG-powered vessel, which achieves remarkable energy economy and traction with a cryogenic tank and a 3,410 kW gas engine [8,18,19].

3.5. The Global Adoption of Electric Tugboats

Globally, the shift to electric and hybrid tugboats is accelerating. Ports like Rotterdam and Singapore have used electric tugs to cut emissions and boost productivity. Through integration with cutting-edge port technologies, this transformation has led to a decrease of almost 20% in overall emissions and by almost a shorter turnaround time in the Port of Rotterdam [20].

The debut of California's first all-electric tugboat, eWolf, in San Diego marks a critical turning point in the acceptance of electric tugboats. Diesel fuel is no longer necessary because the eWolf runs solely on electricity thanks to a 6.2 megawatt-hour battery. Its below-deck battery pack powers its propulsion system, which is refueled by, a shore-based power system that is part of an innovative microgrid with solar-powered energy storage containers [21].

Another noteworthy electric tugboat project is Sparky, the world's first full-size electric tugboat. built in Auckland, New Zealand. It is predicted to reduce CO_2 emissions by 465 tonnes a year. Its 2,240 battery energy storage system can perform up to four port manoeuvres on a single charge.

The ZEETUG45 tugboat in Istanbul, Turkey, is a remarkable example of a zero-emission, fully electric tugboat equipped with an azimuth stern drive system. With a draft of 4.32 metres and dimensions of 26.2 metres by 10.6 metres by 26.2 metres, the ZEETUG45 is specifically designed for port operations. It can achieve up to 12 knots and generate a pulling force of 49 tonnes. Its propulsion system is powered by a 2,215 kWh battery pack that can recharge from 25% to 90% in under 110 minutes.

Furthermore, three smaller electric tugs from the **ZeeTug30 series-Gisas Power, Gisas Power II, and Gisas Power III-**with a 30-ton bollard draw and a speed of about 10 knots are now in use. These tugboats run on Corvus energy storage systems, which can be fully recharged in less than an hour. These systems power two propulsion motors that are coupled to azimuth thrusters. Gisas Power alone has saved about 560.6 tonnes of CO_2 emissions and finished about 2,749 jobs since the start of its operation.

The Smart Tug Energy Management Technology-*STEMS* on the ZEETUG45 maximises electrical energy usage, prolongs battery life, and tracks real-time performance to improve efficiency. This technology gives operators useful information, thereby lowering running expenses and increasing operational efficiency.

Future electric tugboats are planned to be developed as larger ZeeTugs with up to 80 tons of bollard pull and incorporate hydrogen-battery hybrid technology (H2ydroTug60) to increase their operational capabilities and range [22].

3.6. The Future of Sustainable Tugboats

Technological developments in vessels, especially in creating sustainable tugboats, are strongly related to the trend toward greener ports and maritime activities. The need for more efficient and clean tugboats is growing as ports invest in alternative fuel infrastructure and enforce stricter environmental rules. Aggressive goals for cutting greenhouse gas emissions in the maritime industry are set by the European Union (EU) Climate Law and the Fit for 55 legislative package. Essential laws like the Alternative Fuels Infrastructure Regulation, the FuelEU Maritime Regulation, and the expansion of the EU Emission Trading System, are crucial in determining how tugboat propulsion develops in the future. By requiring alternative fuels, constructing port-side charging stations, and increasing energy efficiency, these regulations support the shift to environmentally friendly maritime transportation [23].

In this regard, cutting-edge initiatives like eWolf, ZEETUG45, and Sparky represent the transition to greener maritime technology. They are consistent with EU goals to have a climate-neutral shipping sector by 2050. Some factors, such as cost, regulatory compliance, and environmental impact, influence the selection of propulsion systems and fuel alternatives. These technologies are becoming increasingly feasible due to long-term savings and operational efficiencies, even with their high initial investment costs. The necessity of industry-wide collaboration to hasten the adoption of sustainable solutions is emphasized by collaborative programs such as FASTWATER and Horizon 2020 [24-26].

Another collaborative program is the Greenport Alliances project, which aims to advance sustainability and green capabilities in the maritime port services industry. It seeks to maximize the interaction between people and current technology to lower fuel consumption and improve sustainability in port operations.

Sustainable tugboats and electric port operations are becoming practical and necessary steps toward lowering maritime emissions and enhancing operational efficiency. Creative projects and regulatory frameworks have helped make these developments possible. These developments have opened the door for a more environmentally responsible future for the sector by setting a new global standard for effective, eco-friendly, and climate-neutral maritime transportation.

3.7. Advantages and Disadvantages of Electric Tugboats

Switching to electric tugboats is a significant step toward sustainable maritime operations, as it has financial and environmental advantages. The maritime sector is under growing pressure to lower emissions and increase energy efficiency; electric propulsion is starting to show promise as a substitute for conventional diesel-powered ships. But even with improvements in battery technology and government backing, issues such as high upfront costs, limited charging infrastructure, and operational limitations still exist. With an emphasis on the significant elements impacting their industry acceptance, Table 2 thoroughly assesses the benefits, drawbacks, opportunities, and difficulties related to electric tugboats.

Table 2. *Advantages, disadvantages, opportunities, and challenges of electric tugboats*

Source	Advantages	Disadvantages	Opportunities	Challenges
Gillingham and Huang [2] (2020)	Reduced CO_2 and NO_x emissions.	Higher initial cost	Growing regulatory pressure towards greener maritime solutions	Dependence on the energy grid and charging at ports.
Chen et al. [27] (2023)	Lower operational costs; Renewable energy integration.	Limited battery capacity; There are few charging ports.	Battery and energy management advancements; Renewable energy collaboration.	Uncertainty in battery technology lifespan and replacement costs; Challenges in standardising electric propulsion systems across global fleets.
Ortega-Piris et al. [28] (2022)	Less noise pollution; Better work conditions.	High port infrastructure costs.	Potential government incentives and funding for electrification projects.	Limited real-world operational data on electric tugboat performance.
Vu et al. [29] (2014)	Better fuel efficiency; Real-time power optimisation.	Energy storage degradation; Battery disposal concerns.	Increasing demand for low-emission tugboats in urban port areas.	Market resistance; Risk of supply chain disruptions affecting battery availability.
Kumar et al. [30] (2019)	Better manoeuvrability.	Battery safety risks.	Wireless charging solutions.	Limited skilled workforce for maintaining electric tugboats.
Mirza [31] (2024)	Lower maintenance costs.	Longer refuelling/ recharging times.	Hydrogen fuel cell integration.	High initial costs.
Chua et al. [32] (2018)	Fewer mechanical failures.	Electricity price dependency.	Public-private electrification projects.	Difficult diesel-to-electric retrofitting.
Devarapali et al. [22] (2024)	High energy efficiency (90% vs. 30-40% for diesel).	Expensive batteries, Limited range	Modular battery upgrades; Growing regulatory support for green shipping initiatives.	Training requirements; Uncertainty in economic viability.

***Table 2.** Continued*

Source	Advantages	Disadvantages	Opportunities	Challenges
Kozlowski and Leblowski [33] (2023)	Low maintenance; instant full-power operation; grid connectivity.	Insufficient charging infrastructure; Battery lifespan concerns.	Rapid-charging stations; Hybrid solutions: Expansion of zero-emission shipping corridors.	Slow adoption; Unpredictable battery tech; Costly port electrification.
Windover et al. [34] (2012); Raja Singh et al. [35] (2021)	High energy efficiency; Lower energy consumption; Reduced operating costs.	Grid dependence; Operational complexity.	Smart grid integration; Energy optimisation.	Dependence on renewable energy infrastructure.
Karacay and Ozzosysal [36] (2021)	Lower fuel costs; Reduced environmental impact.	High battery replacement cost.	Cheaper renewable energy and batteries.	High upfront transition cost.
Bernardinis and Moussodjii [37] (2019)	Lower emissions, noise.	High infrastructure investment.	Smart ports and energy balancing.	Ensuring compliance with evolving maritime emission regulations.
Dima et al. [38] (2022)	Renewable-powered charging; No direct emissions	Low battery energy density; Insufficient charging station energy replenishment.	Eco-friendly ports; Battery-fuel hybridisation.	Port upgrades; Charging reliability; Energy density limits.
Vrijdag et al. [39] (2019)	Long-term cost savings.	High cost of batteries and charging infrastructure power grids.	Financial incentives; Industry collaboration; Stronger environmental regulations.	Cost barriers for smaller ports; Slow charging network expansion.
Xin et al. [40] (2023)	Cleaner air in ports.	Battery capacity limits.	Higher-density; fast-charging batteries; Solar integration.	Costly battery replacements; Charging station logistics.
Karagkouni and Boile [41] (2024)	Port decarbonisation.	Expensive grid upgrades and charging stations.	Modernising port energy systems benefits overall port logistics and vessel coordination.	Grid overloading risks.
Li et al. [42] (2023)	Sustainability and lower fuel costs	Industry conservatism; High initial costs.	Training programs; Financial incentives.	Profitability concerns, Port upgrades. Industry resistance success stories.

3.8. Key Advantages of Electric Tugboats

With their substantial economic and environmental advantages, electric tugboats are radically changing the marine sector. Their significant decrease in CO_2 and NO_2 emissions is one of their main benefits, which makes them a more environmentally friendly option than tugboats that run on diesel [2]. In addition to lowering energy consumption and improving fuel economy, this switch to electric propulsion eventually lowers operational expenses [16,35].

According to Devarapali et al. [22] and other reliable sources [43,44], electric motors have a conversion efficiency of above 90% when using energy for productive activities. Diesel combustion engines, on the other hand, only use 30-40% of the energy produced by burning fuel, making them far less efficient.

Research conducted by the Port of San Diego found that, compared to their diesel-powered equivalents, electric tugboats significantly reduced energy usage per assisted vessel by almost 70% [22].

Electric motors can run quickly at full power because they don't need fuel to pre-heat, greatly improving mobility and operating response times [45]. Additionally, fewer moving parts mean fewer maintenance expenses because costly replacements and frequent repairs are avoided [31].

Integrating renewable energy sources like solar and wind power decreases reliance on fossil fuels, further improving financial sustainability.

In addition to their positive environmental effects, electric tugboats can power towed vessels, allowing them to switch off their diesel generators before port entry, lowering fuel consumption and pollution hazards. The advancement of smart port integration maximises efficiency and minimises wasteful energy use by enabling real-time monitoring via IoT, Big Data, and AI-driven energy management [37].

3.9.Main Disadvantages and Limitations of Electric Tugboats

Electric tugboats have numerous advantages, but some drawbacks prevent their widespread use. One of the biggest obstacles is the high initial investment cost, mainly caused by the costly lithium-ion battery technology and the infrastructure needed for port electrification [22,40]. Electric tugboats are less practical for long-distance towing or continuous operations in busy ports due to battery restrictions that limit their operational range [16,40].

Another issue with relying on charging infrastructure is that many ports do not have enough fast-charging stations, which causes operational disruptions [45]. Moreover, battery deterioration over time lowers efficiency and calls for costly replacements or backup battery systems, which raises long-term expenses further [40].

Despite electric propulsion's green reputation, another issue is the lack of clarity surrounding battery recycling and disposal, which raises questions about environmental sustainability. Furthermore, some ports rely on electrical networks that run on fossil fuels, reducing the total ecological advantages of electric tugboats [29].

Electric tugboats are less feasible for time-sensitive tasks due to operational delays caused by longer fueling/recharging times than those of diesel engines [31]. Integrating electric power management systems with maritime operations increases complexity and necessitates a significant investment in grid improvements and maintenance know-how [46,47].

4. Future Opportunities and Growth Potential for Electric Tugboats

Despite these disadvantages, the switch to electric tugboats offers many advantages. The increasing regulatory pressure on the marine sector to embrace green solutions encourages ports and businesses to invest in sustainable technologies [2]. Government initiatives, including financial incentives, carbon levies, and subsidies for renewable energy, can assist ports in switching to electric fleets while lowering their reliance on fossil fuels [40].

Improvements in energy management and battery storage technologies will boost productivity and lower operational expenses. By creating modular charging infrastructure and fast-charging stations, downtime can be reduced, and electric tugboats can continue to operate without significant interruptions [22].

Another exciting prospect is the combination of smart grids with electric tugboats, enabling AI-driven automation to enhance energy delivery. To further reduce operating expenses, ports can increase their renewable energy infrastructure by installing offshore wind turbines and solar panels to power tugboats [38].

In 2023, 24.5% of the EU's total energy consumption came from renewable sources, according to DNV [43] and Eurostat [48]. One of the most essential steps toward sustainable, carbon-neutral maritime transportation is the integration of renewable energy sources into electric tugboat operations. Ports and shipping firms can reduce their reliance on fossil fuels and emissions, and increase efficiency by using renewable energy and storage. In addition to port infrastructure, renewable energy sources can be integrated into electric tugboats. While hydrogen fuel cells and battery-electric propulsion increase range and versatility, solar panels can augment power. Regenerative braking is another technique certain boats use to recover energy while decelerating.

Using renewable energy in electric tugboat operations has several advantages. Lowering emissions and enhancing air quality produces a more sustainable maritime industry. Lower prices for renewable energy eventually result in even lower operating costs. Renewable energy sources give ports greater resilience and independence, reducing their susceptibility to price swings and grid outages.

Renewable integration is crucial since regulatory frameworks, such as those from the EU and the International Maritime Organization, increasingly support green maritime activities. Renewable energy sources and electric propulsion offer the sector a game-changing opportunity. Even though there are still obstacles to overcome, sustained investment in storage, clean energy infrastructure, and hybrid propulsion will hasten the switch to electric tugboats with zero emissions, guaranteeing sustainability and long-term financial savings.

By working together, governments and private enterprises can provide cost-sharing arrangements that lessen the financial strain on particular ports while accelerating investment in electric tugboat technology [40]. Concerns about battery constraints can be allayed by creating hybrid electric solutions that combine batteries with alternative fuels such as LNG to increase range capabilities [49].

4.1. Significant Challenges and Barriers to the Adoption of Electric Tugboats

Implementing electric tugboats requires overcoming several obstacles, especially in the traditional maritime sector, where scepticism about new technologies is still a significant obstacle. Operators frequently worry about dependability problems, wondering if electric tugboats can withstand prolonged use or function adequately in harsh environments [22].

The absence of current infrastructure to support electric fleets is a significant obstacle. To manage the high energy demand of electric propulsion, many ports need to modernise their grids, including installing new transformers, cables, and energy storage devices [40]. These infrastructure expenses remain a significant barrier without industry-wide investments or government assistance, especially for smaller and growing ports.

Reliance on renewable energy is not without its difficulties. If ports depend on electrical grids that run on fossil fuels, the environmental advantages of electric tugboats are reduced [35]. To preserve sustainability, ports must invest in intelligent energy storage technologies that guarantee a steady, clean energy supply, even when renewable power generation is limited [41].

Another challenge is workforce adaptation, since operators and maintenance staff must receive specific training to operate high-voltage electric propulsion systems [22]. Long-term financial commitments are also risky, as many businesses put short-term profits ahead of long-term savings, which delays the adoption of electric fleets [40].

Finally, charging station placement and grid dependability must be carefully planned to avoid operational disturbances, especially in busy ports where delays could affect supply chains and logistics. Strategic investments in infrastructure, policy, and technology will be crucial to overcome these obstacles and guarantee a seamless transition to a more sustainable maritime sector.

Electric tugboats are a revolutionary development in the marine sector due to their significant cost savings, operating efficiency, and environmental advantages. However, the industry's opposition to change, infrastructure constraints, and hefty upfront expenses impede implementation. The maritime industry may effectively shift toward a more sustainable future by utilising technological developments, regulatory assistance, and integration of renewable energy sources. To guarantee broad acceptance and optimise the long-term advantages of electric tugboats, issues including battery constraints, charging infrastructure, and workforce training must be resolved.

Although the advantages of electric tugboats-such as lower emissions, cost savings, and increased efficiency-make a strong argument for their use, some obstacles still need to be overcome, such as expensive initial costs, battery constraints, and significant infrastructural improvements. To learn more about these benefits and difficulties from the viewpoint of the maritime industry, a focus group was held with maritime specialists. By examining operational issues, real-world experiences, and the viability of using electric tugboats in port and commercial operations, this conversation sought to validate the theoretical conclusions. The results of these interviews are shown in the following part, emphasising the viewpoints of industry representatives regarding the advantages and disadvantages of this technological shift.

5. Interviews with Industry Representatives

Focus groups are a qualitative research technique used to collect opinions from a limited number of subject-matter specialists. Finding specific and valuable facts entails a guided discussion to confirm or improve preexisting conclusions. The focus group's efforts to connect theoretical conclusions with practical industry experiences ensured a comprehensive and well-supported analysis [50].

Selected experts from the port and maritime industry participated in the focus group, including a captain, two university professors, two naval architects, one chief engineer of a tugboat with experience in energy storage, one representative of a naval policy-making body specializing in navigation safety, and two representatives from a towing service company.

At the start of the activity, a structured questionnaire was used to gauge participants' opinions on the topic's benefits and drawbacks (see Table 3). Respondents assigned a score to each question on a scale of 1 (not relevant) to 5 (very relevant).

The answers to the questionnaire were used to divide the conversations into two main sections:

1. Identification of Advantages: Participants explored key benefits, incorporating questionnaire responses and additional discussion insights.

2. Analysis of Disadvantages: This stage identifies challenges and limitations and comprehensively assesses the research topic.

The conversation aimed to encourage in-depth analysis based on preliminary data and stimulate the exchange of ideas. Using the questionnaire to determine points of agreement and disagreement, the focus group approach successfully verified and improved theoretical conclusions.

This adaptable strategy allowed for gathering quantitative and qualitative data while considering the participants' real-world experiences. Expert interactions from different fields enhanced the study by providing interdisciplinary viewpoints on business opportunities and challenges.

Table 3. *Questionaire*

Advantages	Disadvantages
1. The adoption of electric propulsion technology in tugboats leads to improved operational efficiency	1. Electric tugboats may have a limited range compared to diesel-powered vessels due to the capacity and weight of onboard batteries. This can restrict their operational flexibility, especially for long-distance towing or extended operations without recharging.
2. Electric tugboats improve air quality by eliminating emissions, benefiting workers' environment, health, and well-being in ports and nearby communities.	2. The initial investment in purchasing electric tugboats, including the necessary infrastructure for charging or battery replacement, can be higher than that of traditional diesel-powered tugboats.
3. Electric tugboats generally incur lower operating expenses than their diesel counterparts due to reduced maintenance requirements and fewer moving components, contributing to cost efficiency.	3. Charging electric tugboats can take significantly longer than refuelling diesel-powered vessels, leading to potential downtime and reduced productivity during charging cycles.
4. Electric propulsion systems typically boast higher energy efficiency levels than diesel engines, resulting in decreased energy consumption and lower fuel expenses.	4. Batteries required for electric propulsion systems can be heavy and bulky, impacting vessel stability and manoeuvrability due to additional weight and space constraints.
5. Electric tugboats can operate in sensitive areas such as nature reserves or near populated areas where strict emissions regulations or noise pollution must be minimised.	5. Electric propulsion systems may have lower power output than conventional diesel engines, particularly in high-demand situations such as towing heavy loads or manoeuvring vessels.
6. Electric tugboats can leverage advancements in energy storage technology, such as high-capacity batteries, to store energy during off-peak times or from renewable sources, enhancing operational efficiency and reducing reliance on grid power.	6. Electric tugboats rely on a stable and reliable electricity supply, which may be subject to disruptions, grid outages, or fluctuations in energy prices. This dependency introduces risks related to energy security and operational resilience.
7. Governments may offer incentives, subsidies, or tax breaks to encourage the adoption of electric propulsion technology, further enhancing the economic viability of electric tugboats.	7. Batteries in electric tugboats may experience reduced performance and efficiency in cold weather conditions.

The results emphasize the benefits and drawbacks of this new technology while fortifying the connection between theory and practice, and providing insightful information about the marine industry's adoption of electric tugboats.

According to most participants, the main benefit of electric tugboats is the decrease in greenhouse gas emissions. Industry representatives strongly emphasised this feature in light of strict emission standards and global goals for reducing carbon emissions. Participants underlined that ports with stringent air quality regulations benefit greatly from electric tugboats.

Discussions, however, showed that this benefit is highly dependent on the energy source. Electric tugboats have a significant positive environmental impact when their electricity is produced using renewable resources. On the other hand, if the energy source is dependent on fossil fuels, the beneficial ecological effect is significantly reduced. As a result, the environmental advantages of electric tugboats are directly related to the advancement of the worldwide green energy transition.

Another significant advantage of electric tugboats was lower operating expenses. Key economic benefits identified include the removal of traditional fuels and lower maintenance needs, ascribed to the ease of use of electric motors. According to industry officials, specific circumstances, like the tugboat's lifespan and the accessibility of charging infrastructure, make these cost advantages especially apparent.

Another benefit, according to some participants, is that electric tugboats can be used at ports with stringent restrictions or in environmentally sensitive areas. These vessels make it simpler to comply with environmental standards, which helps businesses that use them financially and reputationally reputation. They were also emphasized as representations of technological leadership, fostering innovation and sustainability, to give operators a competitive edge.

The limited range of electric tugboats, due to the present battery capacity, was one of the most commonly noted drawbacks among the respondents. Participants stated that these vessels are less appropriate for operations that require continuous availability or for long-duration operations. This restriction is considered a significant obstacle, particularly in ports without sufficient infrastructure for charging.

Throughout the discussions, the high initial investment needed to purchase and deploy electric tugboats was determined to be one of the biggest obstacles to their adoption. While long-term savings can partially offset these expenditures, many participants thought the high upfront costs and lengthy payback period were significant barriers, especially for small and medium-sized enterprises.

Another significant issue mentioned was electrical system maintenance, which necessitates specialist personnel who are hard to reach in some areas. This intricacy may result in extra expenses, and a shortage of qualified personnel may prevent broad adoption.

Many participants voiced concerns over battery technology, highlighting its short lifespan, high cost, and the environmental effects of its manufacture and recycling. According to them, technological developments in this field will determine the future of electric tugboats, and solutions needed to improve performance and lessen environmental effects.

The experts' comments show that electric tugboats are generally seen favourably, but they also point out important issues that must be resolved. Participants concurred that these ships have a great deal of promise to support environmentally friendly maritime transportation. Nevertheless, infrastructure, financial, and technological obstacles must be removed before they can be adopted.

According to the participants' answers, the following factors determine whether electric tugboats are successful:

• The construction of infrastructure for charging, especially in poorer nations and smaller ports;

• Developments in battery technology to increase cost-effectiveness, longevity, and range;

• Subsidies and policy support are required to lessen operators' upfront expenses;

• Renewable energy availability to optimise environmental advantages.

6. Conclusion and Recommendation

This study demonstrated how electric tugboats, with their substantial advantages including lower greenhouse gas emissions, less noise pollution, and increased operational and financial efficiency, have the potential to revolutionise the marine sector and make it more sustainable. However, other obstacles to their acceptance, such as large upfront expenditures, limited autonomy, and intricate infrastructure needs, remain.

The energy source these ships use mostly determines their environmental impact. The results show that ports that integrate renewable energy sources can greatly increase the benefits of these vessels. By incorporating electric tugboats into cutting-edge port systems, operations can be streamlined by reducing waiting times and resource usage.

Although switching to electric tugboats is crucial in creating a more sustainable and effective marine business, the public and corporate sectors must strongly support this change. The development of port infrastructure is priority one for the use of electric tugboats. Included in this procedure are:

• The placement of fast-charging stations in key ports;

• Electrical grid modernisation to accommodate rising energy demands;

• Including renewable energy sources integration, like wind turbines or solar panels.

Implementing tax breaks and subsidies can hasten the transition from a political and financial standpoint, and public-private partnerships can supply the funds required for research and infrastructure investment.

In terms of technology, it is imperative to make investments in:

• Batteries with a high energy density and quick charging;

• Intelligent systems for the best possible control of energy use.

Education and workforce development are also essential. To guarantee a trained workforce for the future of sustainable maritime transportation, initiatives such as specialist courses on the operation and maintenance of electric tugboats and partnerships with educational institutions to incorporate pertinent skills in training curricula are required.

Future studies should concentrate on increasing the operational range of electric tugboats, investigating other energy storage options such as hydrogen fuel cells, and assessing the incorporation of hybrid propulsion systems. Another crucial field is the creation of predictive management systems, which employ artificial intelligence-based maintenance models and energy demand forecast algorithms.

It is also necessary to continuously monitor how electric tugboats affect marine ecosystems by measuring the decrease in noise pollution in protected regions and by evaluating their effects on biodiversity. Thorough economic studies are also required to prove the long-term feasibility of electric tugboats, considering business models that share resources among port operators.

Through the implementation of these suggestions and further research, electric tugboats have the potential to be a key component of the shift to a more sustainable maritime sector, tackling economic issues while making a substantial contribution to environmental preservation.

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Footnotes

Authorship Contributions

Concept design: N. Acomi, Data Collection or Processing: N. Acomi, and G. Surugiu, Analysis or Interpretation: C. Stanca, and G. Raicu, Literature Review: G. Surugiu, and E. M. Popa, Writing, Reviewing and Editing: C. Stanca, G. Raicu, and E. M. Popa.

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