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Technological Alternatives for Electric Propulsion Systems in the Waterway Sector

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Abstract: The trend in the development of maritime and river propulsion systems is to make a transition from hydrocarbon to more environmentally friendly solutions. This contributes positively to the solution of the problems identified by the International Maritime Organization (IMO) regarding the high emissions of polluting gases emitted by maritime transportation. Currently, there is a wide variety of systems available due to the development of mobility technologies focused on decarbonization. This paper presents an analysis of technological alternatives for boats with electromobility applications and propulsion systems in the waterway field. First, a description of the operation of boats with electric motors, the different energy sources, and the alternative propulsion options is presented. Then, the electromobility technologies are characterized, analyzing the different configurations between the power source and the propulsion system. The results show a comparative table of technologies and their advantages and disadvantages. In addition, the most environmentally friendly technologies present significant challenges for large-scale implementation due to their recent development. In the short term, hybrid systems technologies present advantages over the others, as current systems are available, with the addition of equipment with higher efficiency and lower environmental impact.

Keywords: electric boat; propulsion system; river electromobility; renewable energy; fuel cells; waterway electromobility

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1. Introduction

Maritime and inland waterway transport carries approximately 90% of the goods in the world [1]. However, the use of fossil fuel propulsion systems brings about environmental issues that must be addressed [2]. They also bring local water and air pollution [3], dependence on nonrenewable resources [4], risk of spills [5], and create a barrier to the energy transition [6].

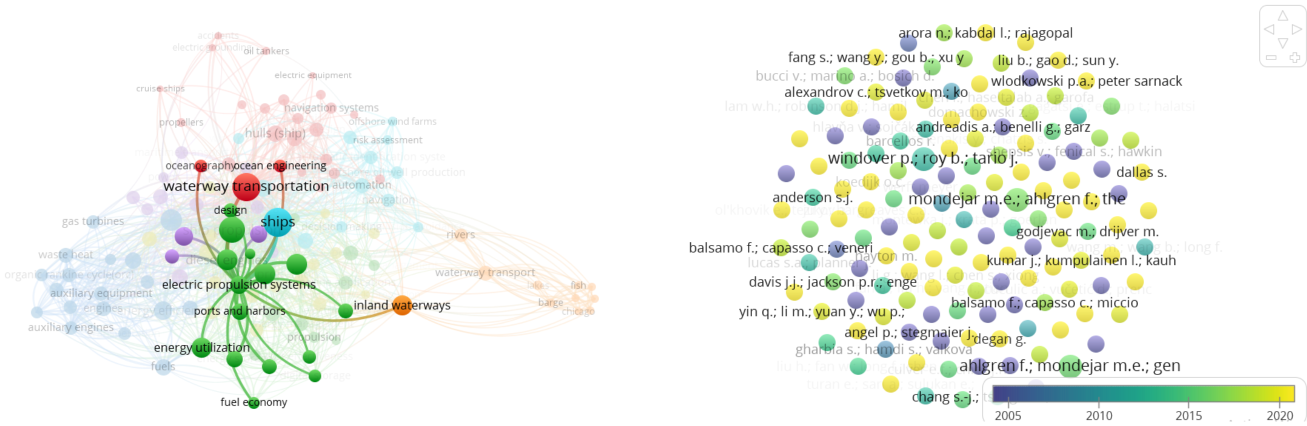
Sustainable transport can face environmental and social challenges, and electromobility is a promising alternative [7,8]. New technologies include boats with electric motors, energy sources, and storage systems [9]. The implementation of these systems leads to a significant reduction in greenhouse gas emissions and air pollution compared to traditional boats powered by internal combustion engines [10].

However, river electromobility presents some issues such as charging infrastructure, limited autonomy of the vessel, initial cost, availability of technology battery life cycle, impact and availability on electricity generation, interoperability, and industry adaptation [11–14]. In addition, migration from conventional systems to electric technologies may involve considerable investments and the need to train staff in new practices and technologies. Concern has also been raised about the proper management of waste batteries, ensuring their recycling and minimizing their environmental impact [15].

Based on the information presented above, the following question arises. What are the advantages and disadvantages of different technological alternatives in river electromobility systems? For this, it is necessary to have a basis for the different technological alternatives available in terms of electric mobility in boats. This is a question that motivated the authors to write this paper, which focuses mainly on presenting an in-depth analysis of technological alternatives for boats with electromobility applications and propulsion systems in the waterway field. The propulsion alternatives are described, ranging from propulsion systems with exclusive use of batteries, to the use of electric motors and different sources of energy in operation [16,17], to hybrids with fossil-fueled generation [9,18,19], through renewable energies (REs) [20,21], and fuel cells (FCs) [22,23]. Electromobility technologies are then characterized by analyzing the different configurations between the power source (batteries, REs, hydrogen, and hydro carbide) and the propulsion system (electric motors and internal combustion engines). This results in a comparative table of technologies showing the advantages and disadvantages.

The search for the literature is a fundamental part of the establishment of research on this topic. In particular, electric mobility in navigable waterways is an interesting research topic, with relevant documents published in high-impact journals. These documents can be found in Scopus, ScienceDirect, and IEEE. The topic has been approached from different perspectives, oriented towards mobility with conventional energy sources, improving the performance of different vessels, electric and hybrid propulsion systems, etc. Hence, Figure 1a presents the co-occurrence of the different keywords that cover the topic. Furthermore, Figure 1b shows the relationship between the different authors who cover these topics in the world.

Figure 1 shows that there is a large amount of research related to transportation on navigable waterways and vessels. However, for electric propulsion systems, the amount of research related to the topic is reduced, which is why this research becomes important. There is a slight connection with navigable inland waterways and there is no connection with issues related to the reduction in emissions due to the use of fossil fuels, which represents a great motivation for the development of this article. Figure 1b shows that there is a large number of authors working on the topic around the world. However, some research networks are not fully articulated.



(**a**) (**b**)

Figure 1. Literature search. (**a**) Co-occurrence of keywords. (**b**) Predominant authors.

The review of international experiences and best practices has identified lessons learned and successful strategies for implementing river electromobility in different contexts. Countries such as Norway [24], The Netherlands [25] , Brazil [26] Canada [27], USA [28], Baltic Sea [8], and China [29] have made progress in electrifying their river transport, and their experiences offer valuable examples of how to address specific challenges. International collaboration and knowledge sharing can help advance electromobility globally.

2. Technological Alternative for Boats with Electromobility

Suitable alternatives for commercial boats with electromobility have been built. For example, EELEX 8000 is a boat that was designed and manufactured in Sweden by Xshore [25]. It comprises 100% electric propulsion system and a hull built with low-environmental-impact materials. EELEX 8000 represents the beginning of a more sustainable maritime tradition by harnessing electric power from a battery of 126 kWh, in addition to a 170 kW electric motor. It eliminates toxic fumes and annoying noise and produces a minimal carbon footprint compared to fossil fuel engines, helping to combat climate change [25]. Another option is the Q30 boat, which was manufactured and designed in Finland by Q-Yachts [29]. It has a 100%-electric propulsion system from two electric motors of 10 kW torqeedo cruise, a battery pack of 30 kWh lithium with the possibility of adding another 10 kWh for a total of 40 kWh, uses state-of-the-art technology, and, thanks to its optimized hydrodynamic hull, it is very efficient. It was achieved thanks to an industry-leading electric propulsion system [29].

The Hynova 40 was manufactured and designed in France by Hynova Yachts [30]. It has a 100%-electric propulsion system with batteries and FC based on hydrogen as an energy source, and it has a 22.5 kg hydrogen tank, as well as two 150 kW electric motors which draw power from a set of two 40 kWh batteries and an 80 kW fuel cell. The yacht is environmentally friendly and silent. It only emits water into the sea and not CO_2. The integration of the hydrogen solution was carried out in a way that does not affect the comfort on board of this first hydrogen-powered dinghy using the most suitable materials [30]. Another option is the Silent 60 vessel, which was designed and manufactured in Austria by Silent Yachts [31]. It is an ideal entry into the world of silent solar-powered sailing. The boat has two electric motors of 340 kW that allow sailing without sacrificing comfort. In addition, the solar-electric power train, with a 16 kWp solar system, a 148 kW diesel generator, and a 286 kWh libitum battery, offers unprecedented levels of reliability and safety, with virtually no maintenance. [31]. Volt 180 was designed and manufactured in Canada by Vision Marine [32]. It comprises a 100%-electric propulsion system and a fiberglass hull. Volt 180 uses an outboard motor that produces 5 HP with a capacity of 11 passengers, achieving a speed of 6 knots and a range of 6.5 h, and the possibility of taking a lithium battery from 1×5 kWh to 3×5 kWh [32].

SAY 29E RUNABOUT was designed and manufactured in Spain by Sayachting. It has a 100% electric propulsion system of 170 kW, a lithium battery of 126 kWh, and a carbon fiber hull. SAY 29E uses an inboard engine that allows it to reach a maximum speed of 50 knots with a capacity of eight passengers and a range of 6.5 h [33]. Candela C-8 was designed and manufactured in Sweden by Candela. It has a 100%-electric propulsion system with a 50 kW motor and a 45 kWh lithium-ion battery system, and a hydrofoil-type hull. It is equipped with a state-of-the-art sensor system that automatically adjusts the wings to keep the boat level and stable [34]. Another option is the Soelcat 12, which is a catamaran designed and manufactured by Premium Catamarans [35] oriented to the "Day Charter" that works purely electrically, generating enough energy in the presence of sunlight, allowing it to sail long distances. The entire roof is a large solar panel made up of 36 panels capable of producing almost 10 kW to power the two 30 kW engines and the 260 kWh battery bank [35].

Table 1 shows the comparative analysis of the eight passenger boats. The table shows the different power sources, the size of the ships, the operating speeds, and manufacturing countries.

Table 1. Features of passenger boats.

Boat	Power Source	Length (m)	Beam Width (m)	Maximum Speed (kN)	Cruising Speed (kN)	Country	Operation	Auto Generation
Eelex 8000	Batteries	8.00	2.50	30.0	20.0	Switzerland	Maritime	No
Yachts Q30	Batteries	9.30	2.20	15.0	9.0	Finland	Maritime	No
Hynova 40	FC	12.00	3.80	25.0	15.0	France	Maritime	FC
Silent 60	Diesel + RE	17.99	8.99	20.0	15.0	Austria	Maritime	Diesel + PV
Volt 180	Batteries	5.40	2.13	5.6	3.4	Canada	Maritime/dam	No
Say 29E	Batteries	8.86	2.76	52.0	52.0	Spain	Maritime	No
Candela C-8	Batteries	8.50	2.45	30.0	25.0	Switzerland	Maritime	No
Soelcat 12	RE	11.80	5.80	15.0	8.0	Spain	Maritime	PV

3. Technological Alternatives for Propulsion

In the reviewed literature, six alternatives applicable to vessels within the electromobility framework have been identified that use batteries, REs, FCs, and diesel generators. These systems are formed by the union of several components, such as the engine, power transmission shaft, and propeller, which together make up the propulsion system. The propulsion system can be formed by an inboard or an outboard motor. The inboard motor is installed inside the hull of the boat, which generates the need for a power transmission train and sometimes gearboxes for its operation. Unlike the outboard motor installed on the outside of the boat, it allows a direct transmission without the need to implement a power transmission train or gearboxes. Integrating various types of technologies makes the systems more profitable, versatile, competitive, and friendly to the environment.

3.1. Battery-Powered Propulsion System

This propulsion system is characterized by its propulsive power [36], which is generated by an electric motor that obtains the energy for its operation from a battery bank that is recharged by a recharging system on land. This type of system is implemented in small boats because of the low autonomy that it provides the boat for its mobility, as it depends 100% on the battery charge. The greater the number of batteries on board, the greater the autonomy; however, the payload capacity is affected. This system is commonly used in fishing and recreational vessels, such as those used in lakes with small outboard electric motors (less than 1.1 kW), small passenger boats, and car ferries equipped with high-capacity rechargeable lithium-ion batteries. This rechargeable system provides much greater autonomy and longer durability, but still has limitations such as load capacity and autonomy. This is why these systems are recommended mainly for smaller boats with a length of less than 24 m. For other types of boats of greater length, the use of mixed systems is recommended.

Energy storage systems are commonly designed with rechargeable lithium-ion batteries, where their open-circuit voltage can be expressed as a function of the state of charge, which represents the remaining battery level. Depending on their state of charge, the open-circuit voltage in batteries can vary by approximately 20%. For this reason, the electrical input and output power vary depending on the state of charge of the batteries. The battery capacity is represented in ampere-hour, and the state of charge is calculated by measuring, in real time, the current value by a Coulomb meter. They have silent engines, do not generate vibrations, since no gearboxes are used for their propulsion, and do not generate pollution. In turn, passengers on board receive a quality experience.

3.2. Renewable Energy Propulsion System

This propulsion system is characterized by having an electric motor, which implements renewable energy, such as a photovoltaic or wind generator, which is stored in a battery bank [20]. The system can have an auxiliary source implemented based on a diesel generator or other type of generation.

3.3. Fuel Cell Generation Propulsion System

This propulsion system is characterized by including an electric motor [37]. Power comes from FCs, in which hydrogen is commonly used as fuel. Then, through a chemical process, it generates energy that is used to power the electric propulsion motors and the auxiliary systems of the vessel and is simultaneously stored in a main and secondary battery system for future use. Different cells can be used in the river field based on the specific operation and infrastructure. The most common are proton exchange membrane cells (PEMFCs), followed by molten carbonate cells (MCFCs) and direct methanol cells (DMFCs).

3.4. Electric Propulsion System with Power Generation from Internal Combustion Engines and Batteries

The system is characterized by including an electric motor, which obtains the energy for its operation from thermoelectric generators [38]. Additionally, electric energy is stored using a battery bank. The structure of this propulsion system comprises one or more internal combustion generators, power converters (DC/DC–AC/DC–DC/AC), direct current busbar that provides power transmission with fewer losses, internal electrical loads of the vessel, and alternating current busbar to supply power to electric propulsion motors [38].

3.5. Electric Propulsion System, Powered by Generation from Internal Combustion Engines without Batteries

The operation of this technology is based on an all-electric propulsion system. It obtains its energy through thermal generators, with the particularity that a balance is obtained between generation and consumption and no storage systems are used [39]. However, the system does not have an electrical energy storage system. The generated electricity feeds the main distribution boards and it is distributed throughout the ship employing wiring and power converters for proper operation of the propulsion engines and all loads. As electrical power normally operates at a constant voltage and fixed frequency, the speed of the propulsion motor is regulated by a variable speed drive that generates a suitable frequency to match the required speed. Compared to conventional propulsion systems, integrated electric propulsion architecture offers enormous opportunities in terms of improved efficiency and ship design [40].

3.6. Hybrid Propulsion System with Generation from Internal Combustion Engines

Hybrid propulsion systems combine mechanical and electric propulsion within the power train, resulting in higher propulsive efficiency. Approximately, the use of diesel–electric propulsion systems reduces fuel consumption by 20% compared to conventional engines. Two important parts can be distinguished within hybrid propulsion systems: first, the generator block and energy transformer, and second, the propulsion by an electric motor and an internal combustion engine [41]. The diesel generators supply power to the switchboards, which send the current to the voltage transformers and subsequently to the frequency converters. Batteries are usually included in this block, even though they do not generate energy.

At the moment of forward travel, the diesel engines act as generators, producing the alternating current that will supply energy to the propulsive synchronous electric motors. The most important parts of this type of propulsion are the frequency converters, as they adapt the current to the type of motor, avoiding motor losses. This allows an effective control of speed and torque [42]. Currently, this type of propulsion has a power electronics system that controls the tail generator. In this way, both the diesel engine and the propeller are synchronized at the same frequency, resulting in a higher operating capacity of the vessel itself. The great advantage of this system is precisely the combination of two engines. The electric motor supports the combustion engine, with the aim of the latter maintaining its optimum efficiency point because the diesel engine will work steadily, so consumption is significantly reduced.

4. Characterization and Topologies of River Electromobility

In this section, we characterize and describe the topology, considering the main components, of electromobility systems.

Figure 2 describes the different configurations proposed in this paper. In this figure, different combinations between the propulsion system and the power supply are presented for navigation in the waterway sector.

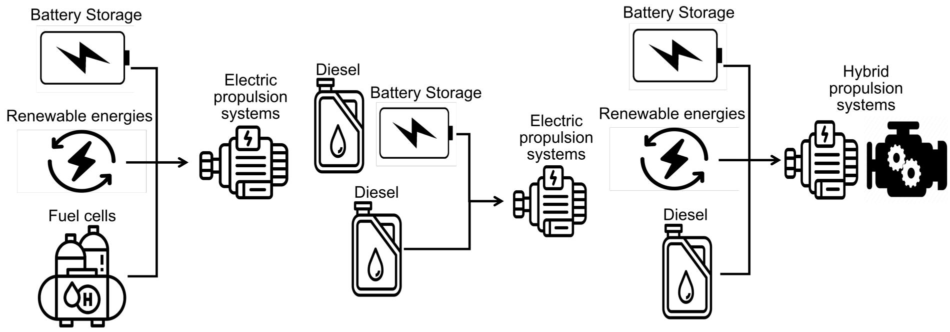


Figure 2. Technologies for electromobility systems in the waterway sector.

Based on the information obtained, the topologies for each technology are characterized and described.

4.1. Battery Storage with Fully Electric Propulsion Systems

Since 2010, battery-powered ships have experienced a significant drop in the maritime market, with the number of these increasing to 364 as of August 2019, including ships under construction and those under development [43]. The International Maritime Organization—IMO has imposed stricter regulations on the reduction in emissions from the waterway transport industry, which has been demanding the inclusion and implementation of electric propulsion systems in all branches of this field (tourism, trade, military, among others) [43]. To achieve zero emissions by 2040, the Port of Auckland tendered a contract with Damen Shipyards Group in 2019 to develop a 70 ton battery-powered electric tug [43]. All recent studies and the exponential use of batteries in boats clearly show that this type of propulsion system will become a system of great impact in this decade. Therefore, there is considerable scope for analyzing the tariff portfolio in relation to the application of ships and efficient energy management in seaports.

In boats with this propulsion system, batteries supply the power to operate all the equipment on board. The power consumed for propulsion and the power used for on-board equipment are examined separately. The development of electric boats with the same performance and resistance as conventional combustion-propelled boats represents a challenge due to the high hydrodynamic resistance combined with the low power density of energy storage technologies. In addition, the weight of the batteries is greater than the weight of the fuel, and the installation of a storage system considerably increases the total weight of the vessel; this, in turn, affects the hydrodynamic resistance of the ship. Therefore, in general, the estimation of energy consumption leads to an iterative process.

Hydrodynamic optimization is a strategy to reduce energy consumption when the boat is in motion, thus obtaining performance improvements. Reducing the speed, the wetted area, and the weight of the boat produces an improvement in the resistance of the boat [17]. The choice of these strategies depends a lot on the mission of the boat; therefore, carrying out an analysis of consumption and performance is necessary if you want to implement this type of propulsion alternative. The boat propulsion power requirements vary depending on the shape and size of the boat. However, in the case of some specific vessels, such as nonplanning displacement ships, the propulsive power is approximately the cube of its speed. In [16], a study was carried out with real measurements and data collection on the relationship between speed and total propulsion power demanded by the "RAICHO N", which is fed entirely by a battery bank. The relationship between these two variables can be found in [16].

Data were taken under conditions of the presence of light wind and light tidal currents. In more demanding conditions, propulsive drag increases due to the opposing effects of wind and strong tidal currents, as well as fouling of the hull and area around the propeller. For this reason, these types of vessels generally have as design criteria a propulsive power margin of 15 to 20% regarding nominal production as a maritime margin [16]. When vessels of this class are used as small passenger craft, the onboard apparatus such as contactor controls, monitors, and air conditioning consume a nearly constant amount of electrical power regardless of the speed of the ship. Heating and cooling equipment used for food service, such as refrigerators and hot stands, generate additional energy consumption. When the boat is in port, no power is required for the propulsion motors and inverter. However, the lights and air conditioning, which account for most of the power load on board, cannot be turned off. Therefore, the power required in a hotel load presents minimal variations that can be considered constant when the vessel is docked and when it is underway. The power required for hotel charging can be estimated using a table of electrical energy consumption during the design and construction of the vessel, in the same way as for standard marine vessels [16].

In the analysis presented in [44], the demand factors in the main loads of three types of vessels in the states of navigation, departure, and berth are shown in percentages. Reference [43] shows the general schematic of a battery-powered electric propulsion system on a small boat. The ship's system operates with bidirectional DC–DC converters that act as controllers in the loading and unloading processes of the storage system. The most widely used batteries in energy storage systems are rechargeable lithium-ion batteries, which have an approximate cost of USD 150/kWh, where their open-circuit voltage can be expressed as a function of the state of charge, which represents the remaining level of the battery. Depending on its state of charge, the open-circuit voltage in the batteries can vary approximately 20% [16]. For this reason, the electrical input and output power varies according to the state of charge of the batteries. The battery capacity is generally represented in units of ampere-hour, and the state of charge is calculated by measuring the current value in real time through a Coulomb meter. The battery bank supply process is carried out at charging stations located in seaports, where different modes are implemented to perform this function. In these systems we can find three types of charging levels, among which we find the slow charge, with a maximum power of 1.9 to 7.4 kW and a recharge time between 4 and 36 h, the semi-fast charge, with a power between 19.2 and 43 kW and a recharge time of 2 to 6 h, and the fast charge, with a power of 50 to 350 kW and a recharge time of 0.16 to 0.5 h [45].

4.2. Self-Generation from Renewable Alternatives with Fully Electric Propulsion Systems

Renewable energy systems, especially the photovoltaic system, have been applied to different types of vessels. Due to low fuel consumption and pollutant emission, environmentally friendly ships with the installation of photovoltaic systems have attracted the interest of many researchers. For example, the first commercial ship with a hybrid solar/wind system, called the Solar Sailor, was designed and manufactured in Australia in 2000 [46]. In 2008, a photovoltaic array with 328 panels was installed on the Auriga Leader in Japan. The Auriga Leader PV system has a maximum power of 40 kW, which can satisfy 6.9% of the lighting requirements and no more than 0.3% of the energy requirements [46]. In 2012, a solar power system with 768 panels (160 kW) and a lithium-ion battery pack with 324,480 batteries (2.2 MWh) was installed on the Emerald Ace in Japan [46]. For all vessels using fossil fuels on a hybrid modality, it is necessary to comply with the regulation issued by IMO 2020—reducing sulfur oxide emissions; the regulation limits the sulfur content of fuel oil used onboard ships operating outside designated emission control areas to 0.50% m/m (mass per mass), as well as 0.10% within specific designated emission control areas. This new limit became mandatory after an amendment to Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL) [47].

Solar panels are used to determine the performance of such a system. The three most widely used types of solar panels are monocrystalline silicon, polycrystalline silicon, and amorphous silicon cells [48]. Monocrystalline silicon cells are the most efficient and widely used, while polycrystalline silicon cells are less efficient but slightly cheaper to manufacture [49]. Batteries can be used to store power produced by photovoltaic panels that can then be used during hours when direct solar power is not produced. In addition to traditional series and parallel connection of the panels, there are different topologies that provide solutions to problems such as hot spots or reverse currents that threaten the safety of the system by causing thermal damage. These topologies are shown below.

1. Bypass and blocking diode. The bypass diode will come into operation when a photovoltaic panel is shaded to such an extent that its voltage drop exceeds 0.7 V; consequently, the panel will be protected. In addition, the unidirectional conductivity of the blocking diode will also prevent the reverse current. The topology of the structure of the bypass and blocking diode topology can be found in [46].
2. Chain and multichain. In this topology, several panels are connected in series at the beginning and each PV string is connected to a separate inverter. Similarly, in the multichain structure, each PV string is connected to a DC/DC converter at the beginning and then 4–5 converters are connected to an inverter [46]. Taking into account the available technologies, solar boats need to maximize the PV surface area and battery capacity to increase the range for long-distance trips.

4.3. Fuel Cell Generation with Fully Electric Propulsion Systems

Pratt and Klebanoff in [15,50] studied GHG emissions and pollutants (nitric oxides, hydrocarbons, particles) related to the maritime sector. In the study, they show how ships with systems powered by hydrogen FCs can drastically reduce these emissions. For example, port vessels (which do not include transoceanic vessels but include coastal vessels) account for 0.35% of California's greenhouse gas emissions and approximately 0.1% of California's pollution. Although these figures may seem minuscule, as pointed out in [51], polluting gases from port vessels constitute a source of visible pollution in neighboring densely populated areas, where emissions negatively affect human health. It is important to note that partial reductions from current emission levels from diesel ships, even reductions of up to 50% per ship, will not be sufficient to lead to large long-term reductions due to the constant growth of the maritime sector worldwide.

This type of propulsion system comprises a fuel storage tank that feeds the cells, normally with hydrogen, so that later, through a chemical process, they generate energy that is used to power the electric propulsion motors and the auxiliary systems of the vessel, and simultaneously store it in a primary and secondary battery system for future use. They consist of an anode, a cathode, and an electrolyte. Depending on the type of battery, the chemical reaction inside the battery is different. The membrane electrode assembly (MEA) can pass positive ions (protons) and resist the conduction of negative ions (electrons). On the anode side, because of the catalysts on the anode surface, the oxidation reaction takes place, generating protons and electrons. Electrons cannot pass through the membrane and flow from the anode side to the cathode side in the external circuit to supply the charge. Therefore, the protons pass through the membrane and reach the cathode. On the cathode side, a reaction of protons, oxygen, and electrons takes place thanks to another catalyst and water, resulting in the desired waste heat [23].

The power train can include some major elements, such as hydrogen storage and release, auxiliary cells, cell stack, and the interface to the electrical power system, which is typically implemented by power electronics converters (in this case, a DC–DC converter). The performance of the fuel cell is heavily dependent on the performance of its auxiliaries. The performance of the cells is changed by four auxiliary systems, including the refrigeration system, humidification, air supply, and hydrogen supply. Each system must be designed according to the characteristics of the cell to have a completely efficient system. Different cells can be used in the river field depending on the specific operation and infrastructure. The most common are proton exchange membrane cells (PEMFCs), followed by molten carbonate cells (MCFCs) and direct methanol cells (DMFCs). The characteristics of the different FC present in the industry can be found in [23].

4.4. Generation from Internal Combustion Engines and Battery Energy Storage with All-Electric Propulsion Systems

Power electronics and advances in variable speed drives allowed the development of new electric propulsion systems, called integrated power systems (IPSs), which had applications in a modernized ocean liner that had nine diesel generators inside to supply power, in real time, operation and maintain charge of the battery systems to supply power to the propulsion system and other auxiliary loads. All this was carried out in the early 1980s [40].

The structure of this propulsion system is made up of one or more internal combustion generators, power converters (DC/DC–AC/DC–DC/AC), direct current busbars that provide energy transmission with fewer losses, internal loads, electrical connections of the vessel, and alternating current busbars to supply power to electric propulsion motors [52]. The outstanding feature of this system is the integration of energy storage, as this contributes to fuel savings operations by optimizing load leveling. This strategy allows the engines to run at constant speed within a region of minimum fuel consumption, while energy storage handles disturbances that are above average [40]. During transient load variations, it is used as a buffer against sudden load demands due to the slow response of the motors to these sudden power changes. The storage system is also designed as a conventional backup system to ensure reliable autonomy in the event of a power outage [40].

This electric propulsion requires replacing the coupling between the propeller and the main engine through a mechanical transmission by a system made up of generators, distribution boards, transformers, drives, and motors. The system is about 90% efficient, which means that there are other losses that must be compensated. The variation in losses between the different electrical topologies is low. However, the electrical losses are always minor compared to the hydrodynamic losses of the propellers and the combustion efficiency in the main engines. Therefore, although electrical losses are created, the lower hydrodynamic and combustion losses translate into a reduction in total system losses. Elimination of this transmission and other mechanical components facilitates the use of unconventional propellers in the boat. The "pod" or capsule propellant is a steerable propulsion unit comprising a propulsion motor installed within a submerged capsule [40]. These types of thrusters, better known as azimuth thrusters, consist of a directional unit where the electric motor is installed directly on the propeller shaft. Mechanically, these pod-type thrusters are of simple construction, the electric motor being integrated with the thrust bearing and propeller bearing. Electrical transmission is via slip rings, which allow the pod unit to rotate at any horizontal angle, thus giving the boat high turning force in any direction without the use of a rudder. The steer pod has also been applied to twin propellers and contra-rotating propellers (CRPs) [40]. In the multiple helix concept, two helices rotate axially in the same or opposite directions. Such propulsions are very relevant for dynamic positioning vessels, tugs, and ferries [40].

From the birth of this propulsion technology three decades ago to its position as a leader in the global shipping market today, azimuth electric propulsion has revolutionized shipping with its performance, efficiency, sustainability, and reliability. This propulsion system is a system within electric propulsion that encompasses two main components: the steering module and the propulsion module, as shown in [53]. The need for a gearbox is eliminated and direct coupling of the propeller into the electric motor system is allowed. Currently, this propulsion system can be considered the most promising technology for small and medium-sized ships. Other types of azimuth thrusters (medium, large units, and high-class icebreakers, among others) have been offered in the current market by the ABB company [54].

4.5. Generation from Internal Combustion Engines without Energy Storage by Batteries with Fully Electric Propulsion Systems

Newer cruise ships use an electric propulsion system, in which electric generators are used to produce electricity that can be used by electric propulsion without mechanical coupling between the generators and the propulsion. Although propulsion trains are electric, electricity generation still requires diesel generators, which require improved fuel quality and must comply with the ISO 8217 2017 standard[55]. This is commonly known as marine gas oil (MGO), with an approximate cost of USD 0.166/kWh [55]. The integration of energy storage devices, such as batteries, in marine vessels has been investigated to complement diesel generators. However, even with the inclusion of renewable energy sources, the use of diesel generators is still necessary to produce electricity. This is due to the high demand for onboard power [38].

Electric propulsion substantially reduces fuel consumption compared to systems using direct mechanical propulsion for supply vessels to offshore facilities. Savings of 15–25% can be achieved under typical operating conditions, and up to 40–50% in dynamic positioning (DP) operations [56]. In a study carried out on a platform tugboat (AHTS) with more than 200 tons of bollard traction, the reduction in fuel consumption was calculated for one year when the vessel operated with mechanical and electrical propulsion. These systems are characterized by operating with integrated electric propulsion technology without battery energy storage [39], which is formed by installing power generators that can be diesel generators or gas turbines to produce a three-phase power output with standard frequency and voltage. The generated electricity feeds the main distribution boards, which distribute it throughout the ship through wiring and power converters for the correct operation of the propulsion engines and all service loads. As electric power normally works at a constant voltage and a fixed frequency, the speed of the propulsion motor is regulated by a variable speed drive that generates a suitable frequency to correspond to the required speed. Compared to conventional drive systems, the integrated electric drive architecture offers tremendous opportunities in terms of efficiency improvement and ship design.

4.6. Generation from Internal Combustion Engines with Hybrid Propulsion Systems

The US Navy's first hybrid-powered vessels were battleships and aircraft carriers that were built in the late 1910s and 1920s and operated well until the beginning of WWII. Fast passenger liners were introduced in the 1920s and 1930s; these were equipped with turboelectric machinery [9]. Oil boilers provided steam for steam turbines, which in turn drove synchronous electrical generators. These provided power to electric motors coupled to the fixed-pitch propeller. The speed was established by changing the speed of the steam turbine. The generator frequency changed with the speed of the turbine, as did the engine. This propulsion was outdated by the geared steam turbine, which turned out to be smaller, more compact, and less demanding on maintenance [9]. Today's hybrid propulsion systems combine mechanical and electrical propulsion within the kinematic chain, obtaining greater propulsive efficiency. Approximately, the use of diesel–electric propulsion systems reduces fuel by 20% if we compare it with conventional engines [18]. Two important parts can be distinguished within hybrid propulsion systems. First, the power generator and transformer block and, second, the propulsion by an electric motor and an internal combustion engine. The diesel generators are used to power the boards. These send the current to the voltage transformers (if they have them) and, later, to the frequency converters. Batteries are often included in this block even though they do not generate power.

Diesel engines act as generators producing alternating current that will supply power to the propelling synchronous electric motors. The most important parts of this type of propulsion system are the frequency converters, as they adapt the current to the type of motor, avoiding losses in it. This allows effective control of speed and torque. Currently, this type of propulsion has a power electronics system that controls the tail generator. In this way, both the diesel engine and the propeller are synchronized with the same frequency, which results in a higher operating capacity of the ship itself [57]. The great advantage of this system is precisely the combination of two engines. The electric motor supports the combustion engine with the aim of keeping the latter at its optimum efficiency point because the diesel engine will work constantly, so consumption is reduced [57]. The basis for hybrid propulsion is found in the modes of operation of the boat in addition to its demand for speed and power.

In diesel drive mode, the ship's propulsion is carried out by the main combustion engines, and it also covers all the power required by the hotel loads thanks to the energy storage system (if it has one). In electric drive mode, the main combustion engines are out of service; the propulsion is executed by the electric motor coupled to the propeller shaft which is powered by the main generators or battery bank. Therefore, gas emissions are reduced in this mode. In generator mode or power take-off (PTO) mode, the main engine provides, in addition to the propulsion power required by the ship, the electrical energy necessary for the ship's consumers. This mode allows a high load on the main engine, which will run with low fuel consumption, so emissions are also reduced. The engine generators stop when the PTO mode is in operation. This means that generator sets do not need maintenance as frequently as they are taken out of service when they are not needed, and this helps to extend their useful life [57].

In impulse mode or power take-in (PTI) mode, the electric machine works as an auxiliary engine that provides support to the propeller. In this case, the generator sets supply the necessary electrical energy both for the propulsion and for the ship's consumers. This mode, known as the boost mode, mainly increases the flexibility of the propulsion system when the ship is under maximum load. Many companies currently offer this propulsion system. The hybrid propulsion system offered by the Rolls Royce company comprises MTU internal combustion engines, electric propulsion modules, transmission systems, batteries, monitoring and control systems, as well as other electronic components.

5. Advantages and Disadvantages of Propulsion Systems

Table 2 presents a compilation of the advantages and disadvantages of alternative propulsion systems in the inland waterway sector. This table considers the technological alternatives of energy sources, which are battery banks, renewable resources, green hydrogen, internal combustion generators with and without battery systems, and systems with internal combustion generators but the propulsion is carried out with electric motors and combustion engines, which configure the hybrid system.

In addition, technologies are linked to their corresponding references, which are used to analyze advantages, in which criteria such as pollutant gas emissions, system efficiency, overload support, environmental impact, autonomy, and required support infrastructure are taken into account. Similarly, for the disadvantages, additional criteria are considered, such as the weight inside the vessel of each technology, the life cycle of the system, and the availability of resources at the places of use.

In summary, the best technology in the short term to achieve an energy transition in the river transport sector is the hybrid system. This technology can be coupled to existing systems, improves the efficiency of the system, reduces greenhouse gas emissions, and supports the infrastructure coupled with current systems.

Table 2. Advantages and disadvantages of propulsion systems.

Technology	Advantages	Disadvantages	Ref.
Battery	No pollution during operation. High energy efficiency in propulsion due to stored energy. It can withstand overloads due to the storage system. It occupies less volume in the vessel than in other systems.	The autonomy in navigation is limited and batteries can increase weight. Specialized charging infrastructure is required, and the supply of propulsion systems is focused on boats with low power requirements. At the end of the useful life of the batteries, they must be disposed of either to a second useful life or to a recycling process. This implies reinvestment into the vessel.	[36]

Table 2. *Cont.*

Technology	Advantages	Disadvantages	Ref.
REs	It has a high-energy efficiency in propulsion due to the self-generation of energy and its use. It can withstand overloads due to the energy stored in batteries.	It generates a weight increase in the vessel due to the use of batteries. The system is dependent on environmental conditions and geopositioning of the vessel. Including self-generation systems implies the use of deck space, especially with self-generation through photovoltaic systems. At the end of the useful life of the batteries, they must be disposed of either through a second useful life or through a recycling process. This implies reinvestment in the vessel each time a second useful life is reached.	[40]
Fuel cell	It does not generate pollution during operation. It could withstand overloads because of the energy storage system. If the hydrogen used as a fuel is produced from renewable sources, then its environmental impact is much lower than that of any fossil fuel.	The extraction of hydrogen from fossil fuels generates a larger environmental footprint than the extraction of diesel or LNG; however, this is mitigated by the GHG emissions generated by using diesel or LNG as propulsion fuel. Hydrogen storage on ships is one of the major limitations of its use as it presents losses, and specialized containers are required for safe storage. It requires a hydrogen refueling infrastructure to support the needs of vessels. This drawback implies not only having hydrogen sources but also having the necessary loading infrastructure to transport and/or store it safely in port. At the end of the useful life, batteries must be disposed of either for a second useful life or for a recycling process. This implies reinvestment in the vessel each time the life cycle of a battery module is fulfilled.	[40]
Internal combustion engines with energy storage by batteries.	The system withstands overloads due to the energy storage system. Allows for greater autonomy than all-electric systems with or without self-generation and can run on both diesel and LNG. GHG emissions are reduced when running on LNG, compared to the same system that runs on diesel.	When using systems such as internal combustion engines or turbines for generation, the efficiency of the system is low compared to fuel cell or all-electric generation systems with or without self-generation, and the GHG emissions generated are high. Due to the use of batteries, the volume occupied by the system is larger than that of a system with direct generation by an internal combustion engine or turbine. It requires refueling infrastructure to support the needs of the vessels. This drawback implies not only having fuel sources but also that it requires charging infrastructure to transport and store it safely in port. At the end of the useful life of the batteries, they must be disposed of either to a second useful life or to a recycling process. This implies reinvestments in the vessel each time the life cycle of a battery module is fulfilled.	[58]
Internal combustion engines without energy storage by batteries.	Greater navigation autonomy compared to all-electric systems with or without self-generation. It runs on both diesel and LNG; in the case of running on LNG, GHG emissions are significantly reduced compared to the same system running on diesel.	When using systems such as internal combustion engines or turbines for generation, the energy efficiency of the system is low compared to fuel cell or all-electric generation systems with or without self-generation, and the GHG emissions generated are high. It requires refueling infrastructure to support the needs of the vessels. This implies having available fuel sources and loading infrastructure to transport and store them safely in port.	[40]
Hybrid propulsion	The constant low speed of the diesel engine in combined propulsion reduces pollutant gas emissions and fuel consumption. Versatility between the different operating modes and flexibility in operation.	It requires refueling infrastructure to support the needs of the vessels. This implies having available fuel sources and loading infrastructure to transport and store them safely in port.	[58]

6. Conclusions

This paper presented an analysis of technological alternatives for boats with electromobility applications and propulsion systems in the waterway sector. Existing vessels were reviewed and compared with each other. In addition, different technological alternatives for energy sources were shown for the operation of vessels. The propulsion alternatives considered in this paper were battery-powered, renewable energy, fuel cell generation, and electric systems with power generation from internal combustion engines and batteries. Furthermore, the paper presented the characterization of electromobility technologies in the waterway field and the advantages and disadvantages of propulsion systems.

The conclusions obtained from the paper are the following:

- The review of the different existing and operating vessels made it possible to identify the main characteristics of the different vessels. This allows the reader to have an overview of the most common sizes, speeds, autonomy, energy sources, operation areas, and predominant manufacturing countries of boats.
- Most commercial vessels offered by the industry are designed for operating at sea. However, considering the specific activities performed by communities on waterways, new considerations must be taken to implement these vessels according to local conditions. This is a great topic for research and provides an opportunity to develop this sector.
- Implementing small electric vessels on navigable waterways with rechargeable docks longer than 50 miles could be a challenging task. Propulsion systems that depend entirely on batteries are difficult to implement, as autonomy is limited and the distances between docks exceed their travel capacity. Some navigable waterways are located in areas with difficult access to electricity due to geographical conditions.
- The different technological alternatives offer a variety of options to implement electromobility in the sector of navigable waterways. This allows the selection of different configurations that best adapt to the requirements of the vessel in terms of travel distances, load capacity, speed navigation, size, and maneuverability.
- The literature showed that there are different possibilities for selecting power sources. Some of them are completely battery-based systems, thermal generators, hydrogen cells, and renewable resources. These sources can be combined with the propulsion train, which can be electrical, mechanical, or hybrid systems. Technologies can be implemented in combination with each other to achieve optimal performance according to the use of the vessel.
- From the table of advantages and disadvantages, it can be seen that the hybrid system is the best alternative. This system improves efficiency by implementing electric propulsion systems and batteries, reduces emissions by utilizing renewable energy, and maintains autonomy by employing fossil resources. This alternative is presented as a short-term solution to the energy transition in the waterway sector.

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