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Alternative Power Options for Improvement of the Environmental Friendliness of Fishing Trawlers

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Abstract: The fishing sector is faced with emission problems arising from the extensive use of diesel engines as prime movers. Energy efficiency, environmental performance, and minimization of operative costs through the reduction of fuel consumption are key research topics across the whole maritime sector. Ship emissions can be determined at different levels of complexity and accuracy, i.e., by analyzing ship technical data and assuming its operative profile, or by direct measurements of key parameters. This paper deals with the analysis of the environmental footprint of a fishing trawler operating in the Adriatic Sea, including three phases of the Life-Cycle Assessment (manufacturing, Well-to-Pump (WTP), and Pump-to-Wake (PTW)). Based on the data on fuel consumption, the viability of replacing the conventional diesel-powered system with alternative options is analyzed. The results showed that fuels such as LNG and B20 represent the easiest solution that would result in a reduction of harmful gases and have a positive impact on overall costs. Although electrification and hydrogen represent one of the cleanest forms of energy, due to their high price and complex application in an obsolete fleet, they do not present an optimal solution for the time being. The paper showed that the use of alternative fuels would have a positive effect on the reduction of harmful emissions, but further work is needed to find an environmentally acceptable and economically profitable pathway for redesigning the ship power system of fishing trawlers.

Keywords: fishing trawler; ship power system; harmful emissions; decarbonization; alternative fuels

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1. Introduction

1.1. Environmental Problems in the Marine Sector

Environmental problems in shipping represent a very important and attractive research topic and there are a number of recent publications discussing technical and operational measures as well as market-based solutions to comply with ever-stringent regulations. This is likely the direct consequence of the ship energy efficiency regulation set by the International Maritime Organization (IMO), which introduced two mandatory energy efficiency mechanisms, the ship energy efficiency design index (EEDI) and the ship energy efficiency management plan (SEEMP), which entered the force in 2013, while in 2021, the technical guidelines for the energy efficiency existing ship index (EEXI) and carbon intensity indicator (CII) were adopted [1–3]. The marine industry consumes 330 Mt of marine fuel a year and 77% of it is Heavy Fuel Oil (HFO). Consequently, the stated energy demand produces 2–6% of global CO_2 and these emissions are projected to rise by 270% by 2050 compared to 2007 [4]. Between 14 and 31% of the global emissions of NO_X and 4 to 9% of SO_X originate from marine vessels [4]. Furthermore, the Paris Agreement has been drawn up with the aim to limit the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 °C [5]. The agreement covers each production sector, regardless of the amounts of harmful gases produced during operations. Energy efficiency improvements for ships are being continuously discussed as can be seen from very recent reviews [6,7]. The environmental research in the marine sector is mainly focused on merchant long-distance fleets [6,7], short-sea-vessels [8,9], or even super yachts [10], or inland waterway vessels [11–13], but the contribution of smaller vessels, such as fishing vessels, is regularly under-investigated. Unlike most ship types, fishing vessels are not subject to IMO regulations, but minimizing their environmental impact is of high importance, although it represents a unique set of challenges compared to other ship types [14]. Recently, the European Commission implemented Regulation (EU) 2022/46 on the identification of energy-efficient technologies and the specification of methodology elements to determine the normal fishing effort of fishing vessels, prescribing that new engines of fishing vessels shall be construed to use energy-efficient technologies [15]. Therefore, there are a number of measures being proposed that include the redesign of specific ship parts such as the hull [16], changing the composition of antifouling coatings [17], or introducing a hybrid power system [18], regardless of the type of ship. Fishing vessels come in many sizes (from approximately 12 to 100 m), with different types of equipment onboard, which change their course frequently, following unfixed routes over the course of days or weeks, making their power needs highly variable [14]. Therefore, scattered applicability of innovative energy-efficient technologies within a fishing fleet can be expected.

Among technical measures, alternative fuels are considered to offer great diversity, which improves the possibility to find an economically viable option, but as shown by Perčić et al. in [8,11], these studies are rather location- and case-specific, and the viability of alternative fuels should be confirmed on a case-by-case basis.

Commercial fisheries are globally distributed and are mostly powered by fossil fuels. As Hua and Wu indicated in [19], overcapacity in the fishing sector leads to increased pressure on fish resources, less profitability, and environmental problems such as GHGs emissions from fuel consumption. Several monitoring systems are integrated for research purposes to evaluate the energy performance of fishing vessels and estimate the emission of harmful gases in different operating conditions. Fuel monitoring is mentioned in [20] as an optimal solution for assessing the carbon footprint and decreasing fuel expenses. The paper introduced the Fuel Use Intensity (FUI) index, a measure of fuel consumption needed for catching 1 tonne of the target species, commonly expressed in liters of fuel per tonne of fish landed (L/t). Latorre [21] investigated the reduction of fuel consumption and NO_x emissions by installing onboard monitoring systems with shore-side satellite connections. The results showed that NO_x emissions correlate directly with vessel fuel consumption, and the reduction of engine load can reduce the emissions by 30%, while the integration of onboard computer systems can contribute to fuel and emission reductions by 15%. Another fuel consumption monitoring system was introduced in [22] and was tested on two semi-pelagic pair trawlers in the Adriatic Sea. Both vessels work at an engine power of 900 kW with gears of similar design and size, with a difference in the propeller design and the hull material. The fuel consumption during steaming conditions at different speeds was estimated and results showed that a reduction of just half a knot leads to a reduction in the fuel rate of up to 18%. Somasundaram et al. presented a different approach in [23] investigating vessels running on compression ignition engines, i.e., engines that use diesel–ethanol–biodiesel blends with nano alumina additives. The addition of biodiesel to the diesel–ethanol mixture permits a higher ethanol concentration and contributes to more stable fuel blends, and adding nanoparticles causes improvements in the fuel radiative and heat/mass transfer properties. The use of diesel–ethanol–biodiesel blends with nano alumina additives reduced CO, CO_2, and NO_x emissions [23].

A good introduction to the social impact of environmental requirements is given in [24], where the focus is on the vulnerability of fisheries due to climate change, following threats that coastal communities are exposed to and the economic factors important to the system. Chu et al. [25] introduced the Fisheries Performance Indicator, which is designed to capture the economic and social performance of a fisheries system in addition to the management and environmental impacts. The environmental impacts of fisheries are also studied in [26], with a focus on small trawlers, emphasizing the importance of the reduction of fuel consumption and controlled fishing. The analysis of the fishing fleet and the implementation of new technologies should help to control the environmental impacts, from the amount of exhaust gas to the regulation of catches [27].

1.2. Effect of Fishing Activities on Ship Fuel Consumption and Emissions

Fishing is one of the oldest sectors developed in countries that have access to the sea or freshwater. Fishing vessels, next to airborne transportation, consume the relatively largest portion of energy and emit high values of harmful gases into the seafood product value chain [28]. More precisely, the fishing sector accounts for 1.2% of global oil consumption, which entails approximately 134 million tonnes of CO_2 emissions in the atmosphere [20]. Energy consumption depends on numerous parameters, from the dimensions of the fishing vessels to the type of fishing activity [29]. For instance, fish populations live in different environments, and the variety can significantly affect the logistic management and harvesting policy [30]. Fishing vessels can be distinguished by fishing gear, fishing patterns, and trips. Basurko et al. [20] reported that fuel costs for a trawler represent 40–50% of the total annual costs, while for tuna purse seiners, this value goes up to 70%. The approach is further confirmed in the FAOs Manual [31], where the difference in fuel usage depending on the type of caught fish is shown, as is the fuel consumption during fishing activities of trawlers and purse seiners. According to the FAO data, purse-seining tuna consumes 1500 L per tonne of land fish while purse-seining herring consumes only 100 L per tonne of land fish. Trawlers consume relatively more than purse seiners but there are also great differences depending on the type of fish landed. In the case of trawling shrimp, 3000 L per tonne of fish is consumed, while trawling cod consumes approximately 530 L per tonne of fish. The differences are confirmed in [20], stating that tuna purse seiners dedicate 56% of total fuel consumption to cruising and trawlers consume approximately 68% of fuel during fishing activities. Other factors also influence the overall performance of fishing vessels as stated in the manuals [31]. The manuals provide practical recommendations to reduce fuel consumption, from reducing the vessel speed to maintaining the engine and preventing underwater fouling. Fouling is a significant factor considering it can increase fuel consumption by 7% after only one month and 44% after six months if antifouling paint is not used [31].

This paper is focused on the environmental and economic assessment of a trawler operating in the Adriatic Sea, and therefore only the characteristics of trawling are described further.

According to FAO [32], there are several types of trawling operations. The technical and operational characteristics of vessels depend on the area of operation, so vessels differ in size, equipment, and tonnage. Depending on the gear and their differences in size, several types of trawling are presented in Figure 1. The categories are (with standard vessel length):

- Beam trawling (all lengths)—specialized medium-sized vessels operating in relatively shallow waters (up to 2000 m deep), often arranged with outriggers and towed in pairs.
- Pair trawling (over 5 m)—a larger net is towed by a pair of trawlers of similar size and power, more common for midwater trawling but also used for bottom trawling in shallow waters (up to 800 m deep).
- Otter trawling (over 10 m)—tow one or more parallel trawls open with the aid of otter boards, operating in midwater and bottom trawling.
- Stern trawling (over 15 m)—the trawl is set and hauled over the stern, built for almost all weather conditions, working in bottom or midwater trawling.
- Outrigger trawling (over 20 m)—characteristic of the outriggers on which the gear is towed, most widely used in shrimp trawling but often combined with otter and beam trawlers.
- Wet-fish trawling (from 12 to 24 m)—the fish is kept in the hold in the fresh, “wet” condition, characteristic in areas close to the landing point.

- Freezer (factory) trawling (over 40 m)—often found in high seawaters where the vessels spend a longer period operating, and they can operate as a fish processing factory (fish can be filleted, packaged, and frozen).

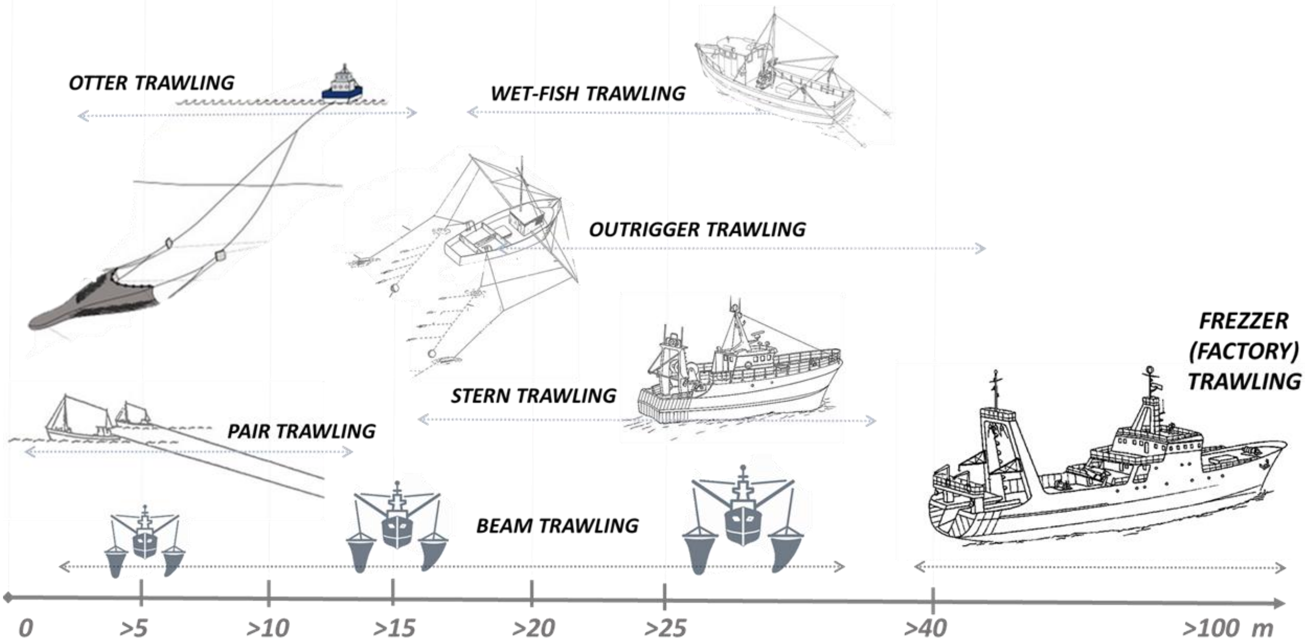

Figure 1. Classification of trawlers by the type of gear and standard length.

Modern trawlers regularly combine several trawling methods mentioned above, therefore making it difficult to distinguish which technique is used, Figure 2.

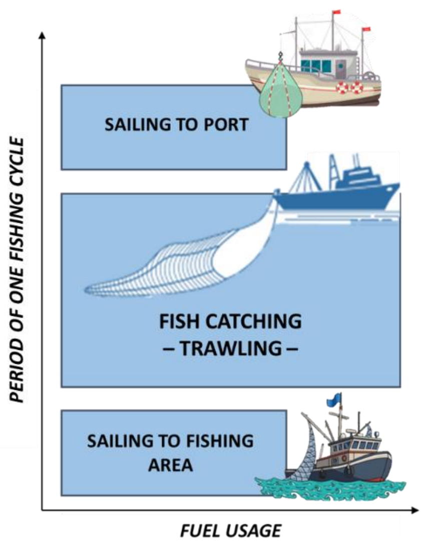

Figure 2. Fishing actions of trawlers.

The trawling net is considered the most influential part of the vessel, directly affecting fuel consumption and catch quality. The trawl net has a cone-shaped body that usually has a baggy or coned end. According to Maynou et al. [33], the net itself plays a significant role in the bioeconomic model of trawling. By changing the mesh size, the selectivity of trawl nets can be improved, thus resulting in significant benefits in biological, environmental, and economic terms of trawling. Gear modifications are also mentioned in [34]. The paper stated that modifying the gear by cutting the rigging twine between the fishing line and the footrope in the central part of the bottom gear could reduce bycatch by 20% (depending on the specie). The energy consumption of trawlers is well explained in [35], which stated that trawlers are the most fuel-demanding fishing vessels since net dragging usually accounts for 60% of total gear resistance. The paper presented several types of trawlers, differing by type of net, and analyzed the fuel savings obtained by reducing the navigation speed. The results showed that changing the trawling net (steeper cuttings in the wings and bellies, mesh size, etc.) can reduce fuel consumption to 18%, and the reduction in navigation speed alone can result in fuel savings of up to 26%. Fuel reduction by optimizing the fishing gear has also been mentioned in [20], where using pelagic or semi-pelagic trawl doors to reduce drag and forward resistance is proposed. From another point of view, given in [36,37], recovering the exhaust heat from the engines, which is wasted and taken away by jacket water, cooling air, and exhaust gas, could provide an effective way for energy saving in fishing vessels. The refrigeration systems could be powered by exhaust heat from engines and the wasted energy could be used for ice making, refrigeration, and air conditioning on fishing vessels.

1.3. Research Gap and Contribution of This Paper

The fisheries sector is facing various environmental issues caused by overfishing, overcapacity, and obsolescence of fishing fleets and reliance on power systems based on fossil fuels. In the case of ro-ro passenger vessels operating in the Adriatic Sea, electrification is considered to be the best alternative powering option from environmental and economic points of view in a lifetime framework [8,9,38]. Even though fishing vessels can be categorized as short-sea vessels, electrification may not be the optimal solution due to scattering in both the technical properties of the vessels and their operative profiles. The energy consumption of fishing vessels is highly dependent on fishing gear, net equipment, and operating activities. Therefore, it is necessary to take into account the specific parameters of an investigated fishing vessel while considering alternative power configurations.

Fishing is a complex system in which social, economic, and environmental aspects intertwine, making it difficult to fully implement certain measures. Therefore, detailed research that includes both environmental and economic aspects of the fisheries sector should be conducted to provide insight into the possibilities for improvement [27].

Based on the above literature review, the following research gaps have been identified:

- New regulations encourage the implementation of alternative fuels into fisheries, but the profitability of these processes is doubtful.
- The fishing sector has been neglected since the environmental impact is smaller compared to passenger and cargo transport on absolute scales.
- Research into environmental issues in fisheries is mainly focused on water pollution and biological impact on marine organisms, while the emissions in the atmosphere are underestimated.
- There is a need for an accurate mathematical model to determine the environmental impact of fishing vessels.
- To the best of the authors' knowledge, there are no relevant studies that analyze the environmental impact of different power systems and the economic analysis of such investments.

This paper addresses all of the above research gaps using the Life-Cycle Assessment (LCA) and Life-Cycle Cost Assessment (LCCA) of alternative powering options for a fishing trawler operating in the Adriatic Sea. Its original contribution includes the application of all relevant steps of LCA and LCCA for the power system of the considered ship, establishing the pathway for improvement of its energy efficiency and environmental friendliness. Although analyses of this type are case-specific due to the above-mentioned scattering in fleet properties, the model is generally applicable, and for a given set of input data, can be applied to any kind of fishing vessel in any fishing area.

2. Mathematical Model

2.1. Life-Cycle Assessment

The environmental impact of fuel production and its usage resulted in a number of studies on the interrelationship between the consumption of a certain type of fuel and its impact on global warming. One of the research methods is the life-cycle approach, used to estimate the amount of harmful gas produced during the lifetime of a product [8,9,11,12], in this case, trawl fishing. The paper analyzes several power configurations and, by using GREET 2021 software [39], compares the emissions released during trawling. Generally, the LCA method includes different stages, from energy and material input to product use, resulting in environmental outputs. As presented in Figure 3, phases of raw material acquisition and production, transport and distribution of the product, its usage, and possible recycling and/or waste management are analyzed during the life-cycle assessment. The level of LCA analysis often depends on the software itself, and for this reason, in this paper, the analysis is limited to fuel production and its use, but the recycling phase is neglected.

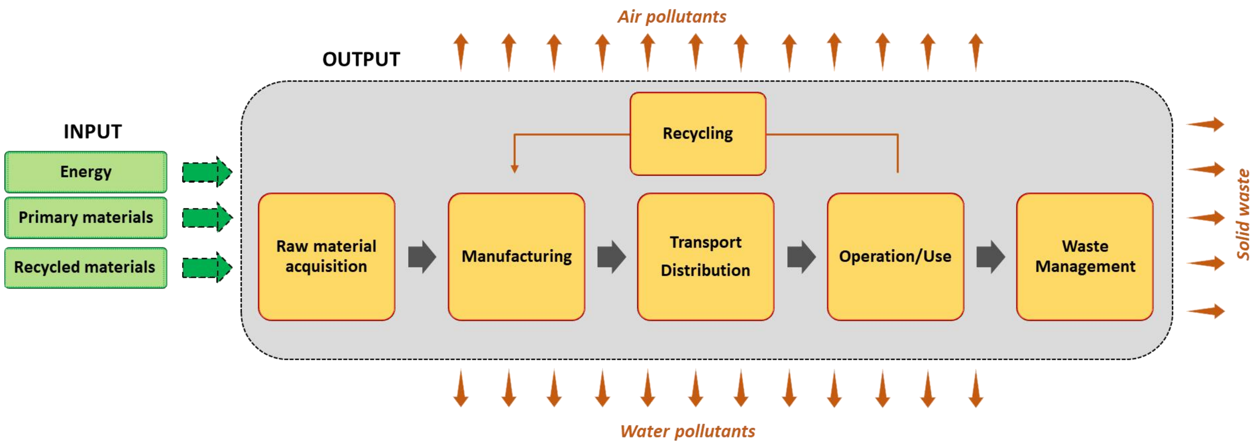

Figure 3. Flowchart of the generalized LCA method.

The emissions are analyzed in three phases, as described in [8]. Well-to-Pump (WTP) considers fuel production, from the extraction of raw material to the production and transport of the final product to the refueling station. When observing the process of fish catching, the Pump-to-Wake (PTW) phase is analyzed. The PTW phase analyzes the fuel combustion and the following tailpipe emissions (*TE*). Tailpipe emissions are a product of fuel combustion in marine engines and are calculated by the following equation [11]:

$$TE_i = FC \cdot EF_i, \tag{1}$$

where EF_i (g emission/kg fuel) refers to the emission factor and i refers to any emissions. The emission factors are obtained from [40,41]. The fuel consumption (*FC*, kg fuel/ kg fish) is calculated by the following equation [11]:

$$FC = EC \cdot SFC, \tag{2}$$

where *EC* (kWh/kg fish) describes the energy consumption and *SFC* (kg/kWh) refers to the specific fuel consumption, which for diesel engines equals 0.215 kg/kWh.

The manufacturing phase (ME), which analyzes the emissions released during the manufacturing of key elements (e.g., engines, batteries, and others), is also taken into account.

Carbon Footprint (*CF*) is a common term for describing the total amount of CO_2 or $CO_{2\text{-eq}}$ emissions caused by indirect or direct activity or accumulated over the life cycle of a product [42]. The CF is expressed here in tons of $CO_{2\text{-eq}}$, using the following equation [11]:

$$CF = GWP_{CO2} \cdot E_{CO2} + GWP_{CH4} \cdot E_{CH4} + GWP_{N2O} \cdot E_{N2O}, \tag{3}$$

where *GWP* refers to the Global Warming Potential, expressed as the appropriate CO_2 equivalent ($CO_{2\text{-eq}}$), and E_{CO2}, E_{CH4}, and E_{N2O} refer to the total emissions released during the ship's lifetime [43].

2.1.1. LCA of a Diesel-Powered Trawler

The Croatian fishing fleet, similar to most of the world's fisheries, uses diesel-powered configurations. The European regulations and programs have a great effect on the modernization of the fleet by introducing alternative power options that are beneficial to the environment. Therefore, the LCA of a diesel-powered trawler is used as a baseline for analyzing alternative power configurations.

The LCA procedure of a diesel-powered trawler is illustrated in Figure 4. The ME phase results in relatively small emissions during engine manufacturing. The WTP phase is influenced by fuel production, which is different depending on the observed country. In Croatia, crude oil is primarily imported from the Middle East. The transportation includes transport by tank trucks from the exploitation site to the port, approximately 500 km. Then, the crude oil is loaded onto a tanker, which sails for approximately 4000 km to the Croatian terminal in Omišalj. Further, a pipeline transfers the crude oil for 7 km to the Rijeka refinery, where the diesel fuel is produced and distributed to a refueling station by tank trunks [11].

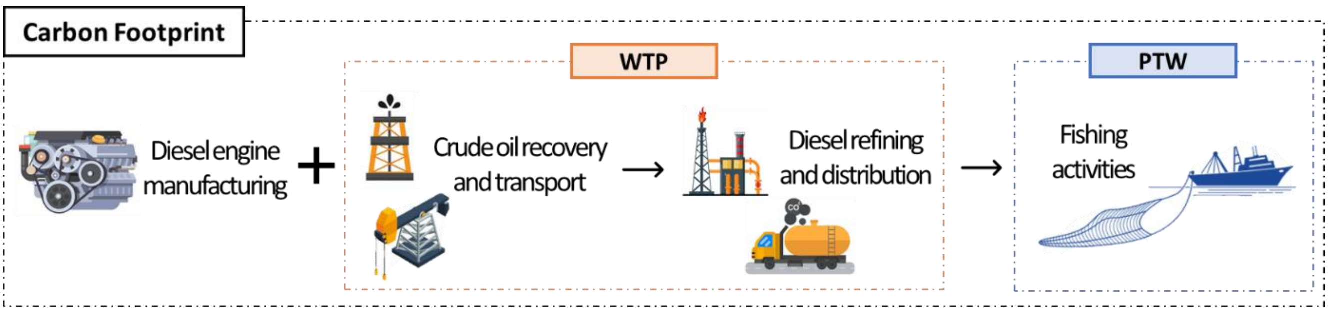

Figure 4. The LCA of a diesel-powered trawler.

The PTW emissions are calculated by Equation (1), with emission factors for diesel listed in Table 1.

Table 1. Emissions factors for different power options.

GHG	GWP	*EF*, g/kg Fuel		
		Diesel	LNG	Methanol
CO_2	1	3206	2750	1380
CH_4	25	0.06	51.2	-
N_2O	298	0.15	0.11	-

2.1.2. LCA of a Battery-Powered Trawler

Electrification as an environmentally friendly power configuration has attracted great attention in recent years [38]. The LCA analysis includes ME, WTP, and PTW phases, as presented in Figure 5. However, PTW emissions are equal to zero since, during fishing, the trawler does not release exhaust gases.

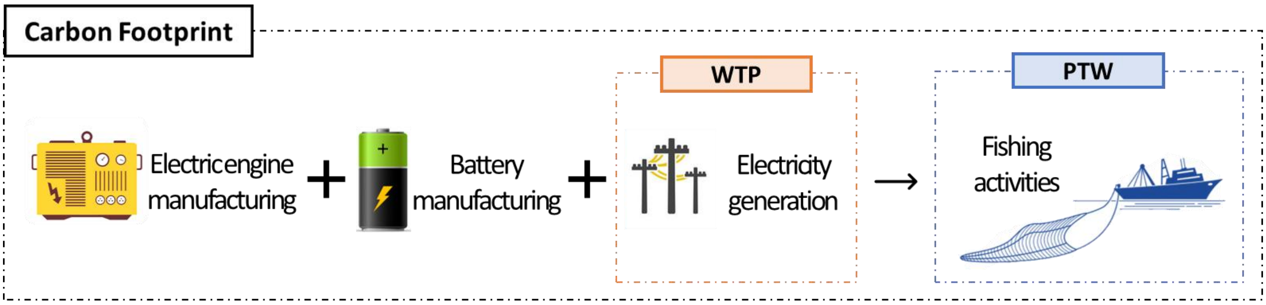

Figure 5. The LCA of a battery-powered trawler.

The most challenging part of electrification, at least in the economic sense, is the investment cost of the battery. There are different types of batteries, but despite the high price, the most commonly used is the lithium-ion (Li-ion) battery [38]. A Li-ion battery is characterized by its high energy density of 0.15–0.22 kWh/kg, especially compared to other types of batteries, and is widely investigated for shipping purposes [38,44]. The battery capacity (*BC*, kWh) depends on the operating requirements and is calculated as follows [11]:

$$BC = P_{eng} \cdot t_{daily}, \tag{4}$$

where P_{eng} stands for engine power (kW) and t_{daily} (h) denotes the daily operating time. For safety reasons, the required capacities are increased by 50%. It is assumed that the need for battery replacement is after 9000 charge and discharge cycles.

Further calculations include electricity generation and battery manufacturing. The environmental impact of battery manufacturing is calculated by using data from the GREET 2020 software database. The battery weight (*BW*) is calculated as follows 11]:

$$BW = \frac{BC}{BSE}, \tag{5}$$

where *BSE* represents the battery's specific energy (0.22 kWh/kg).

Electricity generation has an important role in the overall WTP emissions. The process is location-specific, whereby the LCA analysis is linked to a specific country and the results may not be valid for another one. The Croatian electricity mix for 2020 is taken into account, as shown in Figure 6. The electricity generation capacity includes 17 hydropower plants, 7 thermal power plants, one-half of the installed capacities of the nuclear power plant Krško (Slovenia), and many RES power plants [45].

2.1.3. LCA of a Methanol-Powered Trawler

Methanol is a toxic, biodegradable fuel produced by coal, natural gas, or biomass. It is an aggressive fuel, corrosive to fuel system components because it raises high concerns in engine manufacturing. However, when produced from natural gas, it has a low carbon content making it environmentally acceptable [11,46]. In marine transport, methanol can be easily adapted to be used in the current diesel infrastructure [46]. For instance, a methanol-powered trawler could operate in a dual-fuel mode, such as in MAN dual-fuel engine [47], with 95% methanol and 5% pilot fuel to initiate combustion. Diesel is considered the pilot fuel in this paper.

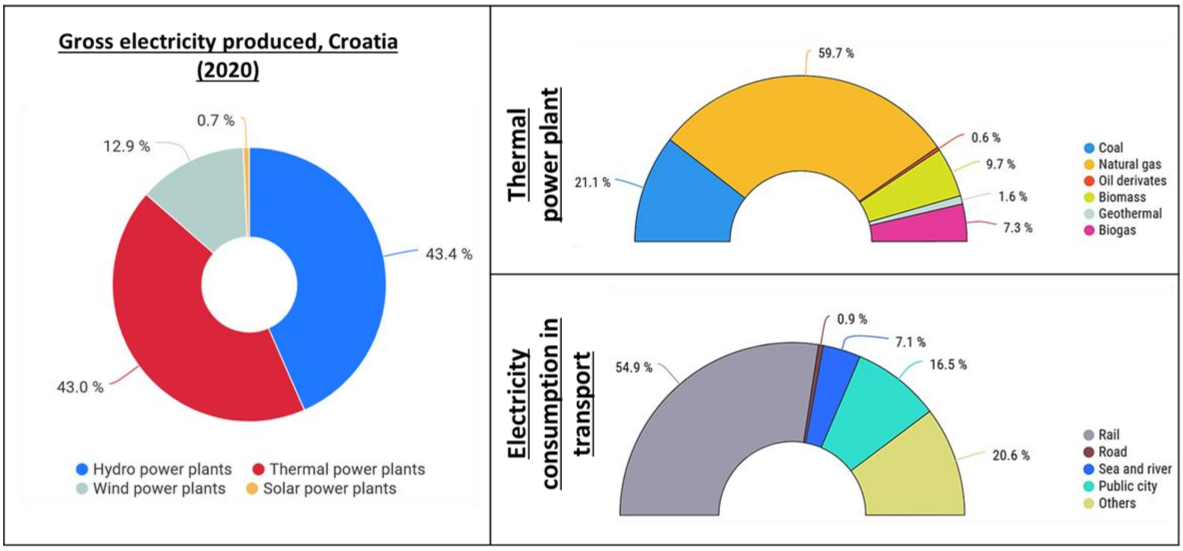

Figure 6. The Croatian electricity mix (2020).

When calculating the fuel consumption of a methanol-powered trawler, the specific fuel consumptions of methanol ($\mathrm{SFC_M}$) and specific fuel consumption of methanol (SFC_{P-M}) need to be considered. The specific consumption refers to a load of 75% and is equal to 327.20 g/kWh for $\mathrm{SFC_M}$ and 10.10 g/kWh for SFC_{P-M} [48]. The following equations are used for calculating the fuel consumption of methanol $\mathrm{FC_M}$ and fuel consumption of pilot fuel FC_{P-M} [11]:

$$FC_M = x_M \cdot EC \cdot SFC_M, \tag{6}$$

$$FC_{P-M} = x_{P-M} \cdot EC \cdot SFC_{P-M}, \tag{7}$$

where x_M and x_{P-M} refer to individual shares of fuels in a dual-fuel engine.

The LCA of a methanol-powered trawler includes emissions released during the dual-fuel engine manufacturing, the WTP phases of methanol and diesel as the pilot- fuel, and the emission released during fishing operations, i.e., PTW emissions. The LCA of a methanol-powered trawler is presented in Figure 7.

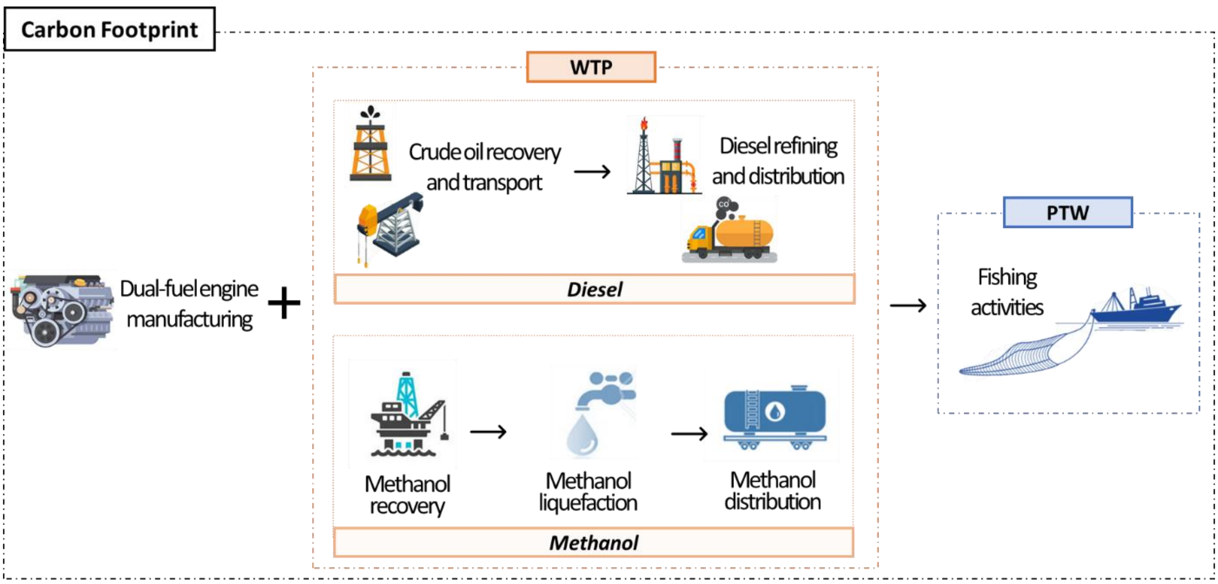

Figure 7. The LCA of a methanol-powered trawler.

The manufacturing phase for the dual-fuel engine is observed as for the diesel engine. Since a methanol-powered trawler consumes both methanol and diesel, it is logical to consider both fuels in the LCA analysis. The WTP phase of diesel is described in Section 2.1.1. The WTP phase of methanol has a similar production line. Firstly, methanol is produced from natural gas recovered and supplied by the Egyptian production facility [49]. The methanol is transported by 3000 km to Croatia by a methanol tanker and transported via tank trunks to refueling stations. The PTW emissions are calculated as similar to the ones in a diesel-powered trawler, with a difference in considering the combustion of both methanol and diesel. The tailpipe emissions are calculated as follows [11]:

$$TE_i = EF_{M,i} \cdot FC_M + EF_{P-M,i} \cdot FC_{P-M}, \tag{8}$$

where $EF_{M,i}$ and $EF_{P-M,i}$ describe the emission factor for different emission i of methanol and pilot-fuel, i.e., diesel, presented in Table 1.

2.1.4. LCA of an LNG-Powered Trawler

Natural gas (NG) is a fuel commonly used in land transport in several countries (Pakistan, Iran, Argentina, etc.) since it produces lower emissions than diesel and, currently, there are around 24 million natural gas vehicles across the world [50]. This non-toxic and non-corrosive fuel has a lower carbon content than diesel, making it competitive in the modern energy market focused on environmental friendliness [51].

Liquified Natural Gas (LNG) is a form of natural gas cooled at −163 °C to make it liquid and thus simplify the handling process. In the liquid state, the volume is 600 times smaller than in the gaseous state [52]. LNG is usually used in a dual-fuel diesel engine with the addition of a pilot fuel, similar to the methanol-powered vessel. In this paper, diesel is used as a pilot fuel in a proportion of 1%. Analogous to the methanol-powered trawler, the fuel consumption of LNG (FC_{LNG}) and pilot fuel (FC_{P-LNG}) is calculated according to Equations (6) and (7), where the specific consumption of LNG (SFC_{LNG}) is 154.4 g/kWh while the specific consumption of pilot fuel (SFC_{P-LNG}) is 1.8 g/kWh [53].

The LCA of an LNG-powered trawler is presented in Figure 8. The diesel part of the power configuration is described in Section 2.1.1. The WTP phase related to LNG describes the processes of natural gas recovery and its liquefaction and transportation. LNG is transported from Qatar to Croatia (7000 km) via LNG carriers and further transportation corresponds to the diesel transportation described in the previous subchapter. The PTW phase includes tailpipe emissions from both LNG and diesel combustion, calculated by the equation:

$$TE_i = EF_{LNG,i} \cdot FC_{LNG} + EF_{P-LNG,i} \cdot FC_{P-LNG}, \tag{9}$$

The emission factors are presented in Table 1.

2.1.5. LCA of an Ammonia-Powered Trawler

Ammonia is mainly associated with the food supply, which reacted to the growth in demand for ammonia of 1.9% from 2006 to 2016. A large share, approximately 79%, is used in the production of fertilizer and the rest for industrial applications. Ammonia is produced in a Haber–Bosch plant that produces anhydrous liquid ammonia from hydrogen (H_2) and nitrogen (N_2) [54]. Haber–Bosch synthesis is a reaction that combines nitrogen from the air and hydrogen at a high temperature (350–550 °C) and pressure (100–250 bar) [54]. Ammonia shows low specific energy and high auto-ignition temperature and has barre flammability limits, while hydrogen has the lowest ignition energy but the highest combustion velocity and widest flammability range. Thus, ammonia-hydrogen can be efficiently used in internal combustion engines [55]. A cracker is used to decompose ammonia into hydrogen and nitrogen and then the hydrogen is purified. A Proton Exchange Membrane (PEM) fuel cell with platinum electrodes is intolerant of impurities and therefore needs to be fed by pure hydrogen [56]. The fuel of ammonia is calculated as follows:

$$FC_{AM} = \frac{EC}{\eta_{CR} \cdot \eta_{PR} \cdot \eta_{FC} \cdot NCV_H \cdot x_H}, \tag{10}$$

where η_{CR} refers to the cracker efficiency (80%), η_{PR} refers to the purifier efficiency (90%), η_{FC} refers to the efficiency of the PEM fuel cell (55%), and NCV_H refers to the net calorific value of hydrogen (33.3 kWh/kg) with the hydrogen content in ammonia x_H of 17.8% [11]. For safety reasons, energy consumption is increased by 15%.

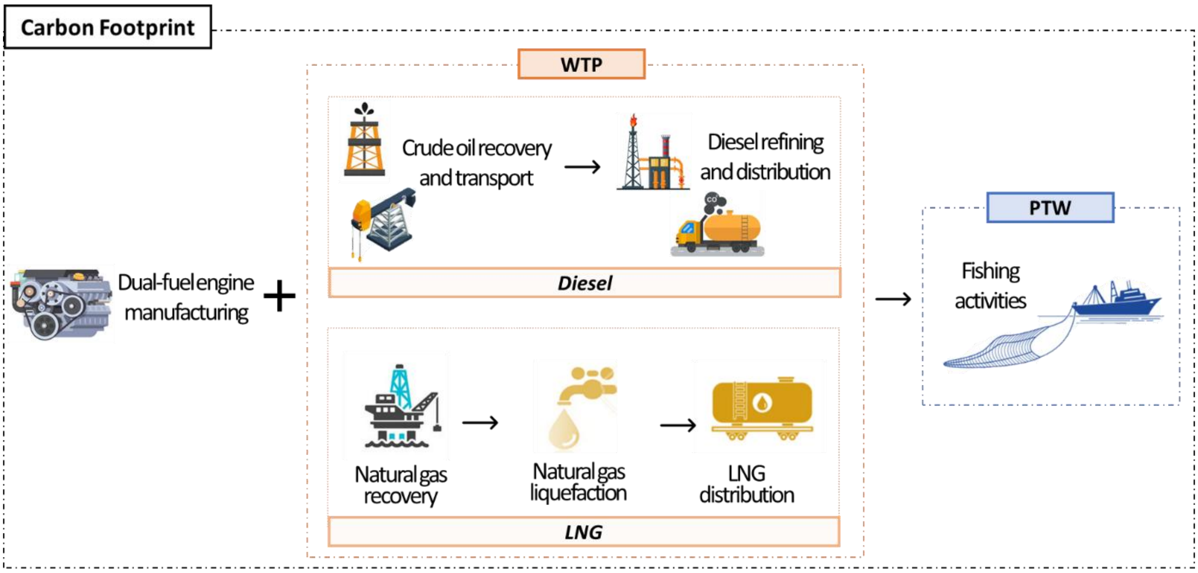

Figure 8. The LCA of an LNG-powered trawler.

The LCA of an ammonia-powered trawler is shown in Figure 9. The first phase includes the manufacturing process of a PEM fuel cell. The weight of materials in the PEM fuel cell is measured according to Perčić et al. [11]. The WTP phase describes the process of natural gas recovery, ammonia production, and its distribution by tank trucks. Ammonia is produced in Western Europe and is transported to Croatia in a liquid state by tank trucks (approximately 1300 km). The PTW phase can be neglected since there are no tailpipe emissions during fishing activities. PEM fuel replacement is considered after 20,000 working hours.

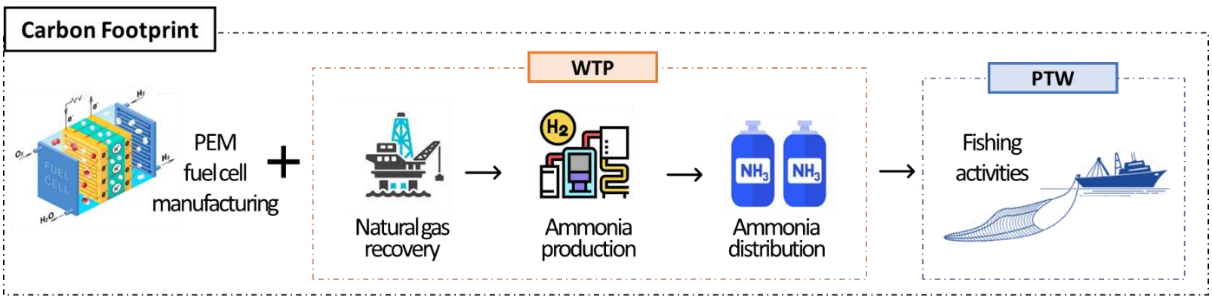

Figure 9. The LCA of an ammonia-powered trawler.

2.1.6. LCA of a B20-Powered Trawler

Biofuels are being widely investigated in recent years. First-generation biofuels are made from sugar and starch from food crops (corn, vegetable oil, sugarcane, etc.), while next-generation biofuels are made from non-food crops such as wastes and agricultural residues [50]. Ethanol is the most commonly used biofuel, made from corn and sugarcane and used as a gasoline component. In this paper, biodiesel is investigated. Biodiesel is made from the esterification of vegetable oil, as presented in Figure 10. The properties are similar to those of diesel fuel, because of which it can be used in a diesel engine without modifications [8]. Biodiesel is usually a blend with fossil fuel and is often described as BXX, where XX indicates the percentage of biodiesel in the blend. In this paper, a soybean–biodiesel–diesel blend, B20, will be used, i.e., 20% biodiesel blended with 80% diesel. The biodiesel is imported from the Veneto region in Italy, where the fuel is processed from soybeans. In the LCA, the WTP phase of B20 includes the process of diesel production and refining, described in Section 2.1.1, and the production of biodiesel, i.e., soybean farming, soy oil extraction, and transportation to the transesterification plant. At a refueling station, the biodiesel and diesel are mixed into a B20 blend and distributed. The percentage of biodiesel in the blend has a significant impact on tailpipe emissions. Since biofuels are carbon-neutral, CO_2 emissions are not included in the LCA, and other emissions are negligible [8]. Thus, the tailpipe emissions depend only on the combustion of diesel and are calculated as follows:

$$TE_i = 0.8 \cdot FC_{B20} \cdot EF_{i,D}, \quad (11)$$

where FC_{B20} refers to the fuel consumption of a B20-powered trawler. The emission factors of diesel are presented in Table 1.

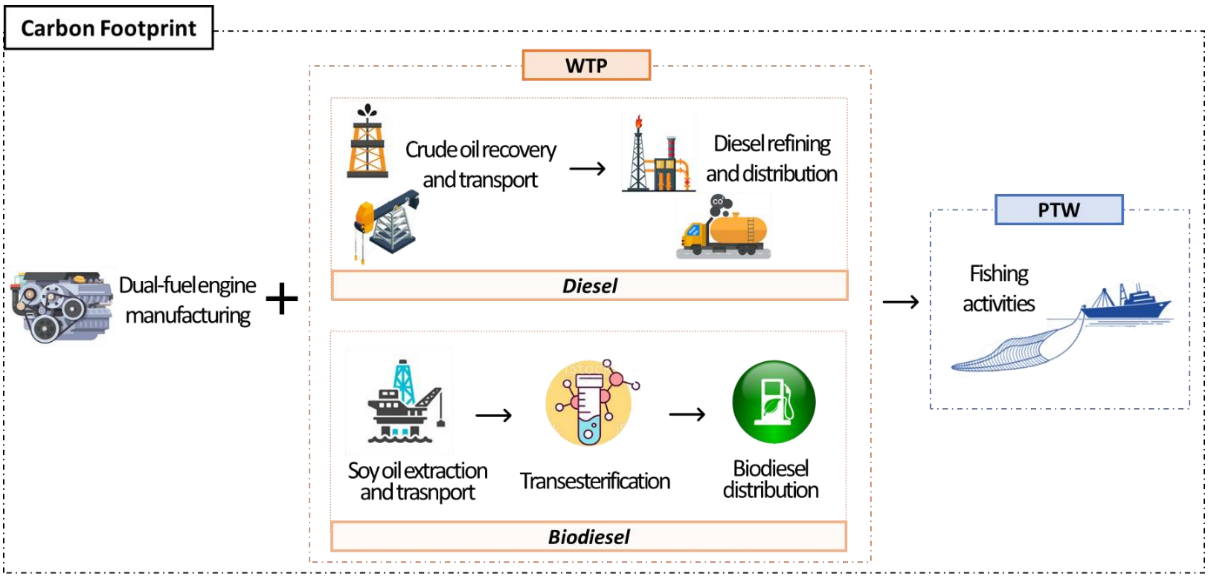

Figure 10. The LCA of a B20-powered trawler.

2.1.7. LCA of a Hydrogen-Powered Trawler

Hydrogen is a non-toxic, inodorous, abundant gas, which generates more energy per mass compared to conventional fuels used for shipping and does not result in tailpipe emissions during combustion [8]. Because of its electrochemical kinetics, it can be applied in fuel cells, such as a Proton Exchange Membrane (PEM) fuel cell with a platinum electrode. Although hydrogen presents a green alternative option, its low storage density, high investment costs, high fuel prices, and complex implementation that requires expert knowledge often make practical implementation impossible [8,11].

Depending on the production process, there are several types of hydrogen that can be distinguished. For instance, grey hydrogen is produced from fossil fuels and thus releases a share of CO_2 emissions; blue hydrogen is produced from fossil fuels, but it is manipulated with Carbon Capture and Storage technology, which reduces the released CO_2 emissions; and green hydrogen is a clean fuel produced by RESs [9].

Similar to the ammonia calculations, the hydrogen consumption is calculated by the following equation:

$$FC_H = \frac{EC_H}{\eta_{FC} \cdot NCV_H}, \tag{12}$$

where EC_H refers to the annual energy consumption of a trawler, η_{FC} is the hydrogen efficiency of 48%, and NCV_H refers to the net calorific value of hydrogen of 33.3 kWh/kg [11]. It is assumed that the PEM fuel cell is supplied with hydrogen produced from natural gas off-board, produced in Western Europe, and transported to Croatia via tank trucks in liquid form [11].

The LCA of a hydrogen-powered trawler is presented in Figure 11. It is shown that the total CF is affected by the manufacturing process of the PEM fuel cell (ME phase), the process of hydrogen production, and fishing operations (PTW phase). The process of hydrogen manufacturing includes also natural gas recovery, hydrogen production and liquefaction, and its distribution (WTP phase). Even though the implementation of hydrogen has a complex WTP phase, there are no tailpipe emissions released during the PTW phase, making it suitable for application [11].

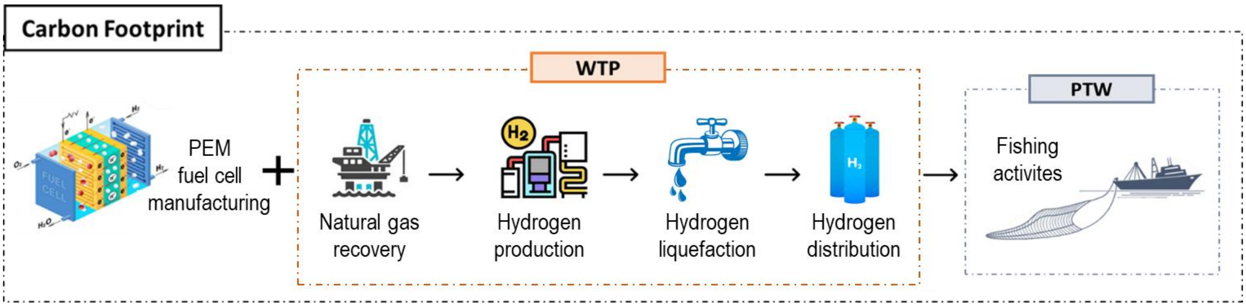

Figure 11. The LCA of a hydrogen-powered trawler.

2.2. Life-Cycle Cost Assessment

The previous subchapter deals with the procedure of evaluating the effect of different power configurations on the environment. To achieve a complete understanding of the mentioned alternative fuels, an economical assessment needs to be conducted. The LCCA considers the total costs (investment costs, maintenance costs, and fuel costs) of a power configuration during the lifetime of a trawler.

The investment cost is related to the acquisition of the power system configuration, such as a diesel engine, dual-engine, battery, or fuel cell. The maintenance cost refers to replacing the main parts of a power system after an exploitation period. The fuel costs include the cost of fuel used during fishing activities taking into account the price of different fuel types and their percentage in different fuel blends. The cost of different fuels in €/kg fuel is presented in Table 2.

Table 2. Fuel prices in 2020 [11].

Fuel Type	Cost, USD/kg Fuel
Diesel	0.81
Electricity	0.081
Methanol	0.34
LNG	1.14
Ammonia	0.72
B20	1.53
Hydrogen	9.81

2.2.1. LCCA of a Diesel-Powered Trawler

The investment cost of a diesel-powered trawler considers the price of a new diesel engine and the average power needed for performing fishing activities. The investment cost IC_D is calculated by the following equation:

$$IC_D = P_{eng} \cdot C_{D,eng}, \tag{13}$$

where P_{eng} refers to the engine power, in kW, and $C_{D,eng}$ refers to the cost of a diesel engine (USD/kW). The life-cycle fuel cost $LCFC_D$ calculated the cost of fuel used during the lifetime LT of the trawler and it is calculated according to the equation:

$$LCFC_D = FC_A \cdot PR_D \cdot LT, \tag{14}$$

where FC_A denotes the annual fuel consumption in kg and PR_D denotes the price of diesel in USD/kg fuel. The life-cycle maintenance cost $LCMC_D$ is calculated according to Equation (14):

$$LCMC_D = EC_A \cdot MC_{D,eng} \cdot LT, \tag{15}$$

where EC_A denotes the annual energy consumption of the trawler in kWh and $MC_{D,eng}$ refers to the maintenance of a diesel-powered trawler and equals 0.015 USD/kWh [11].

2.2.2. LCCA of a Battery-Powered Trawler

The modifications of a trawler needed for implementing a battery-powered system result in a high investment cost, where 45% relates to the battery price and the rest refers to installation, electric engine, and additional costs. The investment cost is calculated as follows [11]:

$$IC_B = \frac{BC \cdot BP_{2020}}{0.45}, \tag{16}$$

where BC refers to the battery capacity, calculated in Section 2.1.2, and BP_{2020} denotes the price of the battery assumed to be 208 USD/kWh in 2020 [11]. The $LCFC$ of a battery-powered configuration is calculated by Equ ation (16) and the assumed electricity price PR_{elec} for a medium-sized Croatian industry is presented in Table 2:

$$LCFC_B = EC_A \cdot PR_{elec} \cdot LT. \tag{17}$$

Since there is no need for a battery replacement during the lifetime of a trawler, the maintenance cost equals zero.

2.2.3. LCCA of a Methanol-Powered Trawler

The installation of a methanol power system results in an investment in a new engine and associated equipment, with a conversion rate of 780 USD/kW:

$$IC_M = P_{eng} \cdot 750. \tag{18}$$

The maintenance cost of a methanol-powered trawler is equal to the maintenance cost of a diesel-powered trawler described in Section 2.2.1. The life-cycle fuel cost of a methanol-powered trawler includes the diesel price, as the pilot fuel PR_{P-M}, and the methanol price PR_M and it is calculated according to Perčić et al. [11]:

$$LCFC_M = LT \cdot (FC_{A,M} \cdot PR_M + FC_{A,P-M} \cdot PR_{P-M}), \tag{19}$$

where $FC_{A,M}$ denotes the annual fuel consumption of methanol and $FC_{A,P-M}$ denotes the annual fuel consumption of diesel, as the pilot fuel. The methanol price presented in Table 2 is the price set by the producer increased by the Croatian VAT of 25%.

2.2.4. LCCA of an LNG-Powered Trawler

Similar to the methanol-powered configuration, the investment cost of an LNG-powered trawler is calculated by taking into account the engine power and the conversion rate of 1207 USD/kW:

$$IC_{LNG} = P_{eng} \cdot 1160. \tag{20}$$

The life-cycle fuel cost is calculated according to Equation (18), where FC and the prices of both LNG and diesel are considered. The price of LNG in Europe varies [11]. In this paper, the higher price is considered to compare the efficiency of implementing an LNG-powered system at the highest current price. The maintenance cost is calculated by the following equation:

$$LCMC_{LNG} = EC_A \cdot MC_{LNG} \cdot LT, \tag{21}$$

where MC_{LNG} denotes the maintenance cost of 0.016 USD/kWh [11].

2.2.5. LCCA of an Ammonia-Powered Trawler

The investment cost of an ammonia-powered trawler IC_{AM} includes the cost of the PEM fuel cell PR_{PEM}, which depends on the power of fuel cell P_{fc}. The IC_{AM} is increased by 30% to consider the cracker and purifier needed in the power system:

$$IC_{AM} = 1.3 \cdot PR_{PEM} \cdot P_{fc}. \tag{22}$$

The maintenance cost includes only the replacement of the fuel cell and equals its capital cost of 382 USD/kW [11]. The life-cycle fuel cost of an ammonia-powered trawler is calculated according to the equation:

$$LCFC_{AM} = LT \cdot FC_{A,AM} \cdot PR_{AM}, \tag{23}$$

where $FC_{A,AM}$ denotes the annual fuel consumption of ammonia and PR_{AM} denotes the price of ammonia (Table 2).

2.2.6. LCCA of a B20-Powered Trawler

The properties of biodiesel are similar to those of diesel, due to which the investment and maintenance costs of a B20-powered trawler are equal to that of a diesel-powered trawler.

The life-cycle fuel cost is calculated according to the following equation [11]:

$$LCFC_{B20} = LT \cdot (FC_{A,B20} \cdot PR_{B20} + FC_{A,D} \cdot PR_D), \tag{24}$$

where FC denotes the annual fuel consumption of B20 and diesel, and PR denotes the price of biodiesel and diesel. The price of biodiesel is assumed to be 1.54 USD/kg, the same as the regular price of Croatian diesel in 2020 [11].

2.2.7. LCCA of a Hydrogen-Powered Trawler

The life-cycle investment costs of a hydrogen-powered vessel include the investment of a PEM fuel cell of 382 USD/kW, increased by 20% and thus considering the additionally required equipment, and the storage cost is calculated by multiplying the amount of hydrogen required for ship operation by the storage price of 5.20 USD/kWh [11]. The maintenance cost considers the replacement of the fuel cell and equals the cost of the PEM fuel cell [11]. The price of hydrogen varies between 5.57 and 9.81 USD/kg [11], and for the calculation of the fuel costs, the upper limit was considered and multiplied by the fuel consumption of hydrogen over a 20-years period.

3. Illustrative Example

Trawlers make up 14% of the Croatian fishing fleet and approximately 8% of the total catches. The catches consist of different types of white fish (cod, haddock, pollock, etc.), mollusks (squid), crustaceans (shrimp), and a percentage of bycatch. Even though trawlers make a small share of the total catch, the price of white fish has a higher market value than the small pelagic fish caught by purse seiners, thus their profit is similar [57].

The trawler investigated in this paper operates in the central Adriatic Sea in Croatia, mainly around the cities of Zadar and Primošten, as shown in Figure 12. The main engine is powered on "Eurodiesel Blue", a commonly used fuel in the marine sector, which consists of diesel with up to 0.5% sulphur [58]. Other particulars of the trawler are presented in Table 3.

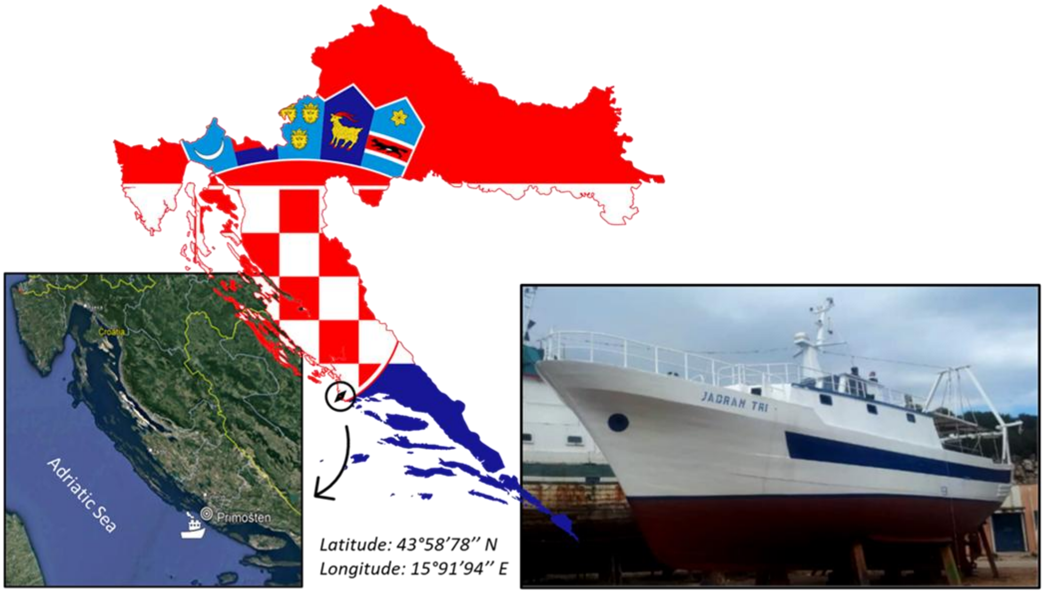

Figure 12. Operating location of the studied trawler.

Table 3. Main particulars of the studied trawler.

Trawler "Jadran III"				
Length overall (LOA), m			22.1	
Breadth, m			5.65	
Draught, m			1.986	
Gross Tonnage (GT)			65	
Engine power, kW			223	
Speed—average, kn			3.6	
Speed—maximum, kn			6.3	
Fuel consumption FC, kg per year				
2015	2016	2017	2018	2019
61,830.8	65,753.3	60,691.4	62,654.8	69,042.7
Landed fish, kg per year				
2015	2016	2017	2018	2019
32,554.4	45,685.4	42,621.1	41,464.8	45,490.1

When evaluating the environmental footprint of different power configurations, the operating time needs to be established. After conducting a review of the Croatian Official Gazette [59] and interviewing the captain of the trawler, it is assumed that trawlers spend approximately 14 h/day and approximately 200 days per year at sea. The lifetime of the trawler is considered to be 20 years.

Environmental and economic assessments of different configurations are conducted and compared with a diesel-powered trawler operating in the Adriatic Sea. The results of LCA and LCCA are presented in Figures 13 and 14, respectively.

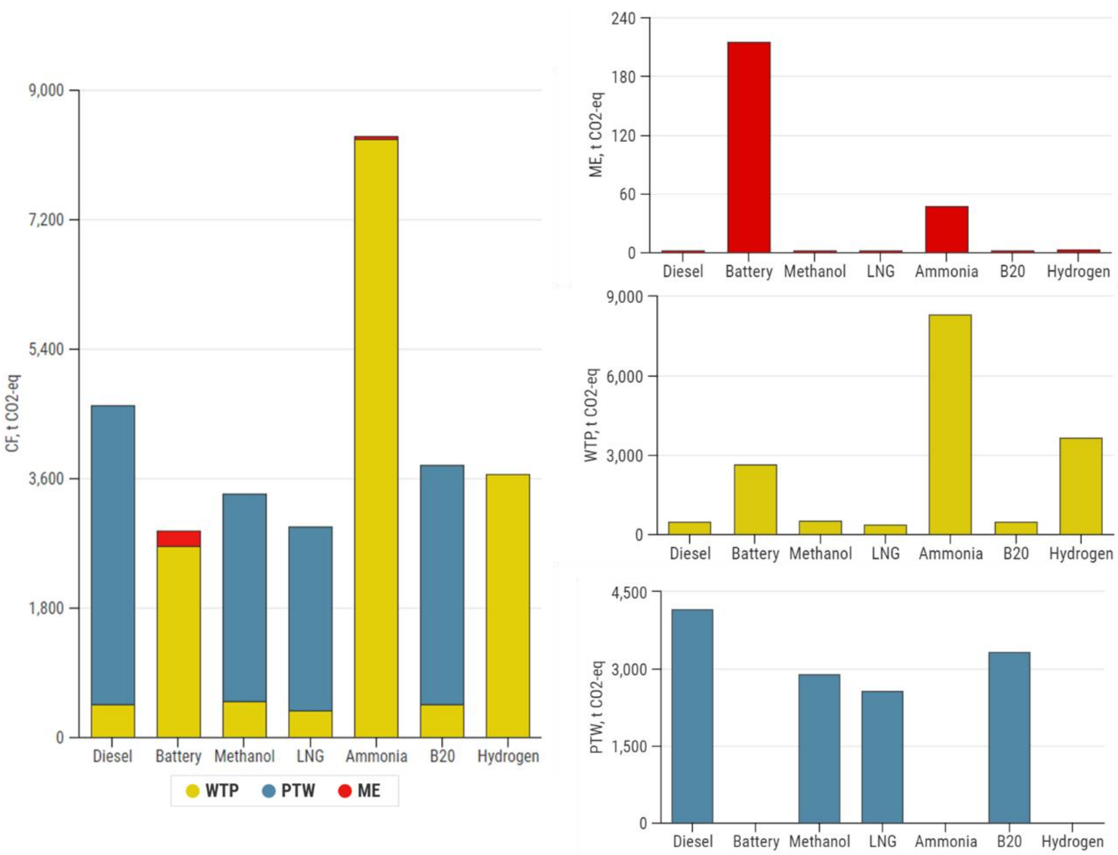

Figure 13. LCA results for a trawler "Jadran III".

The LCA indicated a CF reduction in each alternative option except ammonia. The analysis of the diesel-powered trawler showed the highest emissions in the PTW phase, with almost 90.15%. Emissions during the manufacturing of a diesel engine can be neglected, due to the extremely low values. The WTP phase makes up approximately 9.80% of total emissions. Similar shares are achieved in the cases of methanol-powered, LNG-powered, and B20-powered trawlers. Since all three configurations use a diesel engine, the manufacturing emissions have the same values as those in a diesel-powered trawler. The WTP emissions are slightly higher than in the case of diesel. For the case of methanol, the value goes up to 14.76%, for LNG up to 12.58%, and for B20 up to 11.94%. The PTW emissions make up the rest of the total emissions, and a reduction in $CO_{2\text{-eq}}$ is visible compared to the diesel-powered trawler. Completely different values were calculated in the case of electrification and an ammonia-powered trawler. The LCA of a battery-powered trawler resulted in high WTP emissions (92.50%) and slightly higher emissions during manufacturing. In the case of an ammonia-powered trawler, the WTP phase results in very high values of $CO_{2\text{-eq}}$ emissions that are 99% higher than in the case of a diesel-powered trawler. The LCA of a hydrogen-powered trawler showed a higher share of WTP emissions than the diesel-powered trawler, even 8 times higher. However, hydrogen results in zero PTW emissions, which affects the total CF, making the value lower than that of the diesel-powered one. It can be concluded that ammonia does not present an environmentally friendly solution, and hydrogen needs to be analyzed from an economic aspect to ensure that the investment is justified in relation to the low emission reduction.

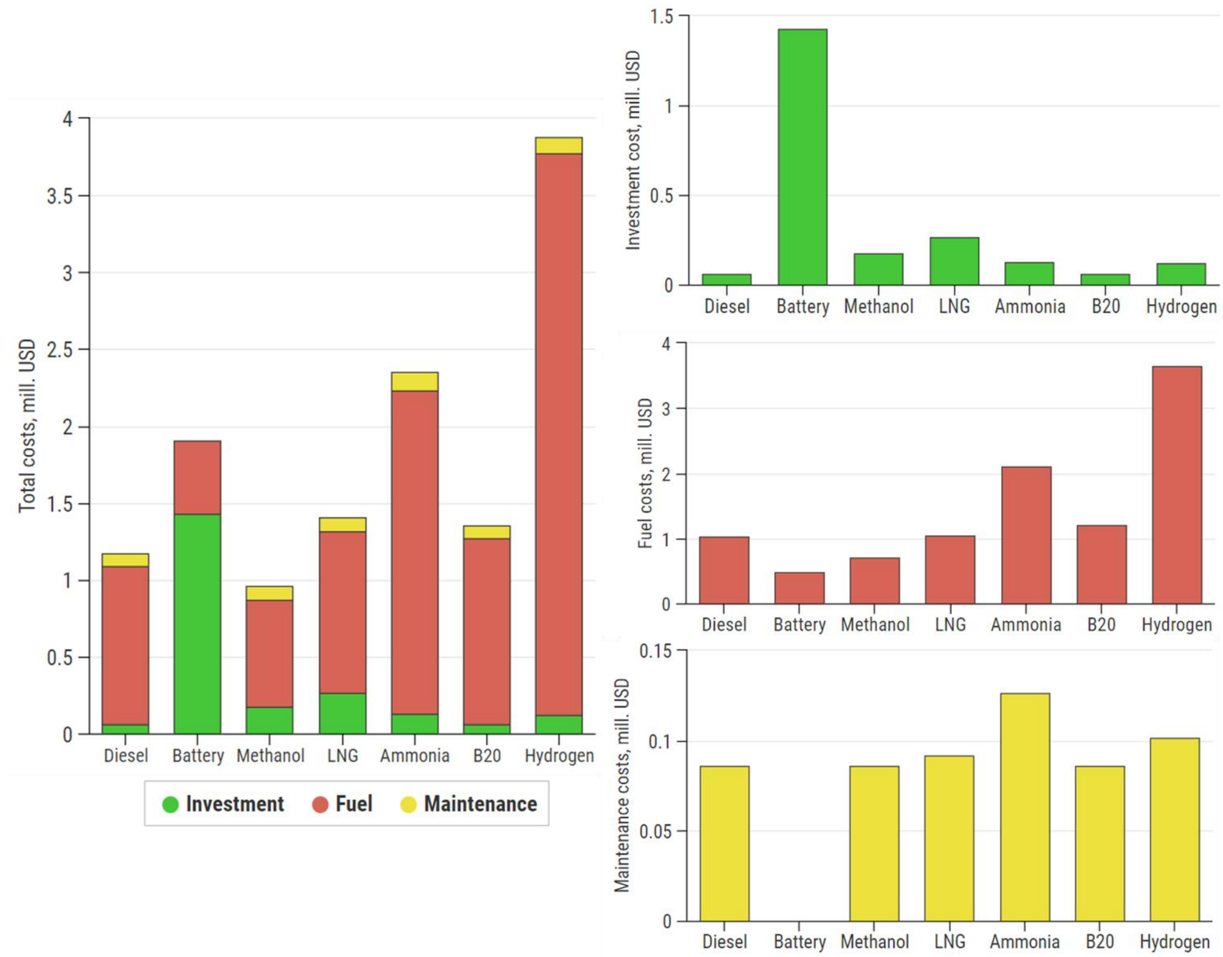

Figure 14. LCCA results for a trawler "Jadran III".

Despite the fact that the LCA showed how several alternative fuels present a possible solution in emission mitigation, the LCCA presented the economic viability of such implementations. It has already been shown in the LCA that an ammonia-powered trawler does not present a suitable solution. The LCCA has confirmed the statement by resulting in very high fuel costs, almost 2 times higher than in the case of a diesel-powered trawler. As expected, the hydrogen-powered solution resulted in very high total costs, especially when considering fuel costs. When the minimal emission reduction achieved by its implementation is taken into account along with the price, hydrogen does not present an optimal solution. A B20-powered trawler also produces higher fuel costs, being approximately 18% higher than diesel fuel but 42% lower than ammonia. Currently, B20 presents a good solution, but further research should include a forecast of the diesel price increase. A battery-powered trawler requires high investment costs, over 20 times higher than in the case of a diesel-powered trawler, which makes it an economically unacceptable solution. Methanol and LNG present two good options. A methanol-powered trawler resulted in the lowest total costs compared to other power configurations. The investment costs for both methanol and LNG-powered trawlers are approximately 2 times higher compared to diesel, but the cost is admissible. The maintenance costs for both options are equal to the maintenance costs of a diesel-powered trawler. The methanol-powered trawler has an advantage over an LNG-powered trawler when considering the fuel costs. The LNG-powered trawler produced approximately 2% higher fuel costs than the diesel-powered one. However, considering the CF reduction that can be achieved by its implementation, the slightly higher investment in fuel can be considered acceptable. The LCCA analysis showed that a methanol-powered trawler results in the lowest fuel costs when neglecting the battery-powered configuration due to extremely high investment costs. The fuel costs are over 30% lower than in the case of a diesel-powered trawler.

The obtained results show the environmental and economic performance of different power options. However, the properties of the proposed alternative fuels are influenced by the production process of the considered country. In the following section, the influencing factors are discussed.

4. Discussion

The study includes the results of an LCA and an LCCA performed for a fishing vessel operating in the Adriatic Sea. Although efforts were made to include as much data as possible, in order to obtain high-accuracy results, in this phase of the research, there were certain limitations, either due to the software tool or the current lack of access to certain data. The limitations of this research are:

- The recycling phase was not taken into account.
- Data on fuel consumption is gathered on an annual basis.
- The impact of the route characteristics and weather conditions were not taken into account while analyzing the fuel consumption.
- Only atmosphere emissions were analyzed while marine pollution or solid waste were neglected in this phase of the assessment.
- It is assumed that the entire diesel system is replaced with one alternative fuel, and hybrid solutions are not analyzed.
- Due to the large variation in energy prices within one year due to the COVID-19 pandemic and political situations within Europe, it was difficult to determine a mean price for 2022, the value of which could be valid for a longer period.

Fisheries are considered the main drivers of environmental changes in global oceans, from degrading marine ecosystems, bycatch, and seabed damage due to trawling to indirectly changing environmental dynamics [17,60]. Research even showed that excessive fishing not only affects the increase in mortality and the creation of dead zones but also the increase in the number of predators (such as seagulls), which changes the natural relationships of species [60,61]. The pelagic birds encounter other pollution in the form of marine plastics, which harms their health but also carries plastic further along the coast [62]. To improve their environmental footprint, efforts are made to reduce fuel consumption by increasing selectivity during the catch, for example, by spatial planning and reducing the discard ratio [63] or changing gear type [64]. Given that previous results showed that engine power is necessary for trawlers, and it is difficult to influence the quality of the catch or change the method of catching, alternative fuels have proven to be the optimal solution in reducing CF [65], which was also shown in this research. The analysis distinguished methanol as the best solution; however, the results may not be applicable to other countries. Different fuel prices, production possibilities (including tillage land, water supply, electricity mix, etc.), and energy demands have an important impact on GHGs emissions. Industry and transport in general are considered the most expensive sectors for decarbonization, especially when considering the costs and emissions during the construction of wind turbines and solar panels and the upgrading of existing infrastructure [66].

Much research has introduced electrification as the most beneficial alternative power option in the marine sector, but the implementation in fisheries may be too expensive in relation to the benefit it would bring. The introduction of electric fuels [67] may resolve the problems regarding high investment costs since the goal of this research is to use existing infrastructure and distribution networks. Since fuel costs are driven by electricity prices, future research will provide a better understanding of the economic efficiency of electric fuels [67]. Despite all the environmental influences, trawling is the dominant fishing practice worldwide for catching demersal and benthic species and is considered one of the most destructive fishing methods [17].

The use of LNG as a marine fuel has gained much recognition. Its resemblance to diesel fuel makes implementation easier to understand and the needed modifications easier to carry out. The liquefcation simplifies transport and distribution, but additional capital costs for infrastructure may occur. The integration of natural gas with fuel cells and internal combustion engines offers the possibility of improving efficiency by over 5% with a NO_X reduction of approximately 30% and a CO_2 reduction of approximately 12% [68].

Fuel cells also showed great potential when combined with bio-methanol. The results of research [69] showed that the fuel production process has an important role in the LCA, and extremely better environmental performances were achieved while using a Solid Oxide Fuel Cell system in comparison with a conventional engine as an auxiliary generator. A methanol-powered system was also presented in [11], where great results in an environmental and economic sense were achieved in the cases of different types of short-sea vessels. A reduction in CF was achieved for the cargo ship by 28%, for the passenger ship by 33%, and for the dredger by 30% [11].

Biodiesel is very dependable on feedstock, land type, crop yield, and the process of production, thus the cost of production is affected by the country's laws and procedures. When comparing the production process in the EU and USA, a significant difference is visible. In the EU, approximately 80% of the biofuel is biodiesel made from edible oil seeds, which produces 80% more CO_2 emissions than the fossil diesel it replaces. The biodiesel produced from palm oil showed even worse results, with three times higher emissions than fossil diesel. In the USA, 46% of corn production is invested in ethanol production, which supplies less than 3% of the total transport energy used. In the case that total corn and soybean production goes to biofuel production, the small energy demand would be met, making the production unprofitable. Since production requires land and water supply, algae present a promising feedstock source for biofuel production in the future. However, the process entails challenges, which need to be resolved in further research [69].

Ammonia, similar to biodiesel, is also impacted by the source of production. Several research studies focused on the production of green ammonia produced from algae, which can be of great importance in the near future [54,55,70]. The price of green ammonia could decline by 2050 and become cost-competitive with fossil-based ammonia. Currently, the algae farm infrastructure requires specific components for CO_2 handling, which can be used as a high-purity source for biofuel production and thus reduce GHGs emissions.

In this paper, the fuel prices from 2020 have been taken into account. In the last year, the prices of raw material had a nonlinear increase, and it is difficult to predict the price fluctuations and their effect on global oil consumption [71]. Because of the sharp increase, it is difficult to assume an average price that could be valid in the future. Therefore, an analysis of fuel price fluctuations and their effect on the total costs was conducted and is presented in Figure 15. Hydrogen and ammonia showed very high values of fuel cost, and thus, compared to other alternative solutions, they are very unsuitable for application. However, if the price of ammonia drops by 30%, the overall costs become lower than in the case of electrification, but, keeping in mind that the emissions released in the case of an ammonia-powered trawler are extremely high, the solution still is not adequate. Considering the current trends, an additional increase in fossil fuel prices is expected, which increases the possibility of their application in fisheries becoming nonviable. Biodiesel resulted in a higher value than diesel, but if the price decreases, the B20 application should be considered. LNG showed similar values as diesel. Considering that the LNG-powered trawler showed a reduction in emissions, further implementation should be investigated. Increases in total costs, even in the case of a 50% higher fuel price, calculated for the case of B20 and LNG can be considered acceptable if the emission reduction is significant and the additional investment is trivial in relation to the profit. The analysis of methanol, next to the LCA and LCCA results, shows that methanol should be considered an efficient solution for the improvement of the environmental friendliness of fishing vessels. Even if the price increases by 50%, it still presents the most economically approachable configuration.

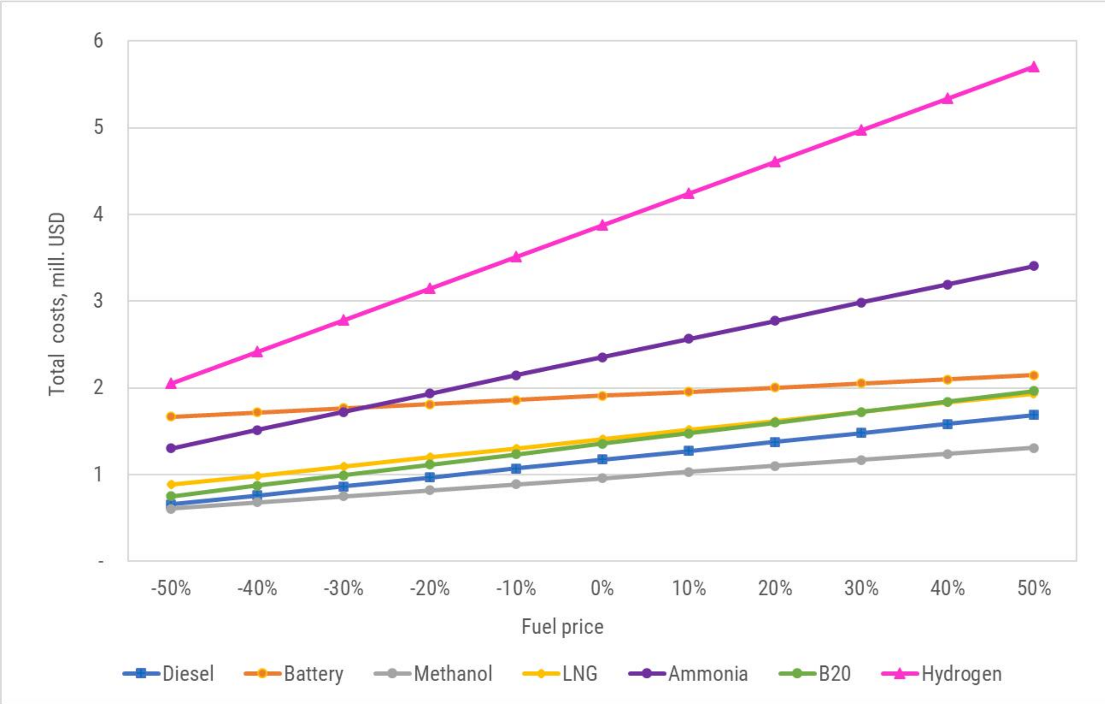

Figure 15. Total costs with respect to fuel price fluctuations.

The fisheries sector is limited when it comes to investment, at least compared to passenger and cargo transport, which have a more stable income. Given that most alternative fuels incur significant costs, there is a good chance that this approach will not be possible to implement in all fisheries. In further investigation, it is important to consider the social benefit of implementing emission mitigation measures, not only in terms of environmental restoration but also the benefit to individuals working in the fisheries sector and their contribution to the coastal population in general.

5. Conclusions

Environmental regulations and strategies aim to implement technical and operative measures in the shipping industry with the goal of reducing its environmental impact. Compared to long-distance shipping, short-sea shipping, and inland waterway transportation, the fishing sector has been neglected through the years, but new measures are being introduced to improve this sector as well. This paper presented a standard trawler operating in the Adriatic Sea and an analysis was conducted to evaluate the viability of replacing conventional diesel fuel with cleaner marine fuels. The analyzed trawler belongs to a group of vessels with smaller dimensions and the engine power is barely 223 kW, making it relatively small compared to purse seiners or passenger vessels. However, the trawler leaves a significant environmental footprint on the marine environment, including the atmosphere and pollution of the seabed. Even though new regulations are trying to ban trawlers to reduce the environmental footprint, due to the specific targeted catch (such as white fish or shrimps), the profit achieved is significant both for the fishermen as individuals and for the country. Croatia is a good example of this since trawlers make up 14% of the total fishing fleet.

Diesel fuel, used almost exclusively in the Croatian fisheries, was compared to six alternatives—battery, LNG, methanol, ammonia, B20, and hydrogen. The results of the LCA were used to establish the most environmentally friendly option, while the results of the LCCA provided insight into the economic efficiency of these options. The main findings of the study are summarized as follows:

- A variety of alternative fuels, RESs, and other strategies related to operational measures allow for finding the optimal methods for improving the environmental friendliness of fishing vessels.
- The LCA of a diesel-powered trawler indicated that 90.15% of the total emissions are produced during the PTW phase, i.e., during fishing activities. Therefore, a reduction in fuel consumption proves to be the optimal solution for reducing CF.
- Even though electrification presents an ideal green energy solution with zero PTW emissions, which is very effective in shortsea shipping, the investment cost and underdeveloped infrastructure in fishing ports make this option ineffective and quite expensive for implementation.
- Fossil-fuel alternatives, such as LNG and biodiesel, provide a CF reduction compared to diesel. The advantage of these types of alternative fuels is their similarity to diesel fuel, making them simple to implement into an existing power configuration. The negative side of LNG and biodiesel is the price of fuel, which is expected to rise through the years.
- Compared to diesel, LNG-powered trawlers result in 2% higher fuel costs, but the positive impact in the form of the emission reduction justifies the additional investment (the difference could be co-financed by the government in the future).
- Results for a methanol-powered system showed a significant CF reduction compared to diesel at reasonable costs.
- Hydrogen also results in zero PTW emissions, but high WTP emissions were obtained during its production and distribution.
- Taking into account that the application of hydrogen incurs very high fuel costs, at approximately 3 times higher than diesel, a hydrogen-powered system is currently not an ideal solution for implementation in fishing vessels.

Further research will focus on hybrid power configurations, which could be applicable in the Croatian fishing sector. Wider research will include purse seiners as they are a type of fishing vessel commonly found in world fisheries. A share of RESs on the vessel will also be analyzed as a solution for powering additional equipment such as lighting, ice production, air conditioning, etc. The viability of such systems will be assessed by taking into account the environmental impact, cost-effectiveness, and social benefit. The overall goal of the research, including future activities, is to create a general approach to replacing diesel-powered systems in fishing vessels with "green" alternatives. By simplifying the process of choosing the optimal power system, hybrid or single fuel, fishermen will be able to easily choose a suitable solution for their fishing vessel and implement it while making a profit. Moreover, the example elaborated on in the territory of Croatia will be generalized and thus be applicable to other locations. With cooperation with other researchers, the dataset will be increased and will be used for the validation of other results, and thus the quality and accuracy of the data will be enhanced over time.

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Nomenclature and Abbreviations

Variables		Abbreviations	
B	ship breadth (m)	CF	Carbon Footprint
BC	battery capacity (kWh)	GHG	Greenhouse Gas
E	electricity consumption (kWh/kg)	GWP	Global Warming Potential
EC	energy consumption (kWh/kg)	HFO	Heavy Fuel Oil
EF	emission factor (g emission/kg)	FAO	Food and Agriculture Organization
FC	fuel consumption (kg/kg fish)	IMO	International Maritime Organization
IC	investment cost (USD)	LCA	Life-Cycle Assessment
LCFC	life-cycle fuel cost (USD)	LCCA	Life-Cycle Cost Assessment
LCMC	life-cycle maintenance cost (USD)	LNG	Liquefied Natural Gas
LT	lifetime (year)	ME	Manufacturing Phase
P	power (kW)	PEM	Proton Exchange Membrane
PR	price (USD)	PTW	Pump-to-Wheel
SFC	specific fuel consumption (kg/kWh)	RES	Renewable Energy Source
T	draught (m)	WTP	Well-to-Pump
TE	tailpipe emission (kg emission/kg fuel)		
v	speed (kn)		
x	share of a fuel (%)		
Subscripts		Units	
A	annual	kn	knot (nm/h)
AM	ammonia-powered ship	nm	nautical mile (1 nm = 1.852 km)
ave	average		
BD	biodiesel		
D	diesel-powered ship		
E	electricity-powered ship		
FC	fuel cell		
i	emission		
LNG	LNG-powered ship		
M	methanol-powered ship		
$P-M$	pilot fuel in the methanol-powered ship		
$P-LNG$	pilot fuel in LNG-powered ship		

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