Progress in Hybrid and Electric Propulsion Technologies for Fishing Vessels: An Extensive Review and Prospects

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ABSTRACT

In the highly competitive era of the maritime and fisheries sectors, the implementation of electric and hybrid propulsion systems in fishing vessels is becoming increasingly relevant. This study aims to review recent advancements in the application of electric or hybrid propulsion systems in fishing vessels. The method used to obtain publication references involved the use of VOSviewer, which functions as an additional tool for examining and displaying publication trends according to authors and keywords. The analysis shows that although some fishing vessels have adopted electric or hybrid propulsion systems, there is still a lack of understanding of the full benefits of this technology. According to recent studies, using environmentally conscious propulsion systems on fishing vessels has the potential to significantly reduce the release of greenhouse gases and improve operating efficiency. Therefore, future research is expected to fill this gap by exploring the potential application of state-of-the-art technology in the development of more efficient and sustainable fishing vessel propulsion systems. In this way, the fishing industry can make a greater contribution to achieving carbon neutrality and sustainability goals in the future.

Keywords: Fishing vessel, electric propulsion, fisherman, modernization, renewable energy

1 Introduction

The transition of fishing vessels' propulsion systems from conventional internal combustion engines to more environmentally friendly hybrid and electric alternatives has gained significant attention in recent years. This shift is driven by the need to mitigate the negative environmental impacts associated with greenhouse gas emissions from traditional propulsion systems, which are widely known to contribute to global warming and marine pollution (Kim et al., 2022; Hung et al., 2022). In the context of international efforts to achieve sustainable development goals, the maritime industry, including the fishing sector, has been under increasing pressure to adopt cleaner and more efficient propulsion technologies. Despite substantial progress in this field, existing research predominantly focuses on regional case studies and often lacks empirical data derived from the actual operational conditions of fishing vessels. This gap necessitates further investigation into the development and deployment of sustainable propulsion technologies that can be validated with real-world data (Beatrice et al., 2022).

Electric vessels first emerged in the early 19th century, utilizing batteries as their power source and laying the groundwork for future advancements in electric ship technology. In the late 1830s, Moritz Hermann Jacobi of Germany invented a rudimentary DC motor driven by power sources that was successfully put on a small vessel (Horne, 1939). In his paper "Proposed Applications of Electric Ship Propulsion," Emmet (1911) discussed the potential uses of electric propulsion systems on ships, which formed a basis for further developments in electric propulsion technology. The first effective electric-powered watercraft was the *Elektra*, a 30-passenger ferry built by the German company Siemens and Halske in 1886. It was 11 m long and 2 m wide, propelled by a 4.5 kW battery-powered engine (Skjong, Volden et al., 2016). Diesel–electric or totally electric hybrid systems are the most practical fuel options for coastal ferries, despite the fact that there are a number of steps with significant future potential (Laasma et al., 2022). The inaugural passenger ship to use this new system was *Yorktown*, originally built as *Cuba* in 1894, which, following an accident in 1916, was retrofitted into a turbo-electric system in 1919 (Skjong, Rødskar et al., 2015).

The maritime sector experienced transformative advancements from the mid-20th century through the 1980s, with the rise of solid-state electronics paving the way for "all-electric" vessels. By 1987, Queen Elizabeth II launched a diesel–electric hybrid propulsion system, signaling a new era in marine engineering (Skjong, Volden et al., 2016). Norway has since led in hybrid propulsion adoption, as seen in the plug-in hybrid ferry *MF Folgefonn*, which effectively reduces emissions and improves efficiency (Tillung et al., 2017). This trend is now gaining traction worldwide, with more than 30 new ferries planned to incorporate fully electric or plug-in hybrid systems, setting a benchmark for other vessel types, including fishing vessels, to explore hybrid technology (Tillung et al., 2017; Budiyanto et al., 2021; Utama et al., 2021). More recent innovations, such as the *Viking Lady* and the *MF Ampere*, which is the world's first fully electric ferry launched in 2015, reflect the continued shift toward hybrid and electric systems in maritime transport (Kolodziejski and Michalska-Pozoga, 2023; Skjong, Volden et al., 2016). These developments underscore the scalability of hybrid and electric systems for various vessel types, including fishing vessels, paving the way for environmentally conscious practices. In the fishing sector, vessels such as Norway's *Angelsen Senior* illustrate the practical applications of hybrid technology. This hybrid diesel–electric vessel combines Scania DI13 diesel generators with Corvus Energy batteries, which reduce CO_2 emissions by up to 200 tons annually (Corvus Energy, accessed October 2024). Similarly, the *Karoline*, equipped with Siemens BlueDrive PlusC, operates as the world's first fully electric fishing vessel, achieving zero emissions and reduced noise levels (Hansen, 2015). Another example, Ragnhild Hatland, a vessel optimized for energy efficiency, exemplifies the progression toward sustainable propulsion in modern fishing (VesselFinder, accessed October 2024). Figure 1 presents the significant milestones in the evolution of electric power systems on maritime vessels from the 1830s to 2023.

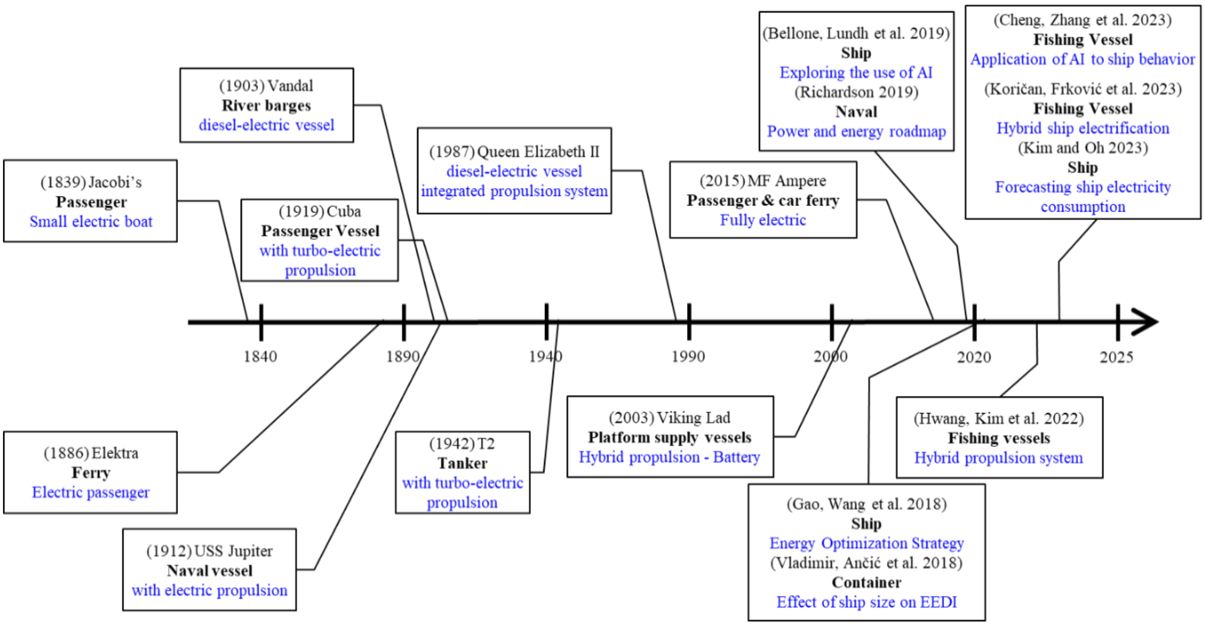

Figure 1. Development of electric ship power systems from 1830 to 2023

In this context, hybrid propulsion systems that combine internal combustion engines with electric propulsion modules have emerged as a promising interim solution for the fishing industry. These systems not only enhance energy efficiency and reduce fuel consumption but also alleviate economic pressure on the fishing community by providing a more cost-effective energy solution (Hwang et al., 2022). Historically, the adoption of electric propulsion was considered feasible only under specific conditions, such as predictable daily load profiles and manageable energy demands that could be met through regular charging intervals (Beatrice et al., 2022). Today, advancements in technology and research methodologies, including the integration of field-acquired operational data, are informing the feasibility and optimization of hybrid systems for a broader range of vessel types and operational profiles (Manouchehrinia et al., 2018).

The proliferation of hybrid and all-electric propulsion systems offers a range of ancillary benefits beyond emission reduction, including improved load response, increased operational efficiency, reduced maintenance, and enhanced system reliability (Inal et al., 2022; Tillung et al., 2017). For the fishing industry, these benefits translate into reduced operational costs and an extended vessel lifespan, both of which are crucial for maintaining profitability in an industry with inherently high operational risks and variable income. Recent research has explored various configurations of hybrid propulsion systems and battery energy storage solutions, leading to the development of more flexible and cost-efficient setups for different vessel operational modalities (Barelli et al., 2018; Nuchturee et al., 2020). Thus, hybrid propulsion systems offer a balanced approach that can be tailored to meet the specific operational needs of fishing vessels.

In supporting the development of hybrid propulsion systems, integrated modeling and simulation tools play a crucial role in delineating optimal propulsion solutions that achieve superior energy efficiency, reduced emissions, and cost-effectiveness (Dong, 2020). A detailed understanding of the vessel's operational profile is essential when selecting the most appropriate power system configuration, particularly for hybrid systems with energy storage solutions (Tillung et al., 2017). The inclusion of alternative low-carbon energy sources, such as wind, solar panels, biodiesel, algae, liquefied natural gas, and hydrogen, alongside enhancements in traditional fuel generators, has been identified as a key strategy for achieving sustainability goals (Xie et al., 2023; Tillung et al., 2017). This comprehensive approach leverages multiple energy sources to optimize performance and sustainability in diverse maritime applications.

However, the implementation of hybrid propulsion systems in the maritime sector faces several challenges, such as high initial costs and limitations in battery technology (American Bureau of Shipping, 2022). Moreover, regulatory compliance and the integration of new technologies with existing infrastructure require significant investment and technological readiness. Key industry players, such as GE, Siemens, and Caterpillar, Inc., are actively addressing these challenges by developing hybrid systems that combine internal combustion engines with renewable energy sources, such as fuel cells, solar, and wind power. These efforts are expected to push the development of cost-effective and operationally efficient hybrid propulsion systems that meet evolving regulatory requirements (Stringent Datalytics, 2024). With these ongoing innovations, hybrid and electric propulsion technologies are poised to play a vital role in the future of sustainable maritime transportation, paving the way for the adoption of clean energy solutions in the fishing industry.

2 Materials and Methods

A thorough study of research articles on electric fishing vessels was carried out in order to meet the research objectives. The inquiry started with the gathering of scholarly articles of the highest caliber. The download data was checked by the researchers to ensure that it met the objectives of the study using the parameters for inclusion and exclusion listed in Table 1. The Scopus screening procedure can directly employ the criteria listed in Table 1. Because keywords naturally define and shape the study emphasis of the returning pages, a strategy is required when using the Scopus search engine. Consequently, it is preferable to use the terms "electric fishing vessel" or "hybrid" and then refine the search in Scopus using the keywords "electric propulsion" and "hybrid propulsion." These two groups of terms typically appear in research publications with distinct topologies. Therefore, in order to maximize data retrieval from the database, our study makes use of these terms. This study applies a time constraint in searching for publications, limiting the data to the last 10 years, specifically from 2014 to 2023. The Scopus filter settings are based on (TITLE-ABS-KEY (hybrid OR electric AND fishing AND vessel)). After obtaining publication data from Scopus, it was further filtered with the more specific keywords "electric propulsion," resulting in 28 documents, and "hybrid propulsion," resulting in 25 documents. An intersection of electric and hybrid publications is illustrated in figure 2 to validate the data from the primary keyword, which yielded 106 documents.

Table 1. Inclusion criteria for publications

	Rationale	Included	Excluded
Types of publications	The aim of this research is to review electric fishing vessel studies.	All types of publications, including research articles and conference papers.	
Publication quality	The validity and dependability of study findings are guaranteed by high-quality content. In this context, publications are sourced only from reputable databases with indexing.	Scopus-indexed	Outside Scopus-indexed
Timeframe	The timeframe is limited to the last 10 years.	2014- january 2023	From 2024 onward
Content	This study aims to review all indexed publications with keywords electric fishing vessel and hybrid.	Titles, abstracts, and keywords encompass electric or hybrid fishing vessels, "electric propulsion," or "hybrid propulsion."	There are no instances of "electric propulsion" or "hybrid propulsion" related to electric fishing vessels in the titles, abstracts, or keywords.

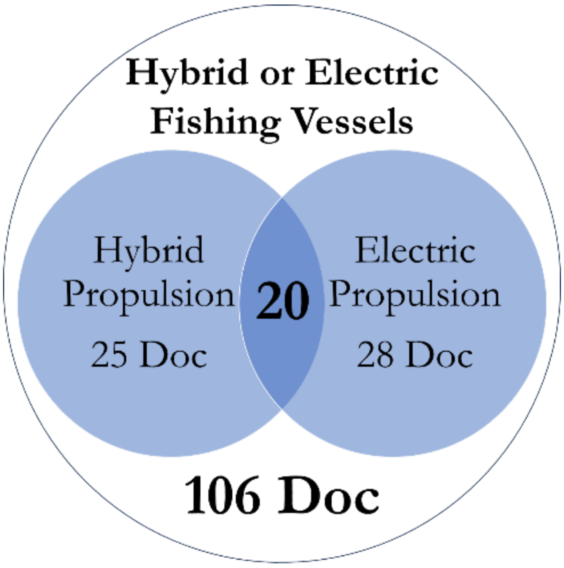

Figure 2. Intersection of Electric and Hybrid Propulsion in Fishing Vessels

Using VOSviewer© data mining software, more research was carried out following the published documents' filtering. An additional tool for visualizing and analyzing publication trends was VOSviewer©. Based on bibliographic details including authors, citations, and keywords, these papers were classified. Figure 3 shows the findings from the use of the keyword filters "electric propulsion" and "hybrid propulsion" to analyze publications about hybrid or electric fishing vessels. The analysis of publication distribution from a scholarly standpoint is the focus of this section. The data was characterized using keywords using VOSviewer©. It is common knowledge that the main keywords in these papers are electric or hybrid fishing vessels. The research results and analysis on hybrid or electric fishing vessels conducted between 2014 and 2023 are presented here. Figure 3 demonstrates how the terms "fishing vessel," "fishing boat," and "ship" polarize the distribution of publications related to hybrid or electric fishing vessels. Furthermore, among these three vessel-related keywords, other keywords indicate the focus on hybrid or electric fishing vessels, including the presence of "emission" and the use of "battery."

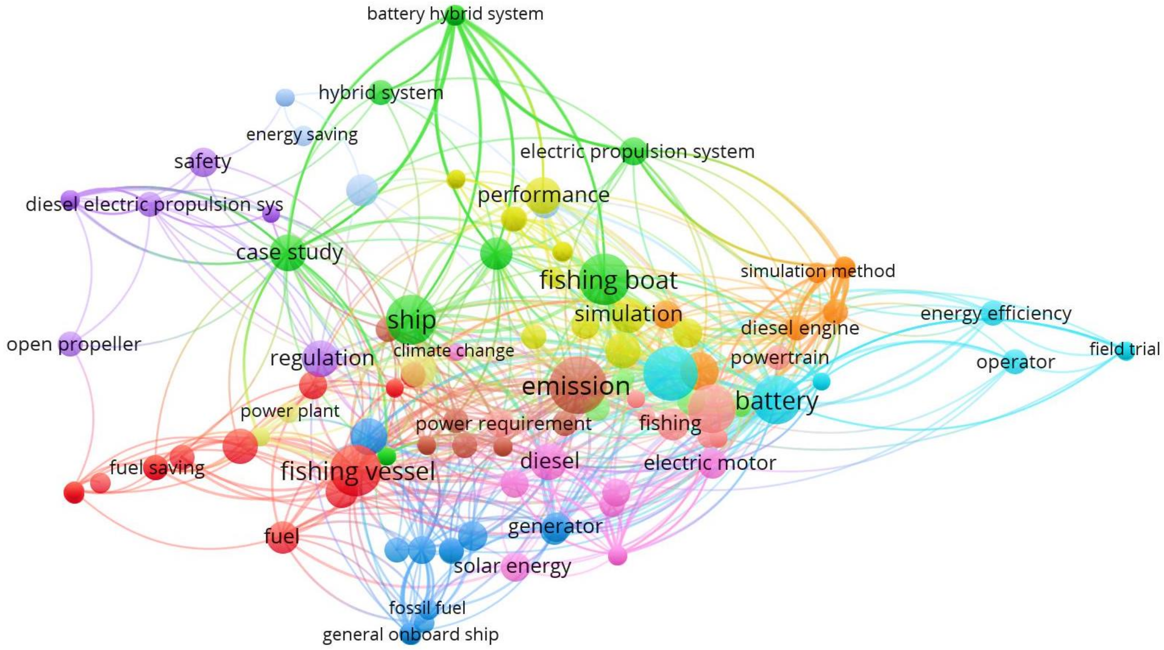

Figure 3. The publication keywords polarization based on Electric and hybrid wedges on fishing vessels

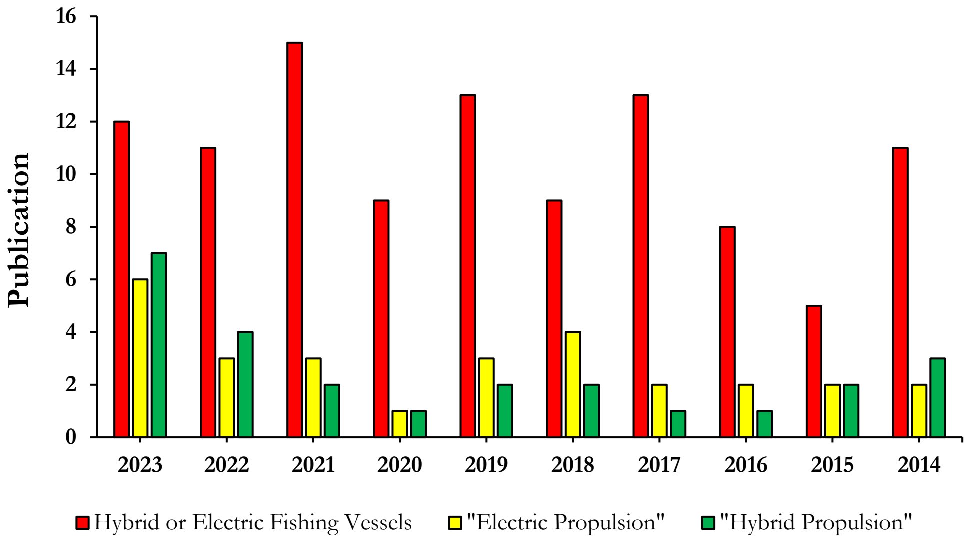

Figure 4. Distribution of research publications on hybrid or electric fishing vessels (2014-2023)

The distribution of research articles on hybrid or electric fishing vessels for the last ten years, from 2014 to 2023, is shown in figure 4. It suggests that although there has been an overall increase of publications over the past ten years, the average trend has been erratic. With 106 documents published in the last ten years, figure 5 shows the distribution of documents according to their types of publishing. These documents are categorized into journal articles (53), conference papers (42), conference reviews (7), reviews (2), and book chapters (1). Based on these figures, the largest share is attributed to journal articles, accounting for 50%, followed by conference papers at 39%, while the remaining 11% is contributed by conference reviews, reviews, and book chapters.

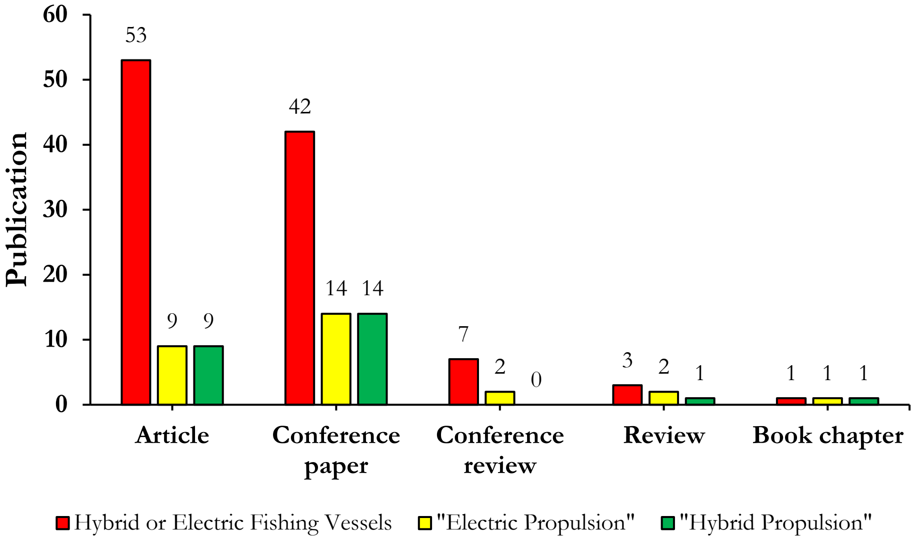

Figure 5. Documents are distributed according to publication kind

3 Types of Vessel Propulsion Systems

Based on their environmental effect, ship propulsion systems are divided into three categories: electric, hybrid, and mechanical (Hwang, Kim et al. 2022). On a ship of a given size, all electrical loads—which fall into the categories of mechanical, electrical, and hydraulic loads—are provided by the main engine. Usually, the biggest power-demanding load is the propulsion system, which is specifically engineered to move the vessel at the desired speed (Capasso, Notti et al. 2019).

3.1. Mechanical Propulsion Systems

Before the 1800s, sails and oars were used to propel ships. Nonetheless, mechanical propulsion technologies were introduced as a result of the advancement of steam engines. (Geertsma et al., 2017). A gearbox and reversing the engine's rotation are not necessary for large-scale ships that run on low-speed diesel engines. Smaller ships, on the other hand, need a gearbox to limit the acceleration at which the motor spins since they are driven by diesel engines that run at medium or high rates. These gearboxes can also be employed to reverse shaft rotation.

Mechanical propulsion systems are highly efficient at their design speeds, typically between 80 and 100% of the maximum speed. Furthermore, the primary engine, the gearbox, and the propeller are the only three phases of power conversion in mechanical propulsion, which minimizes conversion losses. Finally, because mechanical propulsion is straightforward, it has a cheap initial cost. (Geertsma, Negenborn et al. 2017). This justifies the use of mechanical propulsion for smaller fishing vessels equipped with conventional mechanical power systems, such as gasoline or diesel engines connected to mechanical propulsion systems (Manouchehrinia et al., 2018). Compared to traditional propulsion systems, the hybrid electric propulsion system created using the multi-objective optimization technique has demonstrated benefits (Jianyun et al., 2018). Furthermore, compared to traditional techniques like dynamic programming and particle swarm optimization (PSO), the suggested optimal power management approach on a completely electric propulsion vessel exhibits superiority in identifying optimal solutions and improved convergence characteristics (Kanellos et al., 2017). Some larger ships may have hydraulic propulsion systems to enhance torque characteristics compared to mechanical propulsion and use additional generators for loads other than the main propulsion. Figure 6 shows the conventional construction of contemporary ships powered by mechanical means. The propeller (3) is normally driven by the primary propulsion unit (1), which is commonly a diesel engine or gas turbine, either directly or through a gearbox (2) (Geertsma, Negenborn et al. 2017).

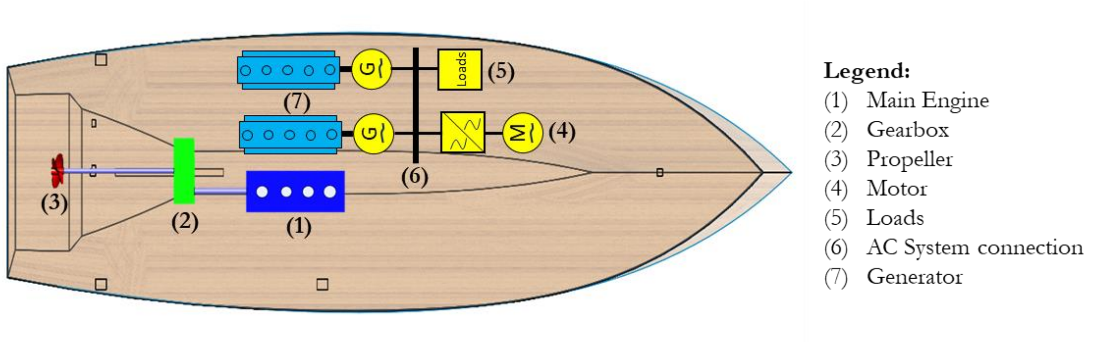

Figure 6. Schematic of a mechanical propulsion system

3.2. System of Electric Propulsion

When opposed to traditional mechanical propulsion techniques, an electric propulsion system has several benefits (Reite et al., 2017). It operates by turning an electrically powered drive motor to drive a propulsion device. The development of power conversion devices and battery technology has fueled the use of electric propulsion systems in ships. (Hwang, Kim et al. 2022).

Figure 7 shows the conventional construction of an electric propulsion system. An electrical bus (2) with a set frequency and high voltage is powered by many diesel generators (1). Through the use of a transformer (3), this bus transfers electricity to the ship's electric drive motor (5) and other loads. The electric drive motor is made up of four power electronic converters, which are frequently employed to regulate both the ship's speed and the shaft line speed.

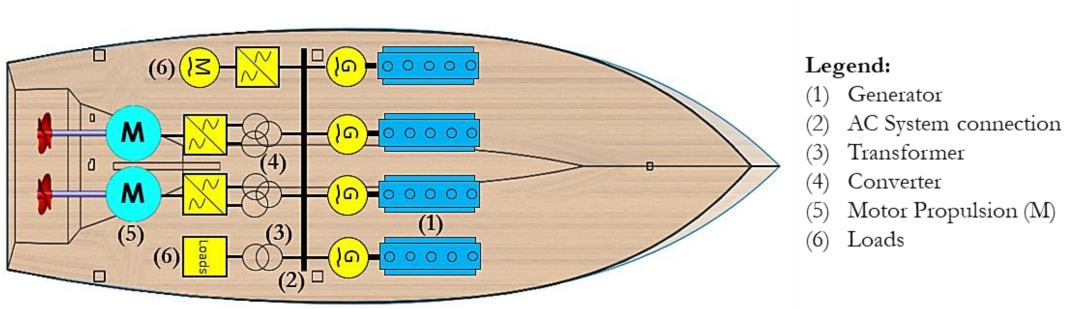

Figure 7. Schematic of electric propulsion system

3.3. System of Hybrid Propulsion

Through the use of a gearbox, hybrid propulsion systems combine mechanical and electric propulsion systems to provide the benefits of both, but they also add weight and bulk. (Kim and Kim 2021). However, a lot of thought has been given to improving ship propulsion systems through hybridization, which combines current mechanical propulsion systems with electric propulsion systems, because of how simple and inexpensive it is to modify the systems. (Notti et al., 2012). In addition to the current diesel gensets, the necessary hybrid propulsion system may be powered by a variety of energy sources, including batteries, fuel cells, ecologically friendly fuel gensets, and renewable energy sources. By doing this, pollutants in the air like the release of carbon dioxide will be reduced (Nuchturee, Li et al. 2020).

Mechanical propulsion in the direct manner (1) offers fast and extremely efficient propulsion in hybrid propulsion. In addition, propulsion for low speeds is provided by an electric motor (2), which can be connected directly to the propeller shaft or through a gearbox (3) to avoid the main engine operating inefficiently while only partially loaded. On the ship's electrical network, this motor may also be utilized as an electrical load generator (4). Figure 8 shows the standard configuration for a hybrid propulsion system. More specifically, a large percentage of the overall operational time of fishing vessels is spent under low- or no-load conditions. Therefore, it would appear that the most efficient way for fishing boats to reduce their fuel costs is to use electricity for propulsion when they are running at low or no load. In addition, when they are traveling to destinations for fishing, they can use both mechanical and electrical propulsion to generate a high output in increase mode.

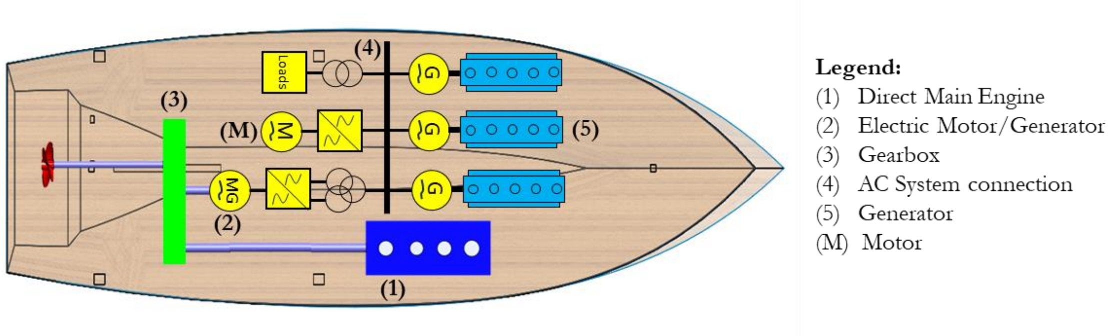

Figure 8. Diagram illustrating a hybrid powertrain

The following table 2 illustrates the trends in propulsion technology implementation along with their advantages and disadvantages.

Table 2. Propulsion Technology Comparison

Propulsion Technology	Advantages	Disadvantages.	Ref.
Mechanical propulsion	- Reliable and often utilized in traditional ships. - Can provide significant power and good range. - Relatively cheaper in terms of initial cost	- Utilizes fossil fuels (typically diesel or gasoline) resulting in greenhouse gas emissions and air pollution. - Tends to be less fuel-efficient compared to other propulsion technologies.	(Bastos, Branco et al. 2021)
Electrical propulsion	- Environmentally friendly with zero direct emissions. - Efficient in energy use and lower operational costs. - Can be integrated with renewable energy sources such as solar panels or batteries.	- Requires external electrical power source during charging or has a need for large energy storage in the form of batteries. - Limited by battery capacity and limited range if adequate charging is not available.	(Koričan, Frković et al. 2023a)
Hybrid propulsion	- Combines the advantages of mechanical and electric propulsion technologies. - Allows flexibility in using various energy sources, such as internal combustion engines and electric motors. - Can reduce greenhouse gas emissions by using electric propulsion in certain modes.	- Requires additional maintenance due to the complex hybrid components. - Initial costs may be higher due to the combination of mechanical and electrical components.	(Inal, Charpentier et al. 2022)

4 Fishing Vessel Types with Their Uses and Regulations

Purse seiners, trawlers, gillnetters, and longliners are examples of fishing vessels classified based on their catch operations. Every vessel has a distinct speed, route, and specifications. There are three types of fishing operations: trawling/dragging, encircling, and stationary. The vessels and purse seiners were two kinds of commercial fishing boats that utilize distinct methods to catch fish. Purse seines ring a group of fish, forming a "pocket" around it, whereas trawlers draw conically-shaped nets down the bottom or water column (Kurniawati, 2019). Purser seines, which have been demonstrated to be more fuel-efficient than trawlers, requiring just 42% of the gasoline per ton of fish collected, are mostly used in fisheries targeting small pelagic species (Basurko et al., 2015). According to table 3, various types of fishing vessels are listed, including specifications such as speed, size, and type of nets used. Additional information includes the species targeted and the operational areas of the vessels. Accompanying graphs illustrate the work and rest hours for each type of vessel over a 24-hour period, with work hours marked in green and rest hours in yellow. These vessels operate in various conditions and water depths, from coastal to open ocean, and adjust their schedules based on operational needs and fishing targets. The technical and operational characteristics of different types of trawling vessels (stake, push, stern, side, wet, and frozen) and purse seiners (Americans, European, tuna, drum, and purse seine) serve a variety of fishing purposes and differ depending on working region, gear used, and tonnage (Korican et al., 2022a; FAO, 2008).

Purse seiners are generally employed to target schools offish such as tuna, sardines in and fish such as herring while trawlers may work on both shallow and deeper rivers, catching a diverse range of species of fish depending on the location and season. In terms of efficacy, purse seiners can capture large numbers of fish in a single trip, but trawlers might require a lot passes to gather the same amount. Trawlers catch more fish species than purse seiners, resulting in higher selling prices (Kurniawati, 2019; Koričan et al., 2022a). Fuel consumption varies between purse seiners and trawlers because to technological and operational differences (Vladimir et al., 2021; Koričan et al., 2022b). Fisheries with purse seiners takes a little longer and energy to sail, but fishing with trawlers requires more time and power to pull nets.

Beam trawlers, medium-sized vessels, operate in waters with depths reaching up to 2000 meters and frequently incorporate stabilizers to facilitate tandem towing. Pair trawlers, larger in scale, are commonly towed by two vessels of equivalent size and power, predominantly employed in midwater environments but also capable of bottom trawling in depths up to 800 meters (Korican et al., 2022a). Otter trawlers utilize otter boards for towing one or more parallel trawls in midwater and bottom zones. Stern trawlers, capable of operating under various weather conditions, are towed from the stern for both midwater and bottom trawling activities. Outrigger trawlers, primarily used for shrimp capture, are towed from outriggers on the vessel and occasionally combined with otter and beam trawls. Wet fish trawlers, which operate proximate to landing points to preserve the freshness of the catch, store the fish in a "wet" state within the hold. Finally, freezer trawlers or factory ships, operational in open seas, are equipped with facilities to process, package, and freeze fish on board, facilitating prolonged maritime operations (Korican et al., 2022a).

In table 3 it has been summarized that, Purse seiners, trawlers, gillnetters, and longliners are four key types of fishing vessels, each optimized for specific fishing methods. Purse seiners capture large pelagic species such as tuna using nets that enclose at the bottom for efficient, large-scale fishing. Trawlers, including beam, stern, and otter varieties, drag nets across the seabed or water column, targeting diverse fish species in various depths. Gillnetters set nets in fish pathways, effectively catching species like salmon and trout. Longliners, deploying long lines with multiple hooks, are suited for deep-water pelagics like swordfish and tuna, minimizing environmental impact. These vessels adjust their operational schedules based on the fishing targets and environmental conditions to ensure sustainable practices.

Table 3. Characteristics and Operation of Fishing Vessels
(FAO, 2008; Korican et al., 2022a; Korican et al., 2023c)

🟩 **Work Hours** 🟨 **Rest Hours**

Type of Vessel	**Speed (knots)**	**Size (Length)**	**Net Type**	**Fish Caught**	**Operational Water Area**	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Purse Seiners	12 – 15	Up to 70 meters	Seine nets	Tuna, Mackerel, Herring	Open ocean, Coastal	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟩
Beam Trawlers	8 – 10	Various	Beam trawls	Bottom-dwelling species	Shallow waters, up to 2000m	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨
Pair Trawlers	9 – 12	>5 m	Pair trawls	Various	Coastal and midwater	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟨
Otter Trawlers	9 – 13	>10 m	Otter trawls	Various	Midwater and bottom	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Stern Trawlers	10 – 14	>15 m	Stern trawls	Various	All conditions	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Outrigger Trawlers	10 – 15	>20 m	Outrigger trawls	Shrimps, Various	Deep and midwater	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨
Wet Fish Trawlers	10 – 13	12-24 m	Various	Various	Near landing points	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Freezer Trawlers (Factory)	10 – 15	>40 m	Various	Various	Open sea	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Gillnetters	8 – 12	20-50 m	Gillnets	Salmon, Trout	Coastal waters	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨
Longliners	10 – 12	25-100 m	Longlines	Tuna, Swordfish	Open ocean, deep sea	🟩	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Table 4 describes various regulations and rules applied to fishing vessels, covering aspects such as occupational safety, energy efficiency, and carbon emission reduction (United Nations, 2024). Each regulation has a different focus depending on its objectives and area of implementation. Some regulations are applied internationally, while others are only applicable to vessels operating in specific regions or with certain sizes and capacities. The implementation of these regulations is crucial to governing fishing vessel operations, ensuring crew safety, and minimizing the environmental impact caused by fishing activities. The adherence to these regulations helps standardize practices across the global fishing industry and promotes a safer and more sustainable working environment for fishing crews.

One important regulation is the Work in Fishing Convention (C188), which sets minimum standards for working conditions on fishing vessels, covering aspects such as minimum working age, occupational safety, health, and social security for crew members. This convention is aimed at preventing exploitation and ensuring decent working conditions for fishermen, who are often exposed to hazardous working environments. The IMO Cape Town Agreement, on the other hand, enhances safety standards for larger fishing vessels (over 24 meters in length) to prevent maritime accidents and illegal fishing practices, and to ensure compliance with safety standards in international waters. These regulations are particularly critical for fishing vessels operating in challenging and remote environments, where the risk of accidents is higher.

On the environmental side, MARPOL Annex VI and the Nitrogen Oxide (NOx) Emission Regulation focus on reducing emissions of harmful gases such as NOx, SOx, and CO_2 produced by vessels. These regulations aim to minimize the impact of air pollution caused by the maritime industry, which contributes significantly to global greenhouse gas emissions. However, many small-scale fishing vessels are exempt from these regulations due to their size and operational range, resulting in disparities in emission reductions across the fishing sector. Additionally, regulations such as the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), and the FuelEU Maritime Initiative are primarily designed for merchant ships, leaving fishing vessels unregulated in terms of energy efficiency measures, which poses challenges for achieving sustainable operations. In addition to technical and environmental regulations, financial policies such as the WTO Agreement on Fisheries Subsidies play a crucial role in promoting sustainable fishing practices. This agreement aims to restrict subsidies that contribute to overfishing and fleet overcapacity by banning financial support for vessel construction, repair, and fuel.

Table 4. Types of Regulations for Fishing Vessels (United Nations, 2024)

Regulation	Description	Implementation
Work in Fishing Convention (C188)	Establish minimum standards for working conditions in the fisheries sector, including minimum age for employment, occupational safety, health and social security.	Countries that have ratified (21 countries)
IMO Cape Town Agreement	Improving safety standards for fishing vessels > 24 meters and preventing illegal fishing, as well as pollution from abandoned fishing nets.	Countries that have agreed to the agreement
MARPOL Annex VI	Setting limits on NOx, SOx, and CO_2 gas emissions, as well as reducing pollution from fossil fuel use.	Ships with a size > 400 GT operating in the ECA area
Energy Efficiency Design Index (EEDI) & Energy Efficiency Existing Ship Index (EEXI)	Regulates energy efficiency for merchant vessels, but fishing vessels are exempt from this requirement.	Merchant vessels except fishing vessels
FuelEU Maritime Initiative	Regulates GHG emission reductions throughout the life cycle of vessels, but does not cover fishing vessels.	Passenger and container ships, does not apply to fishing vessels

WTO Agreement on Fisheries Subsidies	Ban subsidies that support overfishing and overcapacity, including subsidies for construction, repairs, and fuel.	All countries participating in the WTO
Nitrogen Oxide (NOx) Emission Regulation	Sets NOx emission limits for ships with diesel engines > 130 kW, but only applies in Emission Control Areas (ECAs).	Ships with engines > 130 kW operating in ECA
Uni Eropa: Regulation (EU) 2015/757	Requires monitoring, reporting and verification of CO_2 emissions from maritime transport, but exempts fishing vessels.	European Union, but does not apply to fishing vessels

5 Electric Propulsion System Configuration on Fishing Vessels

The propulsion system of a fishing vessel has a significant impact on the hull's characteristics. Furthermore, the schematic and arrangement of the electric propulsion system are outlined below.

5.1 Electric Drive System with Battery

When designing battery integration for vessel applications such as in figure 9, state of charge as well as capacity are taken into account (Misyris, Marinopoulos et al. 2017). Systems with battery energy storage can also supply the extra electrical power required for brief periods of time. To satisfy these demands in a typical driving system, an extra diesel generator must be run. The auxiliary generator may be switched off and fuel and engine wear can be avoided by employing batteries (Kolodziejski and Michalska-Pozoga 2023). Nonetheless, electric drives that use batteries are a greener way to operate since they don't release any emissions into the atmosphere (Koumentakos 2019, Banaei, Ghanami et al. 2020). They can also boost energy efficiency by providing short-term power or reserving energy through the use of rechargeable or emptied batteries. Solar panels are typically used to charge the batteries in fishing boats that use batteries as the primary power source for their propulsion system (Putranto et al., 2018; Chakraborty et al., 2016).

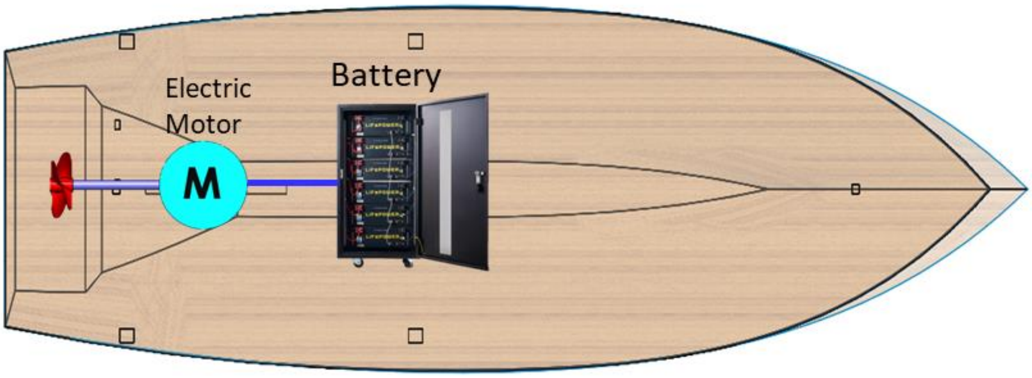

Figure 9. Schematic of Electric Drive System with Battery

5.2 Hybrid Electric Propulsion System

Hybrid energy systems integrate many energy sources to generate energy through mutual cooperation. The most prevalent kinds of hybrid energy systems combine conventional energy sources like grid connections or diesel generators with sustainable energy sources, such as wind and solar (Koričan, Vladimir et al. 2023b). Enhancing energy efficiency and dependability while lowering total costs and the environmental effects of energy generation is the goal of hybrid energy systems. For example, by lowering the amount of fuel needed to drive diesel generators, a system of energy sources that mixes solar and wind power may reduce emissions and expenses. Hybrid energy systems can be equipped with batteries or additional sources of energy storage to store excess energy generated by renewable sources for use during periods of less sunshine or wind (Inal, Charpentier et al. 2022). Three distinct configurations of hybrid propulsion may be identified, focusing on systems for energy management and commonly used optimization techniques: structures in serial, parallel, and series-parallel (Inal, Charpentier et al. 2022, Koričan, Vladimir et al. 2023b).

- Series scheme hybrid energy system

  A serial mixed-energy system is a sort of dual energy system that connects energy resources sequentially (Koričan, Vladimir et al., 2023b). This technology merges every source of energy into a single energy generator, providing the ship with energy in the form of all-electric propulsion. The plug-in hybrid boat system connects the shore power reception system to the internal combustion engine, electric motor, battery, and electric charger. In the meanwhile, it is also advised to complete the electric generator by using the plug-in hybrid boat system (Minami et al., 2017). The propulsion motor is powered by the electrical energy that is collected and converted into AC using a DC/AC converter on the DC bus (Yuan, Wang et al. 2020). Figure 10 shows the schematic series hybrid energy system concept. This model may have a fuel cell storage system after a solar panel array. The surplus electricity generated by the photovoltaic cells is kept in the energy battery system for use at a later time while alternative sources of energy are not available.

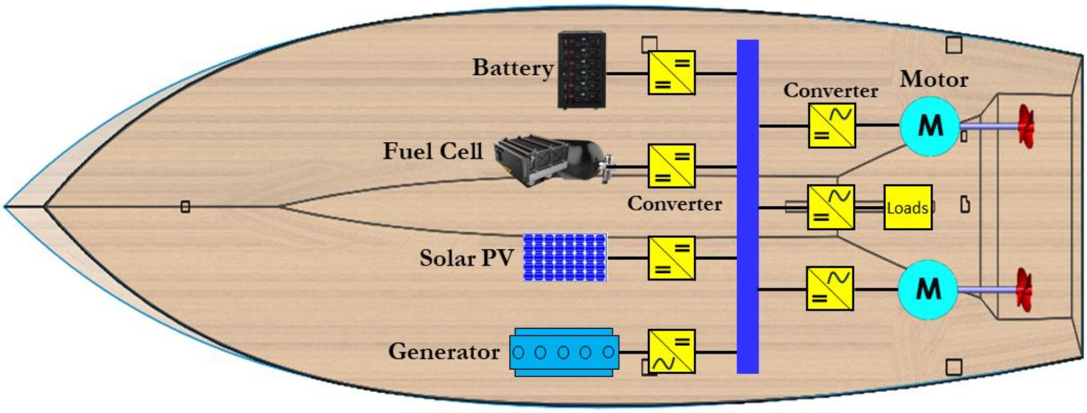

Figure 10. Schematic Hybrid Energy System Series

- Parallel scheme hybrid energy system

  Combining mechanical and electrical propulsion, the parallel topology hybrid power system allows energy sources to be connected to a single point or bus so that they may be utilized separately or in tandem to satisfy energy demands (Koričan, Vladimir et al. 2023b). Energy is transferred from the main engine to the linkages mechanism via a shaft that operates on the mechanical driving side, owing to a coupling device. When the primary engine produces an abundance of electricity, the generator can operate in generation mode, absorbing additional energy and powering the electrical network. The electrical propulsion side converts numerous sources of energy into a direct current (DC) bus to form a hybrid electrical system (Koričan, Vladimir et al. 2023b). The DC network then provides electricity to the power demands and motors (Yuan, Wang et al. 2020). Figure 11 provides an illustration of this kind of setup. Parallel topology hybrid energy systems are more flexible and energy efficient, and they may be made to fulfill different energy requirements and give redundancy (Geertsma, Negenborn et al. 2017, Inal, Charpentier et al. 2022), guaranteeing that electricity will never run out, even in the event that an electrical supply failsThe present obstacles in running parallel hybrid electricity systems are mostly due to the distance among the main engine and consumer demand, power distribution in the generator combination, and dynamic changing between various operating modes (Yuan, Wang, et al. 2020).

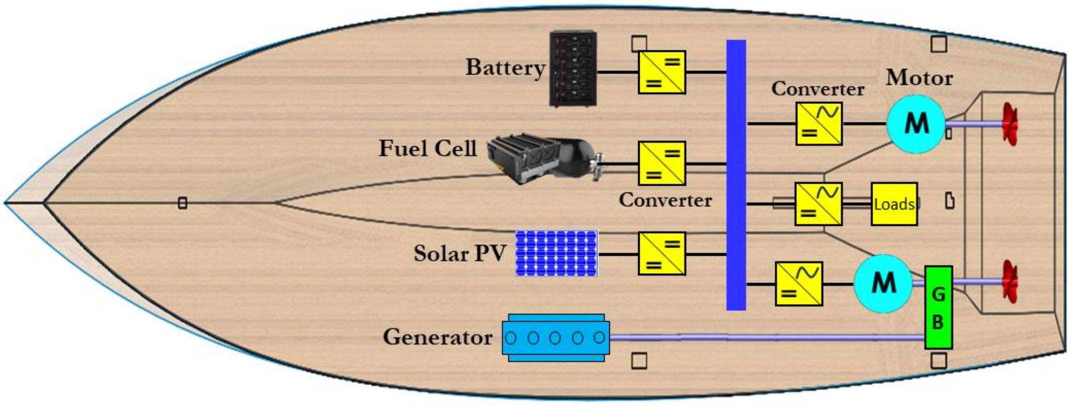

Figure 11. Schematic Parallel Hybrid Energy System

- Schematic of a serial-parallel hybrid energy system

In order to provide a consistent and flexible energy source, energy sources are connected in an energy system that is hybrid that blends series and parallel connections (Koričan, Vladimir et al. 2023b). On the mechanical drive side, both electric and mechanical propulsion may drive the propellers concurrently because of the two various kinds of couplings that are present. The generator can be directly driven by the main engine to power the DC line through the coupling mechanism. On the electric powertrain side, a multi-energy hybrid electric system is constructed by utilizing a converter to integrate various sources of energy into the DC line and using the energy from the DC network to power motors and electrical loads (Koričan, Vladimir et al. 2023b). Figure 12 is a schematic illustration of this kind of series-parallel hybrid energy system. The fundamental concept of the the vessel's management plan is to run in parallel mode during periods of high-power demand and in series mode during those of low power consumption (Yuan, Wang et al. 2020). The benefits of parallel as well as series hybrid energy systems are available with this kind of setup, including increased flexibility, redundancy, and energy efficiency (Inal, Charpentier et al. 2022). The series and parallel hybrid electricity system enables variable energy flow configurations and consumption optimization due to its increased operating modes and decreased fuel consumption. But because of its more expensive cost and more complex system structure, it requires the right control techniques.

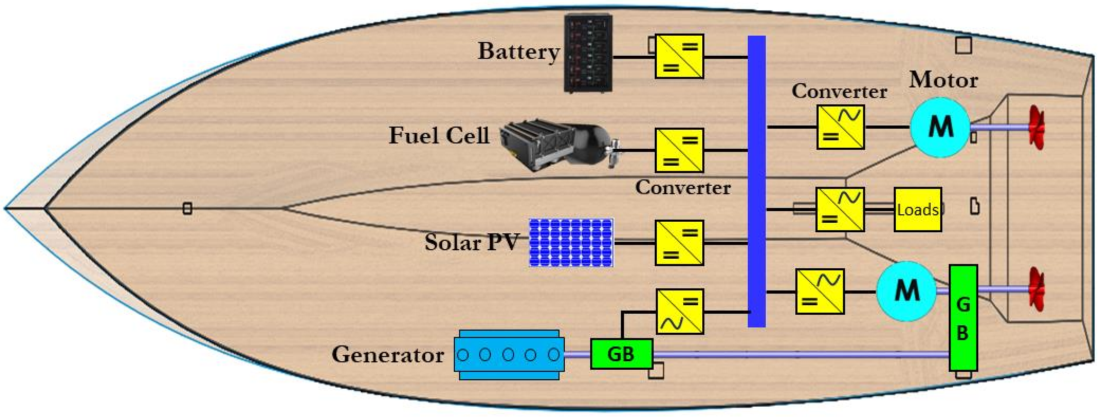

Figure 12. Diagram of a hybrid energy system that is series-parallel

An overview of powertrain configurations and observations on electric or hybrid fishing vessel propulsion systems that are already in use have been provided in table 5, categorized based on series and parallel configurations.

Table 5. Fishing Vessel Propulsion System Configuration

Powertrain Configuration	System configuration type	Vessels Propulsion Observation	Ref.
Generator + battery = Electric engine	Series system	Hybrid Propulsion on fishing vessels	(Manouchehrinia, Molloy et al. 2018)
Battery = Electric engine		Battery propulsion on fishing vessels	
Battery = Electric engine	Series system	Battery propulsion on fishing vessels	(Koričan, Frković et al. 2023a)
Battery + generator = Gearbox + electric engine	Parallel system	Hybrid Propulsion on fishing vessels	(Hwang, Kim et al. 2022)
Battery + generator = Gearbox + electric engine	Parallel system	Hybrid Propulsion on fishing vessels	(Kim, Jeon et al. 2022)
Solar PV + Battery = Electric engine	Series system	Battery propulsion on fishing vessels	(Gamage, Wimalasooriya et al. 2021)
Solar PV + Battery + generator = dc motor	Parallel system	Hybrid Propulsion on fishing vessels	(Sultoni, Ali et al. 2020)
Generator = Electric engine + gearbox	Series system	Hybrid Propulsion on fishing vessels	(Bastos, Branco et al. 2021)
ICE = Propeller	Series system	Conventional propulsion in fishing vessels	(Koričan, Vladimir et al. 2023b)
Renewable energy + Battery = Electric engine	Series system	Hybrid Propulsion on fishing vessels	
Battery = Electric engine	Series system	Battery propulsion on fishing vessels	
Solar PV + Battery = Electic engine	Series system	Battery propulsion on fishing vessels	(Sunaryo, Syahrihaddin et al. 2019)
Renewable energy + Battery = Electric engine	Series system	Hybrid Propulsion on fishing vessels	(Ren, Diao & Wang, 2014)

6 Consequences of Propulsion System Modifications on Electric or Hybrid Fishing Vessels

The transition of fishing vessels from traditional diesel power to hybrid or electric technology has a substantial effect on a number of factors, including environmental, economic, and technological ones. This alteration not only improves the vessels operating performance but also presents chances to enhance energy efficiency and lessen adverse environmental effects. Both the design of electric propulsion systems and the repair of diesel propulsion systems were done in order to ascertain the applicability of electric propulsion systems on fishing vessels. with instance, with a fishing vessel with 10 GT (Zhang et al., 2023). Table 6 shows the total weight and volume of the gasoline and electrical propulsion systems for a one-week sailing scenario. Meanwhile, the electric engine weighs 9.5 times as much as the diesel fuel system and requires 10.5 times the volume. On the other side, the weight of the mechanical system (which includes the propellers, fuel tank, and transfer system) is twice that of the electric propulsion system. However, the total weight and volume are 9.5 and 10.5 times bigger, respectively. When constructing the system, consideration must be given to the battery's performance, volume, weight, and cost, as well as the optimal design (Kim, Kim et al. 2021). Meanwhile, the ideal hull form will influence the real navigation circumstances, and the objective function will be the fishing boat's overall resistance under wave conditions (Tezdogan et al., 2018).

Table 6. Comparison of Changes in Diesel and Electric Propulsion Systems on Fishing Vessels

Aspect	Diesel Propulsion System	Electric Propulsion System	System Changes
Total Weight of Propulsion System	3,717.98 kg (including engine, fuel, tank)	35,434 kg (including electric motor and battery)	The electrical power system weighs 9.5 times more than the diesel.
Total Volume of Propulsion System	5.0681 m^3 (engine, fuel, tank)	53.4268 m^3 (electric motor and battery)	The amount of space of the electric motor mechanism is 10.5 times greater.
Main Engine Weight	1,750 kg	874 kg	Electric engines are lighter than diesel engines
Main Engine Volume	3.2751 m^3	1.5868 m^3	A diesel engine has a larger volume than an electric motor.
Fuel/Battery Weight	1.337,28 kg (fuel for a week)	34.560 kg (battery for a week)	Batteries are much heavier than diesel fuel
Fuel/Battery Volume	1.6 m^3	51.84 m^3	Batteries require more space than fuel
Fish Transport Capacity	No changes	No changes	No changes to the fish cabin

In table 7, the distribution of volume and estimated percentage of power used by various key components on a 7,053 GT fishing vessel is shown (Aalbers, 2018). From the table, it can be seen that accommodation takes up about 13% of the vessel's total volume, with an estimated power consumption of 4% of the total vessel power. The fish processing and sorting system uses 12% of the total volume and is estimated to consume 8% of the total power. Meanwhile, the fish storage area (total holds) accounts for the largest volume contribution, at 39% of the vessel's total volume, but does not significantly affect power consumption as it is merely a passive storage space. The deck hydraulic system, which includes the winch and crane, requires about 13% of the vessel's total power, although the volume used is not mentioned in the table. The tank systems, including fuel and freshwater tanks, take up 10% of the total volume but do not directly affect power consumption. On the other hand, the propulsion system (engine room) utilizes 21% of the vessel's volume and is the largest power-consuming component, using approximately 65% of the total vessel power. Additional components such as lighting, HVAC, and general systems require about 3% of the total power, while the electronics and navigation systems consume a relatively small amount of power, around 2% of the total. Overall, propulsion is the most energy-intensive component on the 7,053 GT vessel, while other components like the deck hydraulics and fish processing systems also contribute significantly to power usage (Gabrielli & Jafarzadeh, 2020).

Table 7. Fishing Vessels Based on Volume and Power Percentage

Aspect	Volume (m^3)	Total Volume Percentage (%)	Estimated Power Percentage (%)
Accommodation	3,349	13%	4%
Processing & Sorting System	3,056	12%	8%
Fish Holds (Total Holds)	9,889	39%	N/A
Deck Hydraulic System	N/A	N/A	13%
Tanks (Total Tanks)	2,724	10%	N/A
Propulsion System (Engine Room, Rest)	5,490	21%	65%
Lighting, HVAC, General Systems	N/A	N/A	3%
Electronics and Navigation Systems	N/A	N/A	2%

Based to this theory, the study's main goal is to find unconventional renewable energy sources in the research region. The energy options selected are meant to complement the ship's locally appropriate electric propulsion system. Using a multicriteria analysis that takes sustainability into account in social, technical, economic, and environmental aspects, the Pacific Econavipesca project created a hybrid renewable energy-based generating system for artisanal fishermen (Bueno-López et al., 2023).

6.1 The Technical Aspects of Enhancements to The Propulsion System

The shift to hybrid or electric propulsion systems introduces additional space requirements for energy storage systems, particularly batteries. This can impact the internal layout of fishing vessels by reducing available space for cargo or fish holds. In the article by Inal et al. (2022), it is mentioned that "the integration of energy storage systems requires larger internal volume, which could affect the structural design of the ship and its load distribution" (Inal et al., 2022). This means that without expanding the vessel, storage capacity may be compromised. The requirement for additional space to accommodate energy storage can directly reduce the vessel's fish-carrying capacity. As described by Geertsma et al. (2017), "large-capacity batteries occupy significant space, reducing the available volume for cargo or fishing equipment" (Geertsma et al., 2017). Therefore, a decrease in the fish-carrying capacity is an expected outcome unless the vessel design is optimized or enlarged.

Fishing vessels require substantial auxiliary power for operations like winching and net hauling. Hybrid systems can utilize batteries to meet these demands, thus reducing the strain on the main propulsion engine and saving fuel. Geertsma et al. (2017) highlight that "batteries can provide power for auxiliary operations such as winches and fishing nets, reducing the load on the main engine" (Geertsma et al., 2017). Hybrid propulsion systems offer greater operational flexibility. At low speeds or during specific operations, vessels can switch to electric power, reducing fuel consumption and emissions. Inal et al. (2022) explain that "hybrid propulsion allows ships to switch between electric and diesel power depending on operational conditions, significantly reducing fuel consumption and emissions" (Inal et al., 2022). Hybrid power systems ship DC systems without energy storage have much lower fuel consumption than standard AC systems (Zahedi et al., 2014), and other studies have found a 20 - 22% reduction in fuel consumption (Wang & Sha, 2014; Son et al., 2018). This flexibility is beneficial in both operational efficiency and environmental impact.

6.2 The Economic Aspects of Enhancements to The Propulsion System

The shift from conventional (diesel) propulsion systems to hybrid or electric systems on fishing vessels has significant economic impacts, including high initial costs as well as changes in long-term operations and productivity. The initial investment costs for this conversion are substantial, covering the purchase of batteries, electric motors, power management systems, and modifications to the vessel (Ammar & Seddiek, 2023; Bastos, Branco et al. 2021). Additionally, the development of charging infrastructure, such as battery charging stations and renewable energy integration, further increases the upfront investment (Ammar & Seddiek, 2023; Beatrice et al., 2022). However, in the long term, operational costs are reduced due to significant decreases in fuel consumption, as electric systems do not use fossil fuels (Bastos et al., 2021; Bui, Dinh et al. 2021). Hybrid systems allow the use of electricity while in port or under low loads, and diesel during heavy operations, further contributing to fuel savings (Beatrice et al., 2022; Bui, Dinh et al. 2021). Another example is a $2,527,700 solar energy system that uses 210 batteries and 56 PV modules to power fishing boat lights in order to lessen carbon emissions and reliance on fossil fuels (El-Khozenadar et al., 2023). Operational expenses will influence the intended degree of flexibility with relation to the ship's future operational profile (Solem et al., 2015). Furthermore, electric and hybrid propulsion systems typically require less maintenance compared to diesel engines due to fewer moving parts, reducing maintenance costs (Bellone, Lundh, Wahde, & MacKinnon, 2019). However, battery charging can present a challenge, as it may take a long time and rely on the availability of adequate infrastructure (Bicer & Dincer, 2018; Geertsma et al., 2017). Long-term economic efficiency is clearly seen in fuel cost savings, which can offset the initial investment costs over several years (Basurko et al., 2015; Kim, Jeon et al. 2022). Additionally, several countries provide incentives to encourage the adoption of environmentally friendly technologies, such as electric or hybrid propulsion systems (Ghimire, Karimi et al. 2022). Sustainability and market value also improve with the adoption of these technologies, aligning with global trends toward more environmentally friendly operations, thus adding market value in international markets (Korican et al. 2022b). However, there are risks and uncertainties related to high battery prices and limited battery lifespan, which add to long-term operational costs (Banaei, Ghanami et al. 2020; Bui, Dinh et al. 2021). The reliance on fluctuating electricity prices and developing charging infrastructure also poses challenges for vessels using electric propulsion systems (Korican et al. 2022c; Inal et al., 2022). Additionally, the 17% increase in daily energy demand for charging electric boats has been a technical and financial benefit to the small grid system (Lukuyu et al., 2020). With a compelling quantity of energy generation and a short payback time, the hybrid grid-PV system has effectively hit its peak in terms of producing high income from selling power to the grid (Salleh,Muda & Abdullah, 2015; Salleh & Muda, 2016a; Salleh,Muda & Umar, 2016b).

6.3 The Environmental Aspects of Enhancements to The Propulsion System

There are significant environmental advantages to fishing vessels switching from traditional (diesel) propulsion systems to hybrid or electric systems, mainly in the form of reduced emissions and increased energy efficiency. Emission reduction is one of the most significant advantages of hybrid and electric systems, as they drastically reduce greenhouse gas (GHG) emissions, including CO_2, NO_x, and SO_x, compared to traditional diesel systems (Ammar & Seddiek, 2023; Bicer & Dincer, 2018). Traditional ship engines with electric propulsion systems can save up to 10 million Rupiah in tax emissions year and save CO_2 emissions by 7.94 tons annually (Octaviani et al., 2023). Transitioning to electric propulsion allows fishing vessels to cut CO_2 emissions by 30% to 50%, depending on the integration of renewable energy in the battery charging infrastructure (Bastos, Branco et al. 2021; Korican et al., 2022b). According to Mehammer et al. (2023), charging electric automobiles is equivalent to charging small fishing boats with electric and hybrid power. Additionally, local air pollution at ports can be significantly reduced by using electric energy while berthed, also known as cold ironing, which avoids the need for diesel generators at dock (Bakar et al., 2022).

Furthermore, hybrid and electric systems contribute to energy efficiency improvements, as they harness cleaner and more efficient energy compared to traditional fossil fuels (Bellone, Lundh et al. 2019). The use of batteries and the integration of renewable energy sources, such as solar panels or wind turbines, allow vessels to become more energy independent and reduce their reliance on fossil fuels (Kim et al., 2022). Another important environmental benefit is the reduction of underwater noise pollution, as electric motors are much quieter than diesel engines, minimizing their impact on marine life (Korican et al., 2023c; Geertsma et al., 2017).

However, there are also environmental challenges associated with the production and disposal of batteries, especially lithium-ion batteries, which can cause pollution if not properly managed (Banaei, Ghanami et al. 2020; Inal et al., 2022). The production of batteries requires rare materials such as lithium and cobalt, and the mining processes for these materials can have negative environmental consequences. Moreover, the limited lifespan of batteries adds to the environmental burden, as they need to be replaced and disposed of after reaching their operational limits (Bicer & Dincer, 2018). Overall, switching to hybrid or electric propulsion systems in fishing vessels provides significant environmental benefits in terms of reducing emissions and improving energy efficiency. However, challenges related to battery disposal and the production of components still need to be addressed to minimize the overall environmental footprint (Ammar & Seddiek, 2023; Korican et al., 2022b). One major obstacle to lowering CO2 emissions in this industry is a lack of understanding and experience with modern propulsion systems' safety, dependability, efficiency, and environmental performance (Hüllen et al., 2023).

7 Power Generation Technologies that are Feasible to Apply to Fishing Vessels

The selection of viable power generation technologies for application in fishing vessels is a crucial consideration. Although internal combustion engines—particularly marine diesel engines—are blamed for the majority of the negative effects, fuel cell technology and alternative sources of energy also offer respectable substitutes because of their capacity to produce energy in an environmentally friendly manner and take care of environmental issues on a worldwide scale. Due to the variety of power alternatives available to them, hybrid systems have an edge over traditional propulsion systems in terms of flexibility. Thus, popular power generating technologies for combination systems will be covered in this section.

7.1 Fuel Cell

The chemical energy generated by the combustion of fuel is immediately converted by fuel cells into DC electricity that powers the fuel cell unit (Inal, Charpentier et al., 2022). Compared to marine diesel engines, their total efficiency is comparatively greater since they only have one energy conversion step, which eliminates the combustion process seen in internal combustion engines (Bicer and Dincer, 2018). Fuel cells function more cleanly than diesel engines since they frequently utilize hydrogen as their main fuel source (Inal, Charpentier et al., 2022). Fuel cells therefore have a lot of potential for powering future ships due to their little environmental effect, especially in light of stringent emission restrictions (Yan et al., 2020). Although they are practical, hydrogen-powered fishing boats have restrictions on their length, capacity to store fuel, and range of operation (Jafarzadeh et al., 2023). The primary feature that sets fuel cells apart from other energy storage devices is their continuous operation, which allows them to produce power for as long as fuel is accessible.

The five varieties of fuel cells that are commercially available are Proton Exchange Membrane Fuel Cell (PEMFC), Phosphoric Acid Fuel Cell (PAFC), Alkaline Fuel Cell (AFC), Molten Carbonate Fuel Cell (MCFC), and Solid Oxide Fuel Cell (SOFC). Fuel cells are categorized depending on the type of electrolyte utilized. PEMFC is the most widely used of these because of its advanced technology and numerous uses in the marine industry as well as other energy-related sectors (de-Troya, Álvarez et al., 2016). Operational experience and economic benefits are provided by technological maturity. The primary disadvantage of PEMFC is that it needs high-purity hydrogen to work; otherwise, carbon monoxide poisoning will cause the fuel cell unit to shut down (Inal, Charpentier et al., 2022).

For instance, a battery pack with an overall capacity of 2.5 MWh, made up of 242 GO1050 modules, has been produced and approved by DNV as part of the creation of this novel hybrid system. EST-Floattech supplies the battery modules, and three marine fuel cell arrays (NT-PEMFC) with a combined peak output of 100kW each are available (EST-Floattech, 2021). The electric motor will be powered by both fuel cells and battery power, but for complete redundancy, they are designed to function independently. In battery-electric mode, the tug can cover a distance of 65 km (40 miles) in 8 hours before needing a recharge. An in-depth research process over several years has produced impressive results. The final design of the Elektra ship is 20 meters long, 8.2 meters wide and 1.25 meters draft. This ship is capable of producing an electrical energy capacity of 21,200kWh for round trips between Berlin and Hamburg, while maintaining zero emissions. Elektra can go at least 100 kilometers (62 miles) a day about 16 hours a day utilizing hydrogen as its source of energy. Figure 13 presents further information.

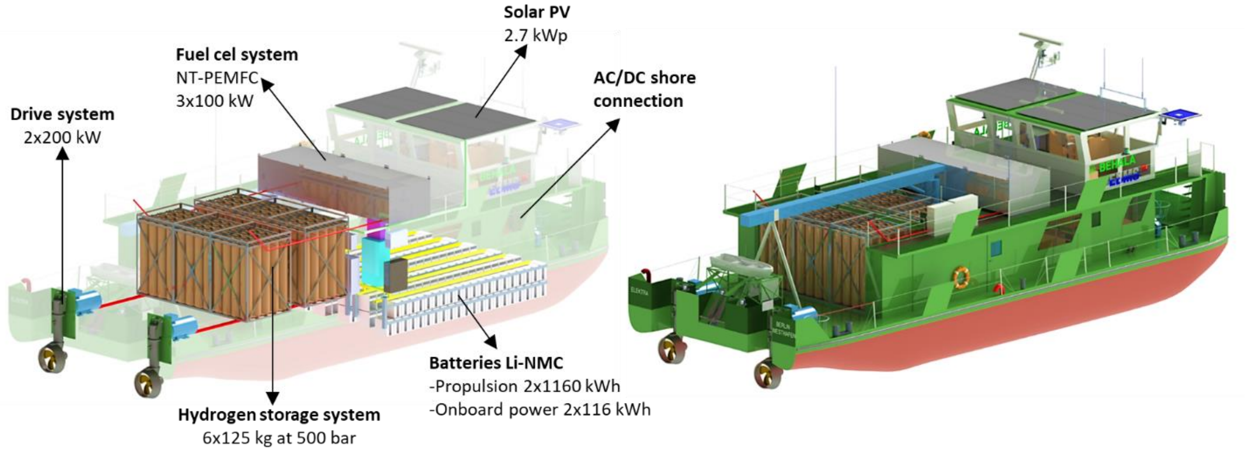

Figure 13. Hydrogen canal tug “Elektra”

7.2 Solar PV

An alternate means of producing electricity is provided by the transformation of radiation from the sun into electrical energy. As a result, ship electric engines effectively employ solar energy as their primary energy source (Sunaryo & Pradhana, 2019). According to Zhu, Zhou, et al. (2017), adding solar PV to newly built ships has an impact on the solar factor, which in turn impacts the energy efficient design index calculations. The geographic latitude and the PV panel's tilt angle with respect to the sun both affect average solar radiation. The photovoltaic conversion effectiveness, which may be maximized by utilizing solar tracking devices and modifying the declination angle, also affects the effectiveness of solar power generation. There have been suggestions for methods for putting up large-scale PV systems aboard ships (Tang, 2017). A modified electrical network structure for the ship is part of the plan, and PV arrays with maximum power point tracking (MPPT), management techniques are put in place. Because weather patterns and ship movements can cause power variations, energy storage integration is necessary to keep power distribution stable in photovoltaic systems.

The optimal size problem for the system design takes seasonal and regional differences into account. Engine efficiency may be maximized by optimizing the diesel generator's output through the use of the most properly sized system. To learn more about solar cell hybrid and energy storage, it is possible to consider the consequences of inconsistent solar power production, such as vessel swinging and ship rolling (Wen, Lan et al., 2016; Wang et al., 2017). For instance, the 12 GT e-boat system uses PV and batteries as its electricity source, consuming 40 kWh/h of electricity for LED lights with a peak load of 4.19 kW. Meanwhile, the Charging Station system uses the ship's load, charging 88 kWh/day with a reach their highest demand of 26.89 kW (Shibghotulloh, Maarif et al. 2021). However, figure 14 provides an illustration of an example of an image of an electric fishing boat configuration with solar PV and wind turbine.

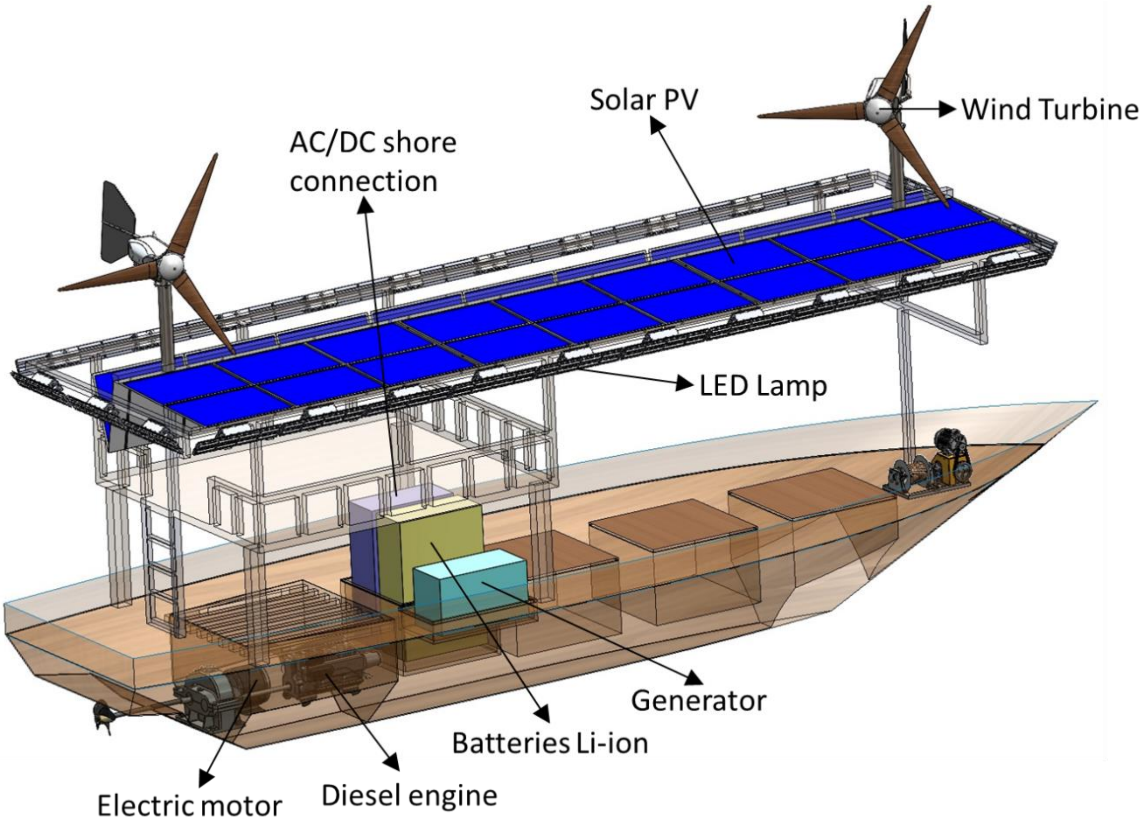

Figure 14. Electric fishing boat configuration with solar PV and wind turbine

7.3 Wind Turbine

The possibility of wind-assisted propulsion is opened up by the conversion of wind kinetic energy into thrust. When navigating, the wind force may be separated into two categories based on the direction of the ship: sideways force and forward force. The sideward force must be reduced while optimizing the forward force necessary to support the ship's propulsion since it produces lateral deflection of the vessel. Utilizing wind energy, wind turbines, wing sails, kite tractors, and Flettner rotors are examples of wind propulsion equipment (Nuchturee, Li et al., 2020).

Wing size and aspect ratio have an impact on a thorough analysis of the energy-effective wing sail design (Viola, Sacher et al., 2015). When a vessel sails against the wind at a low speed, the wing sail's maximum effectiveness is likewise attained. In particular, when the vessel sails at a real wind angle of 90°, the maximum force of the wing sail may be decreased by as much as 10%. The Flettner rotor is an alternate wind-powered propulsion system that uses the Magnus effect. The air around the revolving rotor accelerates when the wind blows through it, but it slows down from the opposite direction when it exits. A thrust energy perpendicular to the direction of the wind is produced by this pressure differential (Traut, Gilbert et al., 2014). The wind's direction affects cylinder efficiency in addition to wind speed. Simulation results also show that Flettner rotors offer the potential for fuel savings of up to 20% (Talluri, Nalianda et al., 2018). On the contrary, the principle of kite traction is relatively simple, but most of the propulsion seems to be achievable by flying kites attached to the front of the ship. Thus, they occupy almost no deck space and have been proven to be applicable to all types of vessels. The potential fuel savings from the proposed kite tractors can exceed 50% (Leloup, Roncin et al., 2016). Another feasibility study involves the installation of wind turbines on ships (Talluri, Nalianda et al., 2016). In contrast, solar panels outperform wind turbines in the design of a hybrid energy harvester for fishing boats, generating 815-817 Wh of energy daily compared to 43-62 Wh from wind turbines. However, with the wind turbine positioned no higher than 1.7 m for stability, this combined system may cover the energy requirements of a boat refrigerator (Banjarnahor et al., 2017). Figure 14 shows an integrated electric boat that runs on a windmill, solar PV, battery, and generator.

A summary of the preceding portion of the literature study is given in table 8, which contrasts the benefits and drawbacks of three practical renewable energy sources that might be used in electric or hybrid vessels for fishing.

Table 8. Benefits and Drawbacks of Suitable Power Generation Technologies for Electric or Hybrid Fishing Vessels

Sumber Pembangkit	Benefits	Drawbacks	Ref.
Solar PV	• A sizable and consistent energy source might be generated via solar energy. • It's not too difficult to set up and maintain solar panels. • As solar panel technology has advanced, prices have gradually decreased. • Does not release greenhouse gas emissions and is environmentally benign. • Solar energy can be harnessed passively while sailing under the sun.	• Historically, installing solar panels has come with significant initial and operating expenditures. • The power output is limited by weather conditions and the ship's location. • Requires a substantial amount of space for panel installation, which may be limited on ships. • Less efficient in regions with frequent cloud cover or overcast conditions. • In comparison to hydrogen fuel cells and wind power,	• (Zhu et al. 2017, Sunaryo, Syahrihaddin et al. 2019, Dolatabadi, Ölçer et al. 2023)

	• It does not require additional fuel and has low operational costs. • Reduces dependence on fossil fuels and lowers carbon emissions.	solar energy productivity is lower. • High initial costs for purchasing and installing solar panels.	
Wind Turbine	• On certain paths and under certain circumstances, wind energy can offer partial propulsion. • Options for utilizing wind energy have been shown to be very successful in several situations. • Environmentally friendly and can generate energy while the ship is sailing. • Can be used as an additional power source when wind speeds are sufficient. • Does not require additional fuel during operation. • Reduces carbon emissions and fuel costs.	• In order to accommodate wind energy, more propulsion systems are required. • Location and meteorological factors affect how well wind turbines generate electricity. • Requires a considerable amount of space for effective wind turbine installation. • Relies on variable wind speeds, making it less consistent. • Wind turbine maintenance and upkeep can be expensive. • Limited to regions with sufficiently strong winds to produce significant power.	• (Talluri et al. 2016, Talluri, Nalianda et al. 2018, Dolatabadi, Ölçer et al. 2023)
Fuel Cell	• High efficiency electricity generation is possible with hydrogen fuel cells. • Fuel cells powered by hydrogen have the potential to drastically cut emissions when in use. • High efficiency in electricity generation with low emissions. • Does not produce greenhouse gas emissions during operation. • Capable of producing electricity with consistent performance. • Can be used as a primary or backup power source.	• There are difficulties with using hydrogen in engines with gasoline or diesel. • Infrastructure and additional development are needed for hydrogen fuel cell systems. • Requires storage and use of fuel (typically hydrogen), which requires additional space. • High initial costs for fuel cell systems and related infrastructure. • Dependence on fuel supply, which may not always be available in specific locations. • Requires regular maintenance and proper fuel management.	• (Bicer & Dincer 2018, Ma, Lin et al. 2021, Dolatabadi, Ölçer et al. 2023)

8 Types of Batteries Suitable for Use on Fishing Vessels

Batteries are devices that use electrochemical processes to directly transform chemical energy into electrical power (Wong, Ramachandaramurthy et al. 2019). In research and the development of energy storage systems for maritime transportation, batteries are frequently employed (Damian, Wong et al. 2022). Because they can be connected to the main diesel propulsion system thanks to batteries, they operate more efficiently because the engine may be turned off when there is little or no load (Zhang and JIA 2019). To accomplish optimization objectives, propulsion power modification and energy storage are employed (Kanellos, 2014). Meanwhile, the conflict between fuel consumption and greenhouse gas emissions is highly sensitive to the number of battery modules and the lowest battery charging state on electric ships (Jianyun et al., 2019). Although there are currently very few ships that use battery propulsion, this is anticipated to change in the upcoming years (Koumentakos, 2019).

As lead-acid batteries have a track record of reliability and affordability, they are frequently utilized in ship battery storage systems (Lashway, Elsayed et al. 2016). Nevertheless, there are drawbacks to lead-acid batteries, including fewer cycle life and the requirement for more robust explosion prevention methods (Damian, Wong et al. 2022). Batteries having a greater density of energy than lead-acid batteries are in high demand due to the growing need for power and energy, particularly from hybrid automobiles. The two most well-known high-energy-density battery types are Li-ion and NaS. But because NaS functions at high temperatures (between 300°C and 350°C) and pure sodium interacts explosively with air, there are particular safety concerns (Damian, Wong et al. 2022). However, a number of studies have determined that lithium-ion (Li-ion) batteries are the most promising option because of their extremely long cycle life, comparatively high power as well as energy density, and comparison to other battery (Nuchturee, Li et al. 2020). Li-ion batteries present a financial problem due to the need for specialized electrical devices for battery maintenance and to guard against overcharging and overdischarging. Consequently, of the three battery technologies, Li-ion batteries are advised for combination propulsion systems in ships (Lashway, Elsayed et al. 2016). While alternative energy storage media are still expensive or unsuitable for marine applications, sodium-nickel chloride (Na–NiCl2) battery are a viable option when evaluating return on initial investment. Table 9 compares the technical features of several energy storage methods.

9 Parameters for Modeling Electric Propulsion Systems for Fishing Vessels

Characterizing fishing vessels is a fundamental step in determining the appropriate modeling for electric propulsion systems, whether for hybrid energy systems with serial, parallel, or serial-parallel configurations. However, parameters in the modeling of electric propulsion systems, such as load profiles, fuel consumption, motor torque, motor power, motor speed, carbon emissions, and so forth, are essential. Table 10 provides an overview of the testing parameters from recent research on electric propulsion systems for fishing vessels using simulation modeling and mathematical algorithms.

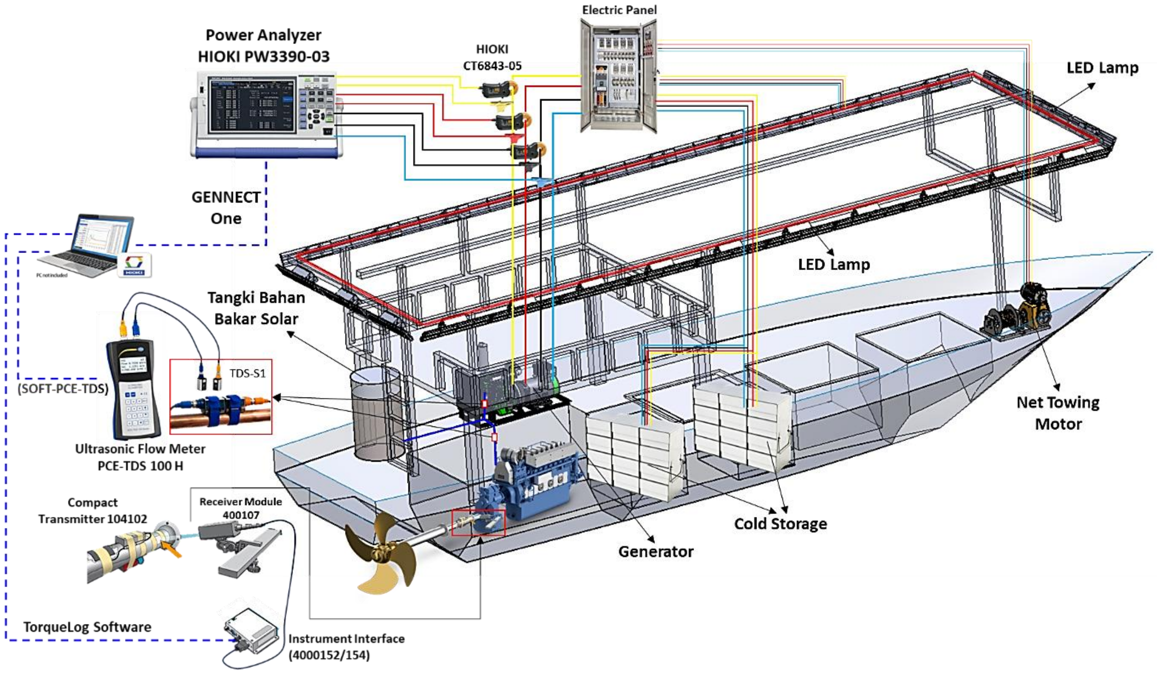

Figure 15. Arrangement of measuring equipment on fishing vessels

Table 9. Comparison of Technical Characteristics of Energy Storage Technologies (Nuchturee, Li et al. 2020)

Energy Storage Type	***Density of Energy*** **(Wh/kg)**	***Density*** **of Power (W/kg)**	**The capacity (MW)**	**Loop (<)**	**Effectiveness**	**Information**
(Pb–H2SO4) Lead acid battery	30 – 50	75 – 300	Up to 20	500 – 1,000	70 – 90%	• Advanced technological • Excellent dependability • Insufficient energy density • Intolerance to temperature • Brief cycle
(Ni–Cd) Nickel cadmium battery	50 – 75	150 – 300	Up to 40	2,000 – 2,500	60 – 65%	• Advanced technological • High reliability • Tolerance of extreme temperatures
(Na–S) Sodium sulfur battery	150 – 240	150 – 230	0.05 – 8	2,500	80 – 90%	• Elevated power and energy density • The ability to use pulse power • Requirements for high temperatures
(Na–NiCl2) Sodium nickel chloride battery	100 – 120	150 – 200	Up to 0.3	2,500+	85 – 90%	• Elevated voltage of the cell • Ability to generate pulses of electricity • High temperature requirements
Lithium-ion battery (Li-ion)	75 – 200	200 – 315	Up to 0.1	1,000 – 1,0000+	85 – 90%	• Elevated power density and energy • Elevated voltage of the cell • Elevated cycling • Lifespan depends on temperature
(VRB) Vanadium redox battery	10 – 30	165	0.03 – 3	12,000+	85 – 90%	• High cycling • Quantifiable energy potential • Insufficient power and energy density
(Zn–Br) Zinc bromine battery	30 – 50	45 – 100	0.05 – 2	2,000+	70 – 80%	• Flat stress profile • Quantifiable energy potential • Insufficient power and energy density

Figure 15, illustrates the arrangement of measuring instruments before the fishing vessel's electric propulsion system is created, including fuel consumption, power, torque, speed, and load profile. In the meanwhile, measurement instruments for sun radiation, wind speed, current and wave height, and other variables must be added if the research results in forecasting or prediction. If the ship is to be equipped with solar PV and windmill technologies, equipment for measuring solar radiation and wind speed must be placed.

The HIOKI PW3390-03 Power Analyzer is used in the context of measurements on ships to measure and analyze the electrical load profile of the ship. This includes measuring energy consumption, power quality, and other electrical parameters with a high degree of accuracy to ensure effective electrical system operation. In order to measure the alternating (AC) and direct (DC) electric current in the system and aid in performance evaluation and issue identification in electrical systems, the AC/DC CURRENT PROBE CT6843-05 is used in conjunction with a power analyzer. The Ultrasonic Flow Meter PCE-TDS 100 H is used to monitor diesel fuel consumption because it can measure liquid flow, including fuel, using a non-invasive ultrasonic approach. This method yields accurate data that can be utilized to improve fuel management. Fuel flow rate is measured via an ultrasonic device that connects to the pipe and includes the TDS-S1 sensor. In the meanwhile, shaft torque and RPM are measured by the Compact Transmitter 104102 and Receiver Module 400107 as part of a torque monitoring system, which is crucial for maximizing engine economy and performance. Data integration and overall process control are made possible by the Instrument Interface (4000152/154), which acts as a link between the transmitter and receiver and the ship's data collection or control system. These gadgets are all essential for energy management, operational effectiveness, and performance monitoring on ships. To measure something in real time, any measuring device may be linked to a laptop.

Table 10. Modeling Parameters of Electric Propulsion Systems on Fishing Vessels

Software	Proposed Method	Research Data Parameters	Ref.
MATLAB/Simulink	Modeling and simulation	- Propeller speed - Motor torque - Motor Power	(Manouchehrinia, Molloy et al. 2018)
EnergyPLAN	Simulation	- Operating time - Motor power - Fuel consumption	(Koričan, Frković et al. 2023a)
MATLAB/Simulink	Data collection in the field and simulation	- Ship speed (knots and Rpm) - Fuel consumption - Power (kW) - Carbon emissions	(Hwang, Kim et al. 2022)
Matlab/Simulink, GaBi LCA software	Simulation	- Operating power - Speed - Output power (kW) - Fuel consumption	(Kim, Jeon et al. 2022)
Mathematical model	Feasibility study	- Solar panel capacity - Battery capacity - Electric motor capacity	(Gamage, Wimalasooriya et al. 2021)
Mathematical model	Design and implementation	- Power consumption (kW) - Ship speed - Solar panel capacity - Battery capacity	(Sultoni, Ali et al. 2020)
-	Comparison and modeling	- Fuel consumption - Electric power consumption - Carbon emissions	(Bastos, Branco et al. 2021)

-	Conventional energy sources	- Motor power (kW) - Fuel consumption - Carbon emissions	(Koričan, Vladimir et al. 2023b)
Mathematical model	Fishing platform design	- Motor capacity - Battery capacity - Solar panel capacity - Electric power consumption	(Sunaryo, Syahrihaddin et al. 2019)

9.1 Load profile

The following is the basis for determining the load profile's parameters: At the start of torque and Speed data collection, the path from the port to the fishing region produces a continuous load profile. After arriving at the fishing area, the boat stops at each location to drop traps or go fishing before moving on to the next target. An interrupted profile of loads with negative torque at each stop is the outcome of this approach (Manouchehrinia, Molloy et al. 2018). The boat docks again once its fishing expedition is over. When the complete data, including torque and speed, is obtained, this step creates the subsequent load profile. Before docking, the ship finally circles the dock to empty the equipment, traps, and catch. At the completion of the velocity and torque data collection procedure, a reduced load profile is taken into consideration. In addition, operational parameters like output power affect the productivity of each part and the structure as a whole. As such, consideration of the loading circumstances is required. Reliable findings are obtained by evaluating efficiency in realistic circumstances by the introduction of genuine load profiles of operational boats into a simulation framework (Ghimire, Karimi et al. 2022). Still, there's a process called "load profile model creation" that usually comprises these five steps: As shown in figure 16, the steps include (i) preliminary processing, (ii) data filtration, (iii) load pattern recognition, (iv) categorization, and (v) scaling coefficient evaluation.

In the first stage, customers' power usage data is gathered with the intention of removing data gathering components that can negatively affect the model's performance and other procedures (Giannuzzo, Minuto et al. 2024). There are essentially two sections to this phase. The goal of the first phase, known as data characterisation, is to increase comprehension of the data set by using suitable visualization methods; the second phase, known as data preparation, is to rid the dataset of outliers, missing values, and inconsistent data.

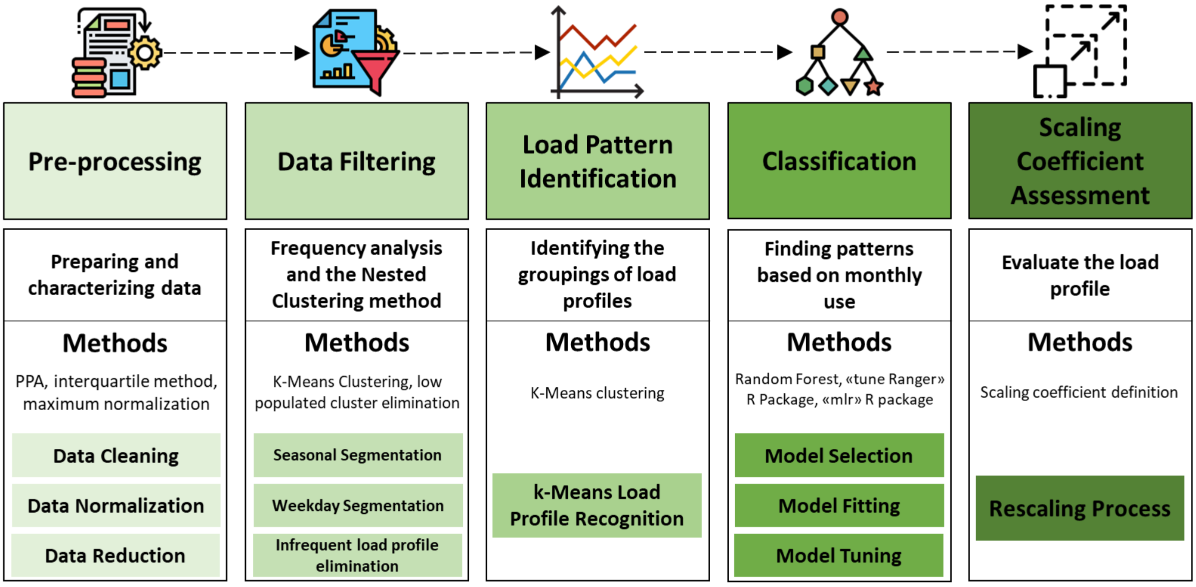

Figure 16. Structure of the phase of model construction

- **Pre-processing**

  Data pre-processing, which involves preparing and transforming data into a format appropriate for mining operations, is a crucial stage in any deployment of data-driven models as it is required to guarantee correct findings and trustworthy analysis. Reducing the amount of data, identifying correlations between it, normalizing it, eliminating outliers, and extracting characteristics are the objectives of data pre-processing. It uses a number of methods, including reduction, transformation, and cleansing of data (Giannuzzo, Minuto et al. 2024). As seen in figure 17, the procedure may be broken down into two primary tasks: data characterisation and data processing. Given the challenge of thoroughly visualizing multidimensional data, the data characterisation stage is necessary to have a basic knowledge of the data. The stage of data preparation is crucial because it makes it possible to gather accurate, suitable, and well-structured data (Giannuzzo, Minuto et al. 2024).

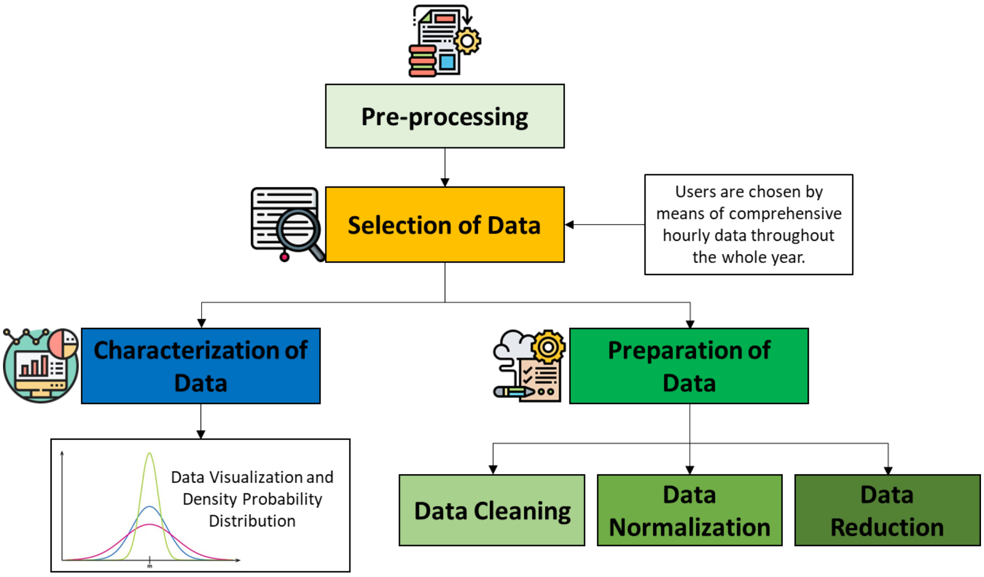

Figure 17. Workflow for preprocessing

- **Data Filtering**

  This phase uses a particular procedure to remove any components from the initial data processing that can negatively impact the efficiency of the data-driven and predictive machine learning algorithms that have been installed in the future (Giannuzzo, Minuto et al. 2024). There are two stages to the procedure, which is carried out to find any unusual daily load profiles in terms of severity and form. Using a predetermined threshold value, the daily profiles for months with low power use are removed for every user in the initial data processing in the first phase (Giannuzzo, Minuto et al. 2024). After that, any irregular daily load profiles were found using a multilevel strategy that started with pre-processing the data segmentation by period before being analyzed by day of the week. K-Mean clustering was then run on each discovered subsection, as shown in Figure 18.

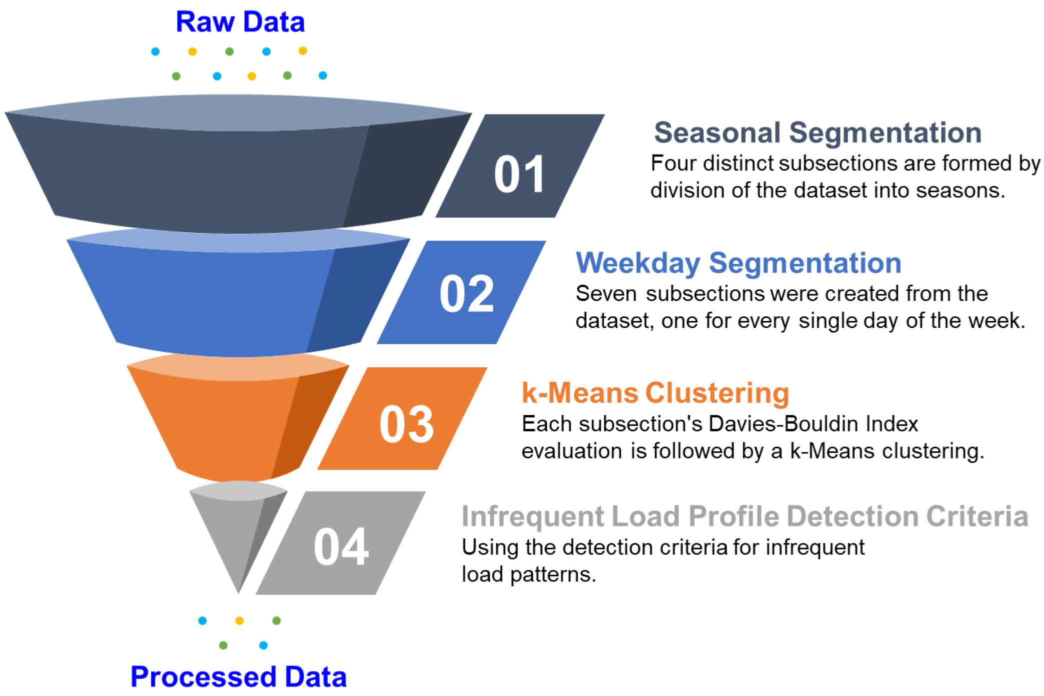

Figure 18. Daily load profile identification process

- **Load Pattern Recognition**

  On the basis of monthly power use, k-Means clustering was performed following pre-processing and data filtering. Once more, the Davies-Bouldin Index (DBI) was used to determine the ideal number of clusters (Giannuzzo, Minuto et al. 2024). Clusters with a limited number of profiles or customers are eliminated using a logic similar to that used in the data filtering process. In this instance, 10% of the overall number of profiles and users is the threshold value utilized to detect clusters containing low-population clusters (Giannuzzo, Minuto et al. 2024). Following the previously mentioned identification of typical load patterns, additional checks were made to exclude clusters that had few profiles and users (Giannuzzo, Minuto et al. 2024). This process was carried out using the same method that was employed to eliminate daily load profiles throughout the data filtering stage.

- **Classification**

  The primary goal of the method of classification is to develop a model that can recognize the monthly patterns of electrical load throughout the year based on monthly consumption numbers. To create a categorization model, you need to take the following actions: Choosing a classification model, defining training variables, defining testing and training data sets, preparing the model, and fine-tuning the model are the first five steps.

- **Evaluation of scaling coefficients**

  The primary stages in determining the scaling coefficients needed to convert the normalized load profile—which is established at the load recognition of patterns stage and allocated to every user for every month throughout the classification procedure—into the actual load profile are described in this section. This phase is the last in the model generation stage and is closely related to the case studies implementation stage.

- **Validation**

  A set of daily and monthly observed consumption data (Giannuzzo, Minuto et al. 2024) and a reconstruction of the load profile utilizing the approach provided and a comparison with the actual load profile were used to validate the study findings. A detailed analysis of the measures frequently used to compare synthetic or anticipated load profiles with real load profiles is given by Köhler, Rongstock, et al. (2022). Certain measures, such as the minimum and maximum numbers, median, standard deviation, and duration curve error, are focused on statistical features of actual and simulation load profiles in (Köhler, Rongstock et al., 2022). These metrics are used to evaluate similarity. Furthermore, complexity-based measures are also proposed, including fractal dimension and number of peaks.

9.2 Operating Time

Determining the operating duration is essential for evaluating if battery charging is feasible and for examining the distribution of energy consumption over the course of an hour. It is acquired by examining the operational profile of the ship in various seasons. The patterns of arrival and departure of fishing vessels are used to predict the yearly electricity consumption at the fishing port. Meanwhile, power charging on fishing vessels occurs during the day, from 10:00 AM until 2:00 PM (Koričan, Frković et al., 2023a). In the meanwhile, two decisions are made in the context with commercial fishing depending on operating time: tactical and operational decisions are crucial to guaranteeing the effectiveness and success of fishing operations (Granado, Hernando et al. 2021). Planning at the tactical level involves choosing landing ports, fishing spots, and departure and arrival times. These decisions are made with medium-term efficiency in mind, taking into account variables like vessel capacity, catch volume, and trip duration. Operationally, the goal is to find the best routes that respond quickly to changing weather conditions and require flexibility. This two-phase method offers a thorough framework for enhancing fishing operations, guaranteeing efficient and long-lasting marine performance.

9.3 Power, Speed and Torque

The total power needs for every fishing excursion include the power required for fundamental fishing functions such as finding your way to fishing spots, looking for fish, projecting lighting, extracting fish, and so on (Koričan, Frković et al. 2023a). In the meanwhile, a cubic function per time describes the link between ship speed and fuel usage (Psaraftis and Kontovas, 2013, Norlund and Gribkovskaia, 2017). Due to increased wave and wind resistance, a ship will use more fuel when traveling at a steady pace in inclement weather than when sailing in calm conditions (Lindstad, Asbjørnslett et al. 2013). According to Norlund and Gribkovskaia's (2017) research, engine power output is presumed to be constant in both calm and turbulent waters. This is because it will take the ship longer to travel the same distance in severe weather due to the higher resistance. Longer sailing times will result in higher fuel consumption over a given distance, but overall fuel demand per hour stays the same. The consumption of fuel $FC_d^w(v)$ as a function of intended sailing speed v on calm waters, whereas the equation 1 may be used to determine additional details for lengthy trips and w wave height:

$$FC_d^w\,(v) = \frac{d}{v - \Delta v_w}\, FC_{v_0} \left(\frac{v}{v_0}\right)^3 \qquad \text{(Eq. 1)}$$

where FC_{v_0} is the gasoline expenditure at the planned speed v_0 and Δv_w is the velocity loss caused by wave height w. It is evident from the preceding equation that the pace at which fuel is used and the weather have an impact on each other. In addition, estimates of fuel usage need to account for the possibility of weather variations during fishing (Norlund and Gribkovskaia, 2017).

In the meanwhile, power and torque variations occur throughout a single fishing excursion. For instance, figure 19 shows that the journey process in fishing contains two constant loads and two dynamic loads. The vessel's propeller engine, generator, net pulling motor, and ship weight are examples of fixed loads on a vessel. Dynamic loads, on the other hand, consist of the ship's fuel tanks, clean water consumption tanks, fish storage hulls, and dry-wet net circumstances upon landing. The ship carries nets in dry weather as it leaves land for the sea. The supply of fuel and potable water is still fully available, though. The cold storage and fish storage hull are still empty in the interim. The ship's power, torque, and speed will be affected by this. Moreover, the gasoline and water levels were down and the fish nets were still moist when the ship finished its fishing expedition and headed back to shore. In the meanwhile, fish storage hulls and cold storage conditions are filled. Measuring throughout the fishing process in real time is therefore necessary to demonstrate variations in power, torque, and speed. Except for sea testing, power shaft torque sensors are still seldom ever utilized on fishing vessels. However, there has been a noticeable increase in interest in engine power assessment recently. The progression of energy efficiency and emissions laws toward increasingly demanding demands from the fishing sector was the driving force behind this. According to Kowalak, Borkowski et al. (2020), torque measurements on board a ship are done to learn more about engine loads than shaft stress conditions. In actuality, torque meters utilized aboard ships obtain torque data from the power transmission shaft; thus, the drive shaft functions as a component of the measuring sensor.

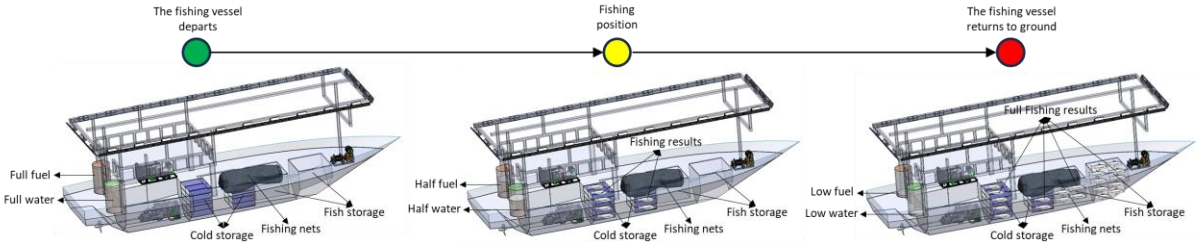

Figure 19. Fishing Vessel Operational Phase: Preparation, Catching, and Catch Results

9.4 Fuel Consumption

When sailing, particularly over greater distances, fishing vessels use the most fuel. As predicted, the relationship between gasoline usage and CO_2 emissions is precisely proportional. Tracking working hours is another feature of the monitoring system. Variations in working hours and fuel usage can be identified by examining the fishing cycles across various time periods (Koričan, Frković et al. 2023a). to gauge the flow velocity without endangering the fishing boat's fuel line system. Furthermore, to compare the flow rates of two distinct vessels with source and output lines recorded concurrently in order to verify the real fuel consumption during combustion (Hwang, Kim et al. 2022). In the meanwhile, each fishing vessel's operational and sailing patterns determine its fuel consumption ratio. This is dependent upon the features of the operations carried out by fishing vessels and notable variations in working hours. The amount of fuel consumed varies greatly based on the kind of engine that is utilized to power a genset engine when sailing or as the primary power source for fishing (Kim, Jeon et al. 2022).

Real-time models of diesel generators, which burn fuel to generate electricity, have been set up to correlate fuel consumption levels with output power. Given that the hybrid ship has X diesel engines, the consumption of fuel of each engine throughout the interval [0, T] may be written as Equation 2. (Gao, Wang et al. 2018):

$$C_{Fuel} = \sum_{k=0}^{T}\sum_{i=1}^{X}\big(A_i(n_i(k)P_i^E(k))\big)^2 + (B_i n_i(k) P_i^E\,(k)), \Delta t \qquad \text{(Eq. 2)}$$

Where $P_i^E(k)$ is the generated power of the ith diesel motor at time k, and T is the total amount of period cycles. The engine's fuel consumption curve yields the constants A_i and B_i, while Δt represents the constant sampling interval. The operational circumstances of the ith diesel engine are indicated by n_i, where $n_i = 0$ and $n_i = 1$ show that the engine is off and running, respectively. In the study, $B_i = 2.5$ and $A_i = 2.1 \times 10^{-4}$. Power, which is determined by the torque and current throughput $P_m = \frac{nT_m}{9550}$, where T_m is the torque and n is the motor speed, is correlated with engine fuel consumption. Normally, the ship's engine runs at a steady speed.

10 Future Progress of Fishing Vessels

In this section, the current state of research that has been or is being conducted is described using keywords such as fishing vessels and similar ones that have similarities, such as tourist ships, passenger ships, and riverboats. This aspect plays a crucial role in identifying and understanding relevant research topics. Thus, it is expected to help identify existing knowledge gaps and potential new contributions to the field. Table 11 summarizes the most recent developments in electric propulsion systems for fishing and similar vessels. In recent years, power generation systems in fishing boats have been constantly improving, and academics throughout the world have developed models to improve system design in novel ways. In recent years, the electrical systems on fishing vessels have continued to evolve and many researchers around the world have proposed models to improve the configuration of these systems in various innovative ways that already use artificial intelligence (AI) technology.

In some of the presented research, the primary focus has been on the development of environmentally friendly ship propulsion technology. Several studies, such as those conducted by Beatrice et al. (2022), Capasso et al. (2019), and Padolecchia, Utzeri et al. (2023), have emphasized the evaluation and optimization of hybrid propulsion architecture for ships. These papers have used simulation models and optimization techniques to achieve goals such as extending battery life and reducing exhaust emissions. This approach provides valuable insights into energy use and energy management strategies in recreational and oceanographic vessels.

On the other hand, research conducted by Gamage et al. (2021), Hung et al. (2022), and Monouchehrinia et al. (2018) has placed greater emphasis on the application of solar panel technology and electric motors in ships. This indicates that the use of solar panels and electric motors can result in significant fuel savings and carbon emission reductions. This represents a positive step towards reducing the environmental impact of ships in water bodies. Research by Hwang et al. (2022) also highlights the importance of reducing air pollutant emissions from older fishing vessels. In the interim, the study examines the use of an electric propulsion system with a hybrid engine to improve fuel economy and lower emissions. This response is in line with increasingly stringent ship emissions regulations. However, some research also acknowledges the weaknesses and challenges of adopting environmentally friendly propulsion technology. For instance, Korican et al. (2023b) highlight the importance of accurate input data for effective simulation and optimization. Similarly, Kim et al. (2022) shows that optimal control in hybrid systems can play a crucial role in emissions reduction, but it also requires precise tuning.

Furthermore, a number of studies, such those by Barelli et al. (2018) and Korican et al. (2022b), highlight how crucial precise fuel consumption monitoring and assessment are. It is noted that fuel monitoring devices can be effective tools for improving energy efficiency in ships. In an economic context, some studies, such as those by Yüksel, Göksu et al. (2023) and Bastos et al. (2021), discuss the economic implications of using environmentally friendly propulsion technology. They propose models that can aid in decision-making regarding investments in this technology.

Meanwhile, various studies have addressed the design of electrical systems for ships. However, there remains a research gap concerning the creation of electrical load profiles for fishing vessels. Existing research, such as that by Swider and Pedersen (2019) and Mehrzadi et al. (2020), focuses on the analysis of operational profiles and general forecasting of electrical loads on maritime vessels but does not specifically address fishing vessels. Regarding the integration of AI into Electrical Load Profiles, while Bakar et al. (2022) and Mehrzadi et al. (2020) employ AI for forecasting and analyzing electrical loads, there is still a scarcity of research explicitly demonstrating how AI can be applied to model electrical load profiles based on the specific operational patterns of fishing vessels.

Subsequently, a further research gap has been identified regarding the optimization of energy storage systems integrated with renewable energy on electric fishing vessels. Studies by Barelli et al. (2018) and Kim et al. (2022) have investigated the optimization of energy storage systems on tourist and fishing vessels in general, but they do not specifically address the integration of renewable energy with the operational patterns of fishing vessels. Moreover, in terms of applying AI to optimize renewable energy, there is a notable lack of studies employing AI technology to specifically optimize energy storage systems integrated with renewable energy on fishing vessels, despite general research in the field like that by Koričan et al. (2023b).

Overall, this research demonstrates that the development of environmentally friendly ship propulsion technology is an important and relevant topic in efforts to reduce the environmental impact of ships in water bodies. However, challenges such as accurate data, proper tuning, and economic implications need to be seriously considered in implementation. Meanwhile, the next research gaps in the development of environmentally friendly ship propulsion technology include the integration of different propulsion technologies, ship operational optimization, economic and financial aspects, the development of more advanced fuel monitoring devices, battery capacity improvement, regulatory assessment and government support, region-based case studies, and efforts to increase awareness and education about the benefits of this technology. Subsequent investigations in this domain will contribute to the development of more effective technologies, mitigate the ecological consequences of the maritime sector, and bolster the industry's sustainability. It may be interesting to review future research developments in the use of hybrid and electric drive systems in fishing vessels. Based on existing references, Trivyza et al. (2022) stated that in order to improve the sustainability of ship energy systems, the current review study examines published research that addresses decision support systems. figure 20 explains several potential trends and developments that may become the focus of future research, including:

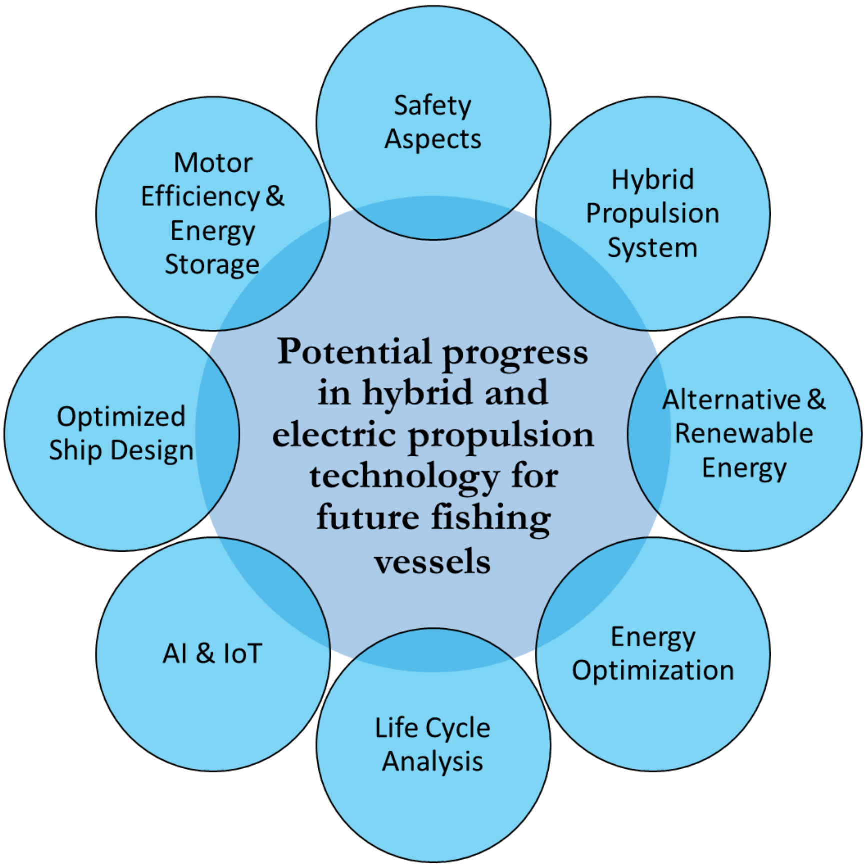

Figure 20. Potential progress in hybrid and electric propulsion technology for future fishing vessels

- **Hybrid Propulsion Systems:** Several references, such as the research by Ammar and Seddiek (2023) and Bastos, Branco, and Arouca (2021), indicate a growing interest in hybrid propulsion systems for fishing vessels. Future research in this area may involve the development of more efficient and environmentally friendly hybrid systems.
- **Alternative Energy Sources:** Research on the use of alternative energy sources, such as hydrogen fuel cells, solar power, and batteries, is becoming increasingly relevant in the context of fishing vessels. References like Dolatabadi, Ölçer, and Vakili (2023) and Zhang and JIA (2019) show an interest in the development of this technology.
- **Energy Optimization:** References like Capasso et al. (2022) and He et al. (2021) have discussed energy usage optimization on ships. Future research may focus on the development of smarter algorithms and control systems to optimize energy usage under various operational conditions.
- **Use of Renewable Energies:** Given the difficulties posed by climate change, more study into how to incorporate renewable energy sources, including wind and solar energy, into boats for fishing propulsion systems, would be worthwhile. A few references have discussed this subject, including Koričan, Vladimir, Haramina, et al. (2023b).
- **Life Cycle Analysis (LCA):** Ling-Chin and Roskilly (2016) have conducted a life cycle analysis of ship propulsion systems. Future research can investigate the environmental and economic impacts of implementing electric and hybrid propulsion systems on fishing vessels. Jeong et al. (2020) stated that, the environmental impacts of a new battery-powered ship and a conventional diesel-mechanical powered ship were assessed using the LCA technique, which showed that battery usage is not always the best option.
- **Advanced Technology Adoption:** Research can investigate the use of cutting-edge technologies like artificial intelligence (AI) and the Internet of Things (IoT) to improve data collection and analysis in order to stay abreast of recent technological developments. A better knowledge of energy usage and system performance may be obtained by doing more thorough study into collecting and analyzing of operational information from fishing vessels.
- **Ship Design:** Research can also be focused on ship designs optimized for electric and hybrid propulsion systems. This includes hull designs that reduce resistance and improve efficiency.
- **Motor Efficiency:** Some references, such as Yang et al. (2020) and Yan et al. (2020), discuss motor efficiency management and energy storage systems. Future research may involve the development of more efficient electric motors.
- **Safety Aspects:** In the context of fishing vessels, safety aspects are also crucial. Future research can consider the development of safer systems, especially in the application of high-tech technologies. The efficiency and sustainability of ship propulsion systems.

11 Conclusion

The implementation of electric and hybrid propulsion systems on fishing vessels has significant potential for reducing greenhouse gas emissions and enhancing operational efficiency. To help the marine and fishing industries meet their carbon neutrality targets, there has been an increase in interest in the use of this technology in recent years. However, the most recent research gap in this context is the need to integrate cutting-edge technologies with more in-depth research to combine electric propulsion systems with technologies, such as the Internet of Things and artificial intelligence. The use of these technologies can improve the operational efficiency and safety of fishing vessels while enabling better monitoring and control in dynamic sea conditions. By addressing this gap, future research can provide more comprehensive insight into how state-of-the-art technology can be applied to holistically optimize fishing vessel propulsion systems, creating more efficient and sustainable operations in the fishing industry. This can contribute to achieving sustainability goals in this sector and reducing the environmental impact of fishing activities.

Research on electricity-based fishing vessel propulsion technologies is still in its infancy. A number of scholarly works have examined how ships could operate more efficiently by reducing air pollution and using electric and hybrid propulsion systems. Therefore, the most urgent research gap that should be addressed at this time is that creating fishing vessel activity patterns is the most important aspect of designing an electric propulsion system. This is the primary factor that determines an electric vessel's performance, together with the power storage system and the fishing vessel's electrical load profile. However, the battery storage process on electric ships is still rarely discussed in terms of the effect of heat transfer on the battery compartment. The energy system on an electric fishing vessel should be projected based on the size of the vessel.

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Table 11. Development of electric propulsion systems on similar fishing vessels

Years	Type of Vessels	Fish Caught	Operational Water Area	Propulsion System		Power Generation Technology			Optimization System				Ref.
				Hybrid	Electric	Generator	Battery	RE	Method	Software	AI	Algorithm	
2017	Fishing Boat	lobster	Atlantic coast	√	-	√	√	-	Experiments & Simulations	MATLAB/ Simulink	-	-	(Manouchehrinia, Molloy et al. 2018)
2018	Ship	-	-	√	-	√	√	-	Simulations	MATLAB/ Simulink	√	Improved NSGA-II	(Gao, Wang et al. 2018)
2018	Tourist Boat	-	-	√	-	√	√	-	Simulations	MATLAB/ Simulink	-	-	(Barelli, Bidini et al. 2018)
2019	Ship	-	-	-	-	√	-	-	Simulations	-	-	Pemodelan statistik	(Swider and Pedersen 2019)
2019	Ship	-	-	-	√	-	√	-	Simulations	-	√	-	(Bellone, Lundh et al. 2019)
2019	Midsize Boats	-	-	√	-	√	√	-	Experiments	-	-	-	(Capasso, Notti et al. 2019)
2020	Ship	-	-	-	-	-	-	-	Simulations	MATLAB dan Python	√	RNN	(Mehrzadi, Terriche et al. 2020)
2021	Ship	-	-	√	-	√	√	√	Simulations	-	√	Load Prediction Algorithm	(Zhang, Shan et al. 2021)
2021	Ship	-	-	√	-	√	√	-	Simulations	-	-	-	(Bui, Dinh et al. 2021)
2021	ship	-	-	-	√	√	√	√	Simulations	-	√	ANFIS	(Gaber, El-Banna et al. 2021)
2021	Fishing vessel	cod and swordfish	deep sea fishing	√	-	√	√	-	-	-	-	-	(Bastos, Branco et al. 2021)
2022	Fishing vessel	-	-	√	-	√	√	-	Experiments & Simulations	MATLAB Simulink	-	-	(Hwang, Kim et al. 2022)

2022	Ship	-	-	-	√	-	√	-	Simulations	-	√	Neural networks	(Kim, Lee et al. 2022)
2022	Ship	-	-	-	-	√	√	√	Simulations	-	√	Forcasting	(Bakar, Bazmohammadi et al. 2022)
2022	Fishing vessel	-	-	√	-	√	√	-	Simulations	MATLAB Simulink & GaBi LCA	-	-	(Kim, Jeon et al. 2022)
2023	Ship	-	-	√	-	√	√	-	Simulations	MATLAB/ Simulink	√	Multistep load forecasting	(Xie, Tan et al. 2023)
2023	Ship	-	-	-	-	-	-	-	Simulations	TensorFlow, PyTorch	√	MBO-SE-CNN-LSTM	(Kim and Oh 2023)
2023	Fishing vessel	-	-	√	-	√	√	√	Simulations	EnergyPLAN	-	-	(Koričan, Frković et al. 2023a)
2023	Fishing vessel	-	-	-	-	-	-	-	Simulations	-	√	-	(Cheng, Zhang et al. 2023)
2024	Ship	-	-	-	√	-	√	√	Simulations	Maxsurf, Savitsky & Wyman	-	ARIMA	(Yüksel, Göksu et al. 2024)

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