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MATHEMATICAL MODELLING AND IMPROVEMENT OF ENERGY EFFICIENCY OF FISHING VESSELS

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MATEMATIČKO MODELIRANJE I POBOLJŠANJE ENERGETSKE UČINKOVITOSTI RIBARSKIH BRODOVA

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NOMENCLATURE

Abbreviations

AHR	Average Hull Roughness
BUA	Business-as-Usual
CA	Carbon Allowance
CapEx	Capital Expenditures
CDEP	Critical Deficit of Electricity Production
CEEP	Critical Excess of Electricity Production
CF	Carbon Footprint
CII	Carbon Intensity Indicator
CH_4	Methane
CO_2	Carbon Dioxide
EC	Energy Consumption
ECAs	Emission Control Areas
EF	Emission Factor
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EEI	Energy Efficiency Index
EI	Environmental Impact
EMS	Energy Management System
ETS	Emissions Trading Scheme (EU ETS)
FC	Fuel Consumption
GHG	Greenhouse Gas
GPS	Global Positioning System
GT	Gross Tonnage
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
IEA	International Energy Agency
IES	Isolated Energy System

IMO	International Maritime Organization
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Assessment
LOA	Length Overall
LNG	Liquefied Natural Gas
MDO	Marine Diesel Oil
ME	Manufacturing Emissions
NPV	Net Present Value
NZES	Net Zero Emissions Scenario
OpEx	Operating Expenditures
P_{AE}	Power of Auxiliary Engines
PM	Particulate Matter
P_{ME}	Main Engine Power
PTW	Pump-to-Wake
PV	Photovoltaic
SEEMP	Ship Energy Efficiency Management Plan
SFC	Specific Fuel Consumption
SI	Sustainability Index
SPS	Stated Policies Scenario
TE	Tailpipe Emissions
V2G	Vehicle-to-Grid
WTP	Well-To-Pump

Variables

AFL	Coating price per liter (€/l)
AHR	Average hull roughness (mm or µm)
AHR_D	Dry-docking roughness (mm or µm)
AHR_{FO}	Biofouling roughness (mm or µm)
AHR_{NB}	Newbuilding hull roughness (mm or µm)
AHR_S	Service roughness (mm or µm)
AP	Acidification Potential (kg SO_2-eq)

A_{wet}	Wetted surface area (m²)
CA	Carbon taxation costs (€)
$CapEx$	Capital expenditures (€)
DCF	Roughness allowance (–)
E	Emissions (kg)
EC	Energy consumption (kWh)
EF	Emission factor (g emission per kg fuel)
E_i	Emissions (kg)
EP	Eutrophication Potential (kg PO_4-eq)
FC	Fuel consumption (kg)
GWP	Global Warming Potential (t CO_2-eq)
h_i	Increase in roughness of species i (mm)
LWL	Length at waterline (m)
n	Number of coating layers (–)
NPV	Net Present Value (€)
$OpEx$	Operating expenditures (€)
P	Installed engine power (kW)
P_{AE}	Auxiliary engine power (kW)
P_{eng}	Diesel engine power (kW)
p_i	Attachment probability of fouling species i (–)
P_{ME}	Main engine power (kW)
PR_{eng}	Engine price (€/kW)
PR_i	Price of species i (€/kg)
r_i	Growth rate of fouling species i (mm/month)
S	Wetted surface area (m²)
SFC	Specific fuel consumption (g/kWh)
t	Operating time (h, months or years)
v	Vessel navigation speed (m/s or kn)
V	Required coating volume (l)
η	Propulsion efficiency (–)
ρ	Density of seawater (kg/m³)

ABSTRACT

The fishing sector consists of energy-intensive vessels, mostly powered by diesel engines, which generate high levels of greenhouse gases. In order to reduce their harmful impact on the marine environment and human health, international and local organizations propose a number of technical and operational strategies for its decarbonisation. However, the specific characteristics of fishing vessels, particularly their diverse operating profiles and high dependence on fossil fuels, have limited the applicability of these measures and left the sector insufficiently addressed compared to cargo and passenger shipping. In the doctoral thesis, a mathematical model for assessing the energy efficiency of fishing vessels has been developed, providing insight into the environmental impact of vessels to their benefit for society. The model quantifies the relationship between vessel operation, fuel consumption, emissions, and broader societal impacts, allowing for a detailed evaluation of the sustainability of different fishing activities. By integrating publicly available statistical data with high-resolution direct measurements obtained through onboard monitoring systems, the model has been successfully applied to the entire fishing fleet and validated across multiple vessel types and fishing gears. The study further analysed the transferability of technical and operational decarbonisation measures to the fishing sector. Emphasis was placed on hybrid energy systems, including diesel-battery and plug-in hybrid configurations. Through scenario analyses, techno-economic assessments, and life-cycle modelling, the thesis provides evidence-based recommendations that support the implementation of low-carbon technologies in fisheries. The results demonstrate that the fishing fleet is highly energy-intensive but also offers substantial opportunities for decarbonisation. Measured operational data confirm the inefficiency of current diesel systems, while modelling and techno-economic analysis show that hybrid and electrified systems can significantly reduce fuel use, emissions, and long-term costs. At the same time, hull maintenance, fuel choice, and carbon taxation strongly influence sustainability outcomes. The research proves that applying technical and operational measures from other maritime sectors, combined with tailored hybrid solutions, can greatly enhance the energy efficiency and environmental performance of fishing vessels.

Key words: decarbonisation, fishing vessels, environmental-economic performance, technical and operational measures, alternative power options, sustainability.

Prošireni sažetak

I. Uvod

Izgaranje fosilnih goriva u pomorskom sektoru rezultira visokim razinama stakleničkih plinova poput ugljičnog dioksida (CO_2), metana (CH_4) i dušičnog oksida (N_2O), što uzrokuje globalno zatopljenje i ekološke probleme. To je potaknulo usvajanje globalnih klimatskih sporazuma [1] i uvođenje mjera Međunarodne pomorske organizacije (engl. *International Maritime Organization*, IMO) poput Priloga VI Međunarodne konvencije o sprječavanju onečišćenja s brodova (eng. *International Convention for the Prevention of Pollution from Ships*, MARPOL), Projektni indeks energetske učinkovitosti brodova (eng. *Energy Efficiency Design Index*, EEDI), Plan upravljanja energetskom učinkovitošću broda (eng. *Ship Energy Efficiency Management Plan*, SEEMP) i noviji Indeks energetske učinkovitosti postojećih brodova (eng. *Energy Efficiency Existing Ship Index*, EEXI), usmjerenih na poboljšanje energetske učinkovitosti trgovačkih brodova s veličinom od 400 GT (eng. *Gross Tonnage*) ili više u međunarodnoj plovidbi [2]. Budući da se te mjere ne primjenjuju na ribarske brodove, ribarski sektor ostaje regulatorno zanemaren unatoč rastu emisija, povećanim troškovima goriva i inicijativama Opće komisije za ribarstvo Sredozemlja (eng. *General Fisheries Commission for the Mediterranean,* GFCM) kojima se potiče primjena tehničkih i operativnih postupaka u ribarskom sektoru s ciljem promicanja dekarbonizacije.

Energetski intenzivni ribarski brodovi emitiraju značajne razine stakleničkih i štetnih emisija. Emisije stakleničkih plinova globalnog ribarstva povećale su se za 28 %, u periodu od 1990. do 2011. godine, rezultirajući emisijama od 179 milijuna tona $CO_{2\text{-ekv}}$ nastalih sagorijevanjem 40 milijardi litara fosilnih goriva [3]. Olmer i sur. [4] su istraživali ekološki utjecaj ribarstva u periodu od 2013. do 2015. godine i primijetili povećanje razine emisija od 17 %. Ekonomske analize su pokazale da troškovi goriva mogu činiti i do 60 % ukupnih troškova ribarske industrije [5]. Propisi u sektoru ribarstva sadržani su u Zajedničkoj ribarstvenoj politici (eng. *Common Fisheries Policy*, CFP) [6], ali su više usmjereni na obnovu ribljeg fonda, kontrolu ulova, poboljšanje ekonomske izvedbe itd., a smanjenje emisija je popratni produkt implementiranih postupaka. Iako smanjenje stakleničkih emisija nije fokus, ipak se očekuje prilagodba ribarskih brodova prema aktualnim globalnim propisima i ulaganje u održivu niskougljičnu budućnost.

Ribarski brodovi se mogu klasificirati prema vrsti ribolovnog alata i operativnim zahtjevima, a potrošnja goriva ovisi o konstrukciji, opremi i ribolovnim aktivnostima. Radne značajke broda, poput brzine, rute i drugih značajki, definirane su ciljanom vrstom ulova. Ribolovne operacije se mogu podijeliti na povlačenje mreže, karakteristično za koćare, i okruživanje mrežom, karakteristično za plivaričare. Plivaričari u jednom potezu hvataju velike količine uglavnom malih pelagičnih vrsta, dok koćari uz više povlačenja mreže ostvaruju raznolikiji i često tržišno vrjedniji ulov [7, 8]. Operativno gledano, plivaričari koji love tunu su 42 % energetski učinkovitiji po toni ulovljene ribe u usporedbi s koćarima [8]. Ribarski brodovi troše 1,2 % globalne potrošnje nafte, a dizelsko gorivo se često koristi zbog visoke energetske gustoće i široke dostupnosti. Potrošnja goriva je izrazito ovisna o vrsti broda i njegovoj konstrukciji, korištenoj ribolovnoj opremi, karakteristikama ribolovne rute, ciljanim vrstama i dr. [9].
Iako su alternativna goriva (poput ukapljenog prirodnog plina, biodizela, vodika, amonijaka itd.), obnovljivi izvori energije (solarna, energija mora, vjetra…) i potpuna elektrifikacija detaljno proučeni u pomorstvu [10–12], istraživanja u ribarstvu su ograničena te često zanemaruju hibridna rješenja koja mogu pružiti fleksibilnost i smanjenje emisije [13–17]. Brojni autori su napomenuli štetnost ribarstva na okoliš, ali istraživanja još nisu u fazi primjene tehničkih i operativnih postupaka [18–20]. Uz navedeno, ekonomske analize su također važan dio istraživanja, ali većina izračuna ne uzima u obzir fluktuacije na tržištu goriva, već se vrijednosti temelje na konstantnim, prosječnim cijenama goriva, umanjujući time preciznost rezultata dobivenih cjeloživotnim analizama. Pregled literature ukazuje na potrebu za formuliranjem indeksa energetske učinkovitosti za ribarske brodove, koji će na prikladan način uzeti u obzir njihov utjecaj na okoliš i dobrobit za društvo, kao i postupak poboljšanja tako kvantificirane energetske učinkovitosti putem primjene tehničkih i operativnih postupaka.

II. Cilj i hipoteze istraživanja

Cilj istraživanja je kvantificirati i poboljšati energetsku učinkovitost i ekološku prihvatljivost ribarskih brodova primjenom različitih tehničkih i operativnih postupaka, pritom uzimajući u obzir njihove operativne značajke.

Hipoteza ovog istraživanja je:
Kombiniranjem tehničkih i operativnih postupaka, po uzoru na one primjenjivane na trgovačku flotu, moguće je poboljšati energetsku učinkovitost ribarskih brodova, uvažavajući pritom specifičnosti brodova i vodeći računa o cjeloživotnim troškovima i emisijama.

III. Materijali i metode

Ovo istraživanje obuhvatilo je četiri međusobno povezana koraka koji se nadovezuju. Najprije je provedena analiza tehničkih i operativnih značajki hrvatske ribarske flote, koja je uzeta kao reprezentativan uzorak za istraživanje, pri čemu su se tehnički podaci preuzeli iz baze Opće komisije za ribarstvo Sredozemlja filtrirane za Jadransko more, a fokus istraživanja usmjeren je na koćare i plivaričare zbog njihova dominantnog udjela u hrvatskoj gospodarskoj ribarskoj floti. Operativne značajke, poput brzine, ribolovnih ruta, potrošnje goriva i dr., pokušale su se prikupiti iz dostupne literature, ali je uočen veliki nedostatak vjerodostojnih podataka, pogotovo što se tiče potrošnje goriva. Stoga je osnovan i instaliran mjerni lanac koji prikuplja podatke o operativnim značajkama plivaričara i koćara, odabranih zbog njihovih fundamentalnih razlika u operativnim režimima. Na temelju tako prikupljenih informacija formuliran je indeks energetske učinkovitosti koji omogućava procjenu ekološkog utjecaja brodova u odnosu na njihovu društvenu korist, uzimajući u obzir specifičnosti operativnog režima i kvalitetu, odnosno vrijednost ulova. Indeks je poslužio i za analizu utjecaja različitih tehničkih i operativnih postupaka na emisije, pri čemu je ekološka procjena uključivala stakleničke plinove, ali i dušikove okside NO_X i sumporne okside SO_X, uz razmatranje emisija tijekom cijelog životnog ciklusa broda. Ekološki dio analize pružio je uvid u razinu emisija koju proizvodi hrvatska ribarska flota i omogućio usporedbu sa svjetskim trendovima. Istraživanje je uzeo u obzir emisije proizvedene tijekom cijelog životnog ciklusa ribarskih brodova, bez obzira na korišteni pogonski sustav. Zamjena postojećih pogonskih sustava samo s jednim izvorom energije uzeta je kao polazna točka za smanjenje korištenja fosilnih goriva te se dalje razvila prema hibridnim rješenjima. Svi istraženi postupci su morali zadovoljiti energetske, ali i ekonomske zahtjeve ribarskog broda, odnosno omogućiti nesmetan daljnji rad uz postizanje jednake ili veće dobiti kroz duži period. Konačno, ekonomska analiza je objedinila cjeloživotne troškove, varijabilnost vrijednosti ulova i različite scenarije ugljičnog poreza, uključujući i analizu osjetljivosti cijena goriva kako bi se nadvladalo ograničenje dosadašnjih pristupa koji su se oslanjali na prosječne i statične cijene goriva.

IV. Rezultati

Provedenom analizom ustanovljeno je da su ribarski brodovi izrazito energetski intenzivni te da dizelski pogon uzrokuje visoke emisije stakleničkih plinova. Analiza podataka prikupljenih sustavom za izravno mjerenje potrošnje goriva omogućila je razvoj matematičkog modela koji precizno procjenjuje potrošnju energije i emisije za različite vrste brodova u cijeloj floti. Simulacije različitih energetskih sustava pokazale su kako elektrifikacija i hibridni pogon

značajno smanjuju potrošnju goriva, emisije i dugoročne troškove. Potpuna elektrifikacija daje najveće ekološke koristi, ali uz visoke investicije, dok se plug-in hibridi pokazuju najisplativijim rješenjem zbog velikih ušteda goriva i smanjenog utjecaja na okoliš. Modeliranje korelacije elektrificiranih brodova i otočnih energetskih sustava pokazuje da flota može smanjiti viškove proizvodnje iz obnovljivih izvora i povećati stabilnost sustava. Analiza obraštaja potvrđuje da ono značajno povećava potrošnju goriva, a aktivni sustavi zaštite daju najbolji omjer troškova i učinkovitosti. Razvijeni indeks energetske učinkovitosti pokazuje da trenutni dizelski brodovi postaju ekonomski neodrživi uz strože klimatske politike, dok alternativna goriva i hibridni sustavi poboljšavaju održivost flote. Optimacijski modeli konačno potvrđuju da hibridne i plug-in hibridne konfiguracije predstavljaju najpovoljnije rješenje za većinu ribarskih brodova.

V. Zaključak

Pregled literature i regulatornog okvira pokazao je da je ribarski sektor, unatoč svojoj izrazitoj energetskoj intenzivnosti i značajnom doprinosu emisijama stakleničkih plinova, sustavno zanemaren u globalnim inicijativama dekarbonizacije pomorskog prometa. Međunarodni i europski propisi primjenjuju se isključivo na trgovačku flotu, dok ribarski brodovi ostaju izvan propisanih energetskih zahtjeva i obveza smanjenja emisija. Takva regulatorna neusklađenost dodatno je naglašena činjenicom da se znanstvena istraživanja uglavnom fokusiraju na teretni i putnički promet, dok su ribarski brodovi analizirani djelomično i bez cjelovitog energetskog, ekološkog i ekonomskog pristupa.

U okviru doktorskog rada provedena je detaljna analiza tehničkih i operativnih značajki hrvatske ribarske flote, pri čemu je posebno istaknut prazan prostor u dostupnosti podataka o stvarnoj potrošnji goriva. Taj nedostatak je nadomješten uspostavom sustava izravnog mjerenja potrošnje goriva i brzine na reprezentativnim plivarićarima i koćarima, što je rezultiralo preciznom bazom podataka o energetskoj potrošnji hrvatskih ribarskih brodova. Na temelju prikupljenih podataka razvijen je matematički model energetske učinkovitosti i emisija, prilagođen specifičnostima ribarskih aktivnosti. Model omogućuje vjerodostojnu procjenu utjecaja različitih tehničkih i operativnih mjera na energetsku potrošnju i emisije, uključujući integraciju alternativnih goriva, elektrifikacije i hibridnih energetskih rješenja. Posebna vrijednost modela leži u mogućnosti primjene na cijelu flotu, neovisno o tipu broda, ribolovnog alata ili režima plovidbe. Rezultati potvrđuju postavljenu hipotezu da se kombinacijom tehničkih i operativnih postupaka, prilagođenih specifičnostima ribarskih brodova, može postići

znatno poboljšanje njihove energetske učinkovitosti, ekološke prihvatljivosti i dugoročne ekonomske održivosti. Doktorsko istraživanje doprinjelo je znanstvenoj literaturi i ponudilo cjelovit, empirijski utemeljen i praktično primjenjiv metodološki okvir za procjenu i unapređenje energetskih sustava ribarskih brodova.

VI. Izvorni znanstveni doprinos

Znanstveni doprinos doktorskog rada je:

1. Indeks energetske učinkovitosti za ribarske brodove i izračun vrijednosti indeksa za hrvatsku ribarsku flotu.
2. Alternativne konfiguracije brodskih energetskih sustava i operativni režimi koji daju niže vrijednosti indeksa energetske učinkovitosti.

1. Introduction

1.1. Research background

In recent years, global attention has increasingly focused on the environmental impact of maritime activities, driven largely by concerns about climate change and the commitments established under the Paris Agreement (2016) [21] and the Glasgow Climate Pact (2021) [22]. These agreements set ambitious targets to limit global warming and require emission reductions across all sectors, including shipping and fisheries. The International Maritime Organization (IMO) has responded with technical and operational measures aimed at reducing Greenhouse Gas (GHG) emissions from ships, most notably MARPOL (International Convention for the Prevention of Pollution from Ships) Annex VI [23]: Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP), Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) [24, 25]. Furthermore, the findings of the Fourth IMO GHG Study [26] highlighted the continued growth of maritime GHG emissions and emphasized the need for accelerated decarbonization across the sector. Building upon these findings, IMO adopted the 2023 IMO Strategy on Reduction of GHG Emissions from Ships [23], establishing a pathway towards net-zero GHG emissions from international shipping by or around 2050, supported by indicative checkpoints for 2030 and 2040. More recently, the development of the IMO Net-Zero Framework [27] has introduced a combination of technical and economic measures designed to support the transition to low- and zero-emission fuels and technologies. Although these regulations primarily target merchant shipping, they are expected to influence the fishing sector indirectly through future environmental policies, fuel standards, carbon pricing mechanisms, and broader maritime decarbonization efforts.

To address these challenges, numerous studies have explored technical, operational, and market-based strategies to decarbonize the fleets. Technical measures include hull optimization, improved antifouling systems, waste-heat recovery, alternative fuels such as methanol, biodiesel, Liquified Natural Gas (LNG), and full or partial electrification. For instance, methanol has emerged as a promising option, offering up to 22.4% reductions in GHG emissions and 23.3% lower life-cycle costs compared to diesel [12], while electrification remains limited by battery costs, vessel power variability, and inadequate charging

infrastructure [12, 26]. Hybrid and microgrid power systems have also been proposed to bridge the gap between traditional diesel engines and fully electric propulsion. These types of systems further facilitate flexible and efficient energy use [29], but their true performance depends on real-world load patterns, vessel behaviour, and local energy system characteristics [30]. The analyses rely heavily on accurate load profiles derived from real-time measurements, reinforcing the importance of high-quality operational data. Operational measures such as slow steaming, optimized routes, advanced gear design, and catch-selective fishing techniques can yield substantial fuel savings [31]. However, their effectiveness varies widely across vessel types and operational profiles [32]. An overview of other technical and operational measures is shown in Figure 1.

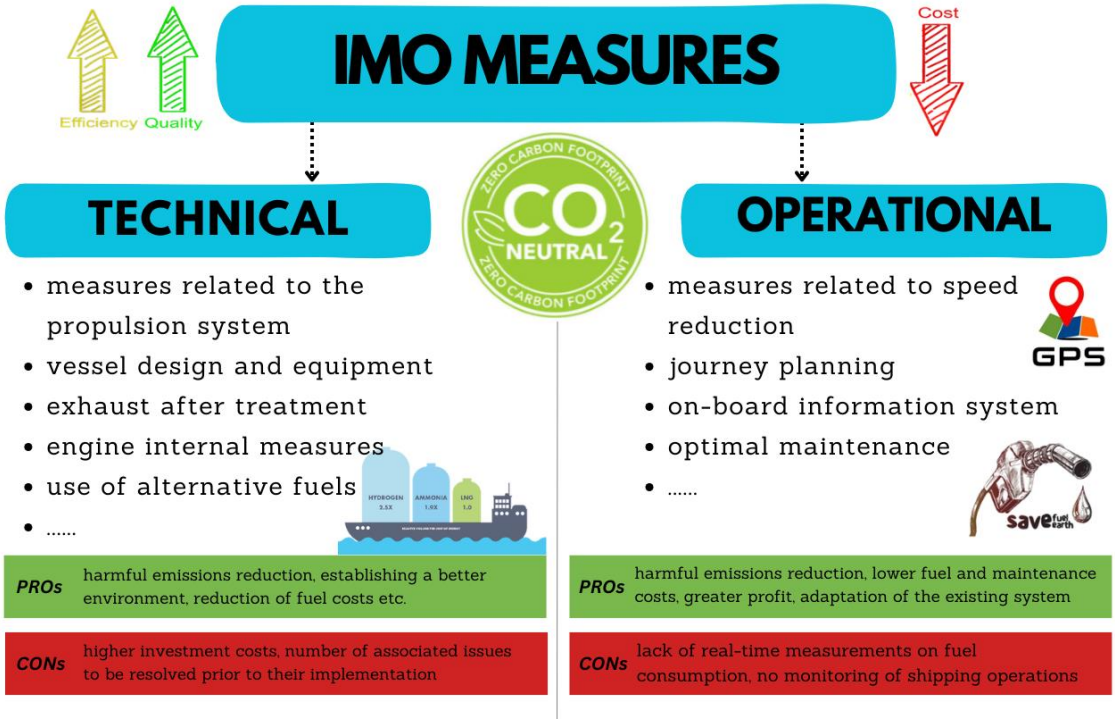


Figure 1. Technical and operational measures for the improvement of ship energy efficiency [33]

The IMO frameworks apply predominantly to vessels above 400 GT, in case of EEXI, or 5000 GT, in case of CII, which excludes a large portion of the global fishing fleet. Consequently, although fishing vessels operate primarily in coastal areas, where emissions have a direct and localized impact, the sector remains largely underregulated in comparison to cargo and passenger shipping [34]. Despite this regulatory gap, the fishing sector contributes significantly

to global emissions. Studies estimate that it accounts for roughly 1.2% of global oil consumption, translating to approximately 134–179 million tons of $CO_{2\text{-equivalent}}$ annually, depending on the year and methodology [3, 8]. The scale of this impact is evident when considering that most fishing vessels are powered by aged, inefficient diesel engines, which produce disproportionately high emissions relative to their size and power output [34]. This growing recognition of the environmental effect has prompted increased interest in decarbonisation strategies tailored specifically to fisheries, but the path forward is complex due to the sector's operational, economic, and social characteristics.

The diversity and operational complexity of fishing vessels make emissions mitigation particularly challenging. Purse seiners and trawlers, the dominant vessel types in many fisheries, illustrate the spectrum of energy consumption patterns within the sector. A good representation of the diversity of these vessels is given in Figure 2. Purse seiners use encircling nets to capture large schools of small pelagic species and devote much of their energy to high-speed cruising to and from fishing grounds. Trawlers, on the other hand, drag heavy nets through the water column or along the seabed, requiring continuous power output over prolonged periods. This makes trawling one of the most energy-intensive fishing methods, with towing operations alone accounting for up to 68% of total fuel consumption. Although purse seiners are typically more fuel-efficient per tonne of fish landed, trawlers frequently target a wider variety of species with higher market value, a factor that complicates purely environmental assessments of vessel performance. Seasonal variations, fish migrations, legally imposed fishing bans, and quota regulations further modify operational behaviour, producing a highly irregular pattern of fuel use that cannot be adequately captured through annual averages or imprecise reporting practices.

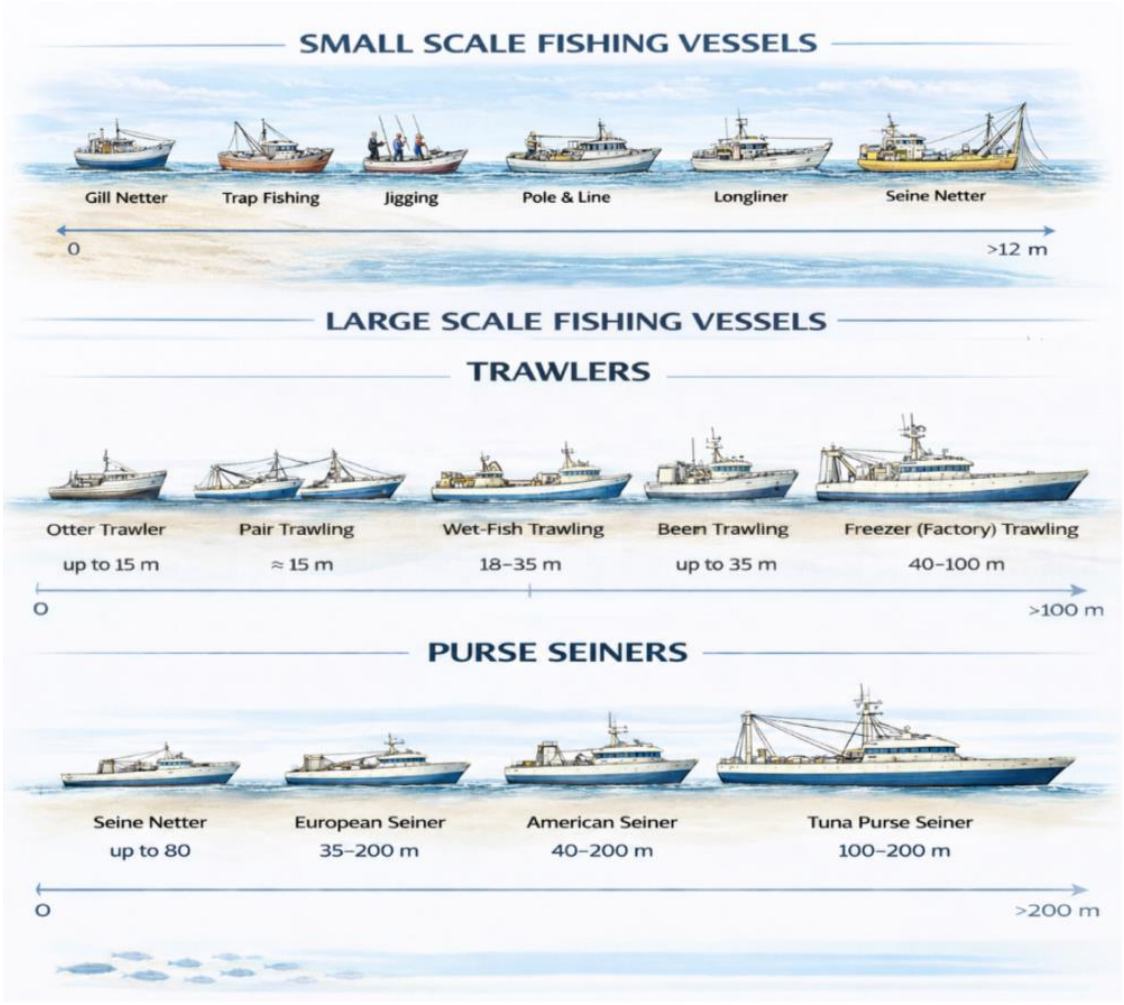


Figure 2. Comparison of trawlers and purse seiners by length overall [34]

A major challenge in assessing the energy efficiency and environmental impact of fishing vessels is the persistent lack of accurate operational data. Many fleets still depend on manual logbooks, fuel receipts, or simplified consumption models that often diverge substantially from real use [33]. Modern real-time monitoring technologies, ultrasonic and turbine flow meters, capacitive fuel-level sensors, Global Positioning System (GPS)-based telemetry, and software are helping bridge this gap by providing precise, high-resolution measurements of fuel flow, speed, route, engine load, and operating mode [35]. Their application clearly demonstrates that real-time data greatly improves the reliability of energy and emission estimates, enabling more accurate characterization of operational profiles, energy needs, and emissions across different gears and seasons [18, 26, 32]. Alongside improved monitoring, numerous technical measures have been proposed to reduce emissions from fishing fleets.

The VOSviewer visualization in Figure 3 presents a co-occurrence network of key words that reflects the current research landscape surrounding energy transitions, maritime applications, and advanced power systems. Each node represents a frequently used key word, with its size indicating occurrence frequency and its colour denoting its belonging to a particular thematic cluster. The spatial arrangement of nodes shows the strength of their interconnections, revealing how different research areas converge and interact. The largest and most prominent cluster is centred around electrification, which is closely linked with terms such as energy efficiency, electric vehicles, and energy transition, highlighting a strong academic focus on shifting from conventional power systems to electric propulsion, both on land and at sea. Surrounding clusters emphasize topics related to microgrids, hybrid microgrid architectures, and renewable energy, accompanied by methodological terms such as optimal sizing, HOMER Pro, net present cost (NPC), and sensitivity analysis. These clusters illustrate the growing importance of integrating batteries, photovoltaic (PV) systems, and grid-independent solutions, and evaluating these technologies through techno-economic modelling. From the maritime viewpoint, the red cluster centred around shipping, shipping emissions, green shipping, and fishing vessels underscores the increasing attention being directed toward decarbonizing the broader maritime sector, with fisheries emerging as a distinct and relevant sub-topic. Overall, the visualization reveals a research field characterized by strong cross-sectoral connections, where advances in renewable energy systems, hybrid configurations, and electrification directly inform ongoing efforts to modernize and decarbonize maritime operations, including fishing fleets.

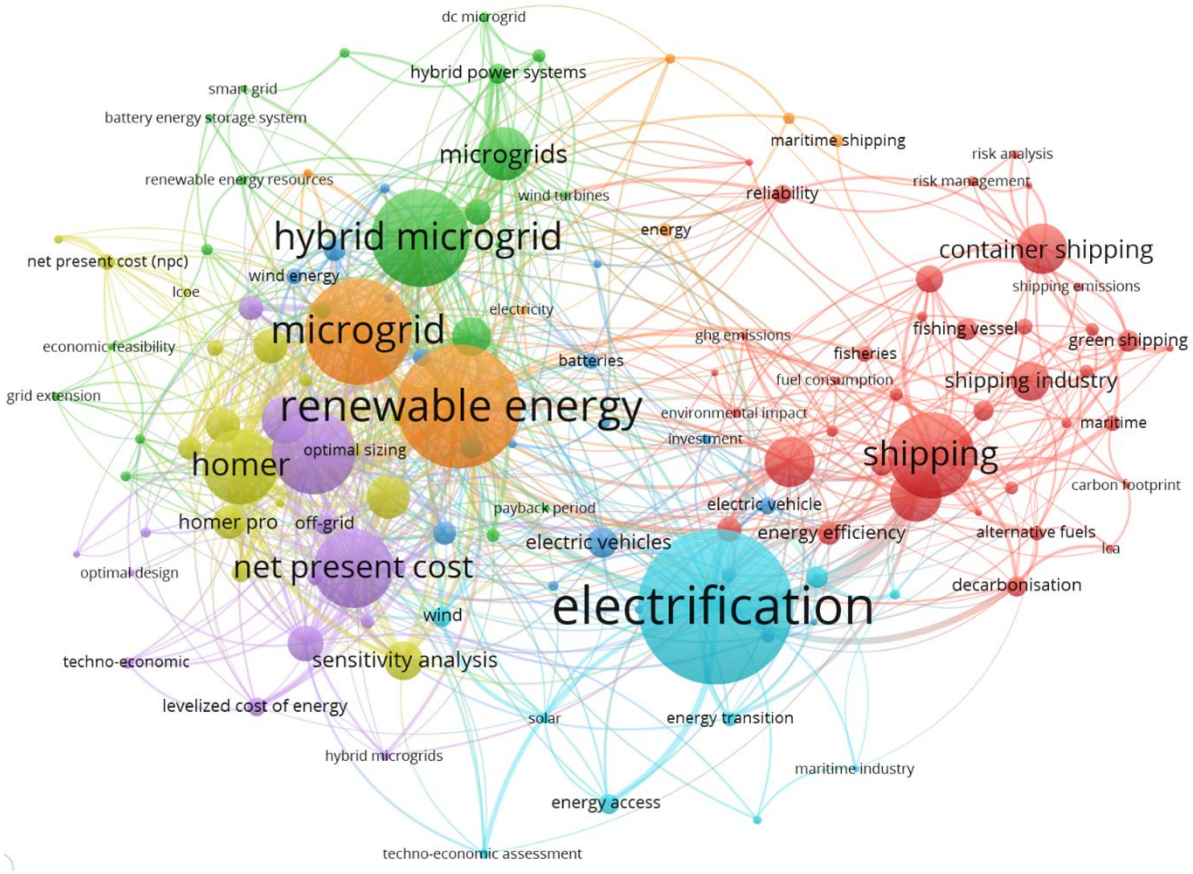


Figure 3. VOSviewer co-occurrence mapping of key words [30]

Despite these developments, several major research gaps persist. Existing maritime energy-efficiency indicators such as EEDI, EEXI, and CII are based on transport work metrics, making them inapplicable to fishing vessels, whose effectiveness is defined by landed catch rather than cargo movement. Most studies focus either on environmental emissions or on economic performance but rarely combine the two in a unified framework. In addition, the lack of accurate fuel-consumption and catch-rate data continues to limit the development of robust models. The heavy case-specific nature of alternative fuel assessments, the operational diversity within fishing fleets, and the influence of gear type, fish species, and fishing location further complicate generalization. Moreover, few studies explore the synergistic potential between fishing vessel electrification and renewable isolated energy systems, an area that could offer substantial long-term environmental and economic benefits for coastal and island communities.

1.2. Motivation

The fishing sector, although often overlooked in international maritime regulations, is a significant contributor to greenhouse gas emissions due to its widespread reliance on aging diesel engines, highly variable operating profiles, and limited adoption of modern energy-efficient technologies. Unlike merchant ships regulated under IMO frameworks, fishing vessels operate in coastal areas where environmental impacts are immediate, yet standardized tools for assessing their sustainability are lacking. Recent global decarbonisation goals, combined with rising fuel prices and emerging carbon taxation, have intensified the need for accurate, real-time fuel consumption data and comprehensive environmental-economic assessments. At the same time, technological options such as alternative fuels, hybrid systems, electrification, and integration with renewable energy systems offer promising but case-specific pathways for reducing emissions. These challenges highlight the urgent need for data-driven methodologies and tailored sustainability metrics capable of capturing the complexity of fishing operations and guiding the sector towards feasible and effective decarbonisation strategies.

The motivation for this research arises from the urgent need to support the decarbonisation of the fishing sector, which remains underregulated, data-poor, and technologically outdated despite its significant environmental and economic importance. With fuel costs representing a major share of operational expenses and global climate policies increasingly targeting all maritime activities, fishing fleets face growing pressure to reduce emissions while maintaining profitability. Yet fleet owners and policymakers lack accurate fuel consumption data, reliable sustainability metrics, and clear guidance on the feasibility of alternative fuels, hybrid systems, and electrification. By leveraging real-time operational measurements and evaluating both environmental and economic performance, this research aims to fill critical knowledge gaps and provide practical, evidence-based tools to help fishing vessels transition towards cleaner, more efficient, and economically viable technological solutions.

1.3. Objectives and hypothesis of the thesis

The objective of the research is to quantify and improve the energy efficiency and environmental friendliness of fishing vessels by applying various technical and operational measures while considering their operational characteristics.

The hypothesis of this research is:
By combining technical and operational measures, modelled on those applied to the merchant fleet, it is possible to improve the energy efficiency of fishing vessels, while respecting their specifics and taking into account lifecycle costs and emissions.

1.4. Scientific contributions of thesis

The scientific contribution of the doctoral thesis is:

1. Energy efficiency index for fishing vessels and calculation of the index value for the case of the Croatian fishing fleet.
2. Alternative configurations of the ship's energy systems and operational regimes that give lower values of the energy efficiency index

1.5. Thesis outline

The structure of this thesis has been developed to systematically address the defined research objectives, test the proposed hypotheses, and achieve the intended scientific contributions. The research is based on a series of published scientific articles (Articles I–VII), each contributing to a specific thematic area and collectively forming a coherent methodological framework for designing energy-efficient, environmentally sustainable, and economically viable power systems for fishing vessels in the context of global decarbonisation. To this end, the research activities are organized around several key thematic areas, each corresponding to specific contributions, as demonstrated through the published works. The overarching aim of the thesis is to develop a comprehensive methodological procedure that quantifies the energy efficiency of fishing vessels, evaluates their environmental impact relative to societal benefit, and identifies technological and operational measures capable of improving sustainability at both vessel and fleet level.

Article I, based on the study of alternative powering options for trawlers, provides the conceptual foundation for the thesis by outlining the environmental and economic implications of traditional diesel propulsion and assessing feasible low-carbon alternatives. Through the comparative analysis of biodiesel, methanol, ammonia, hydrogen, and other decarbonisation options presented in the article, it becomes evident that the fishing sector requires new modelling tools capable of capturing interactions between environmental impact, operational

efficiency, and cost. This initial work confirms that the selected research objectives are grounded in real technological and regulatory needs and that substantial gaps exist regarding integrated modelling of future-ready propulsion systems.

Articles II and III directly support the development of mathematical models for fishing vessel power systems by providing empirical data and simulation tools. Article II represents the central foundation for the development of the mathematical model used in this thesis. This article provides the first comprehensive, data-driven investigation of the energy efficiency of fishing vessels in the Adriatic Sea by analysing the technical characteristics of 163 purse seiners and 82 trawlers from the GFCM database and combining them with a two-year dataset of direct fuel-consumption and operating-profile measurements. The study formulates an index that relates environmental impact to the societal benefit (catch quantity or income), demonstrating large differences in efficiency between purse seiners and trawlers, primarily due to differences in operational regimes, engine power, and catch structure. Article II fills a critical research gap by providing a standardized, bottom-up method for calculating energy efficiency for fleets traditionally excluded from IMO regulations. It supplies validated input data and modelling logic that directly feed into the methodological framework of the thesis.

Article III extends this work by analysing the potential of electrification of fishing vessels and their integration into isolated energy systems powered by high shares of renewables. It demonstrates the feasibility of full battery-electric operations, proposes battery-sizing methodologies, and uses EnergyPLAN simulations to evaluate interactions between vessel charging profiles and island-level renewable electricity supply.

Article IV introduces an essential dimension to the methodological framework by addressing the long-term effects of biofouling on fuel consumption, added resistance, and environmental impact. Through detailed modelling of hull roughness development and life-cycle cost assessment (LCCA) of different antifouling technologies, the article demonstrates that maintenance strategies significantly shape both operational emissions and total costs over a vessel's lifetime. This contribution ensures that the methodological procedure accounts not only for propulsion system selection but also for degradation and performance losses that influence energy demand and sustainability outcomes.

Article V develops a comprehensive environmental-economic sustainability index for fishing vessels, integrating capital expenditure, operating costs, carbon taxation, and revenue derived from species-specific catch profiles. Its methodology enables a transparent comparison of diesel, battery, methanol, and biodiesel power systems using economic indicators that incorporate both emissions and profitability. This index plays a central role in the validation phase of the thesis, as it provides the decision-support mechanism that translates technical modelling results into practical guidance for shipowners, policymakers, and regulators. It also strengthens the claim that the research framework can be used to evaluate future regulatory scenarios and market-based decarbonisation mechanisms.

Article VI applies microgrid optimization tools (HOMER Pro) to evaluate hybrid and plug-in hybrid power system configurations for both purse seiners and trawlers, relying on measured load profiles and realistic operating schedules. The analysis demonstrates that plug-in hybrid and hybrid systems can achieve significant reductions in NPC compared to diesel vessels, even when initial investment costs are higher. This article provides the final validation of the proposed methodological procedure, showing how the developed models can be employed to design optimized vessel power systems under real economic, operational, and environmental constraints.

Finally, article VII further extends the research framework of the dissertation by analysing advanced alternative propulsion options based on methanol and hydrogen in a dual-fuel configuration. In the paper, a detailed energy, environmental and economic model of a dual-fuel engine is developed and applied that enables the flexible use of low-carbon fuels while maintaining the operational reliability characteristic of conventional diesel systems. Special emphasis is placed on the reduction of GHG emissions, nitrogen oxides and other harmful emissions through different ratios of diesel substitution with methanol and hydrogen. The results show that dual-fuel propulsion can significantly reduce carbon dioxide (CO_2) emissions compared to conventional diesel engines, with acceptable changes in efficiency and life-cycle costs, especially in scenarios of increased carbon taxes and rising fossil fuel prices. This confirms that methanol and hydrogen represent a viable transitional option for the decarbonisation of the fishing fleet, especially in combination with hybrid energy systems.

Bringing these contributions together, the thesis achieves several scientific advancements. It identifies and analyses the key differences between conventional and low-carbon fishing vessel

power systems, grounded in empirical measurement and real-world operational variability (Articles I, II, IV). It develops and applies a set of modelling tools, from EnergyPLAN to HOMER Pro, that integrate vessel-level simulation with broader energy-system behaviour (Articles III, VII). It incorporates maintenance effects and biofouling dynamics into long-term energy and cost models, ensuring realism and completeness (Article IV). It introduces an operationally meaningful sustainability index that links environmental performance with economic viability (Article V). Finally, it validates the methodological framework through case studies that demonstrate its practicality and relevance for fishing fleet decarbonisation (Articles III and VI). Thus, the structure of the thesis evolves logically from empirical data collection, through model development and integration, to validation and final synthesis. Each article contributes a necessary component to a unified methodological procedure for designing future-ready power systems for fishing vessels, ensuring that environmental sustainability, operational efficiency, and economic feasibility are addressed in a coherent and scientifically robust manner.

2. Materials and methods

2.1. Vessel monitoring system and database development

A core difficulty in assessing the energy efficiency and environmental impact of fishing vessels lies in the scarcity and inaccuracy of operational data. Many fleets worldwide still rely on manual logbooks, fuel receipts, or simplified models of fuel consumption that may differ substantially from actual use. Such coarse measurements conceal errors, prevent the identification of consumption peaks across different operating modes, and limit the potential for both technical and operational optimization [32, 33]. In recent years, regulatory frameworks such as the EU's Monitoring, Reporting and Verification (MRV) [36] system and the IMO's Data Collection System (DCS) [37] have improved the availability of fuel collection data by requiring systematic reporting of energy use and emissions from commercial vessels of 5000 GT and above, thus leaving fishing vessels outside this scope. Real-time monitoring systems, such as ultrasonic and turbine flow meters, capacitive fuel-level sensors, GPS-integrated telemetry devices and platforms, have begun to address this gap by providing accurate, high-resolution measurements of fuel flow, vessel speed, route, engine load, and operating mode. To address these shortcomings in the Croatian fishing fleet, a modern monitoring system is established to collect real-time data on fuel use, vessel movement, and key operating conditions, forming the foundation for a comprehensive research database. The system, presented in Figure 4, is designed in response to recognized gaps in existing studies, where fuel consumption is often predicted using computational models with limited validation. While white-box, black-box, and gray-box models provide useful theoretical or data-driven estimates [10], their accuracy ultimately depends on the quality of the input data, which is frequently insufficient for variable operations such as fishing. There is almost no research comparing real-time fuel-use measurements with annual averages to quantify the underlying error [34]. This gap justified the need for a system capable of capturing instantaneous fuel usage under realistic operating conditions.

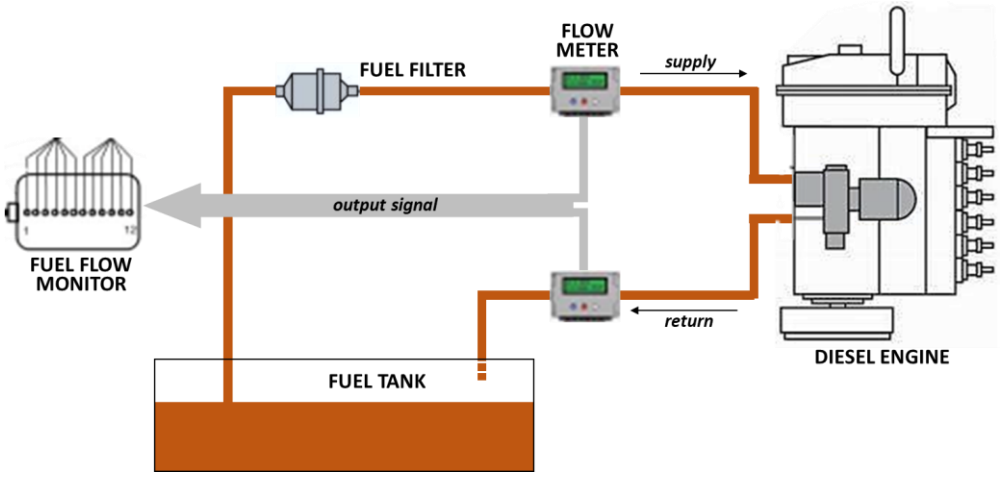


Figure 4. Fuel flow meter system [35]

To obtain precise and continuous fuel-use information, two types of monitoring technologies were implemented across the research fleet: flow meters and capacitive fuel level sensors. Flow meters measure consumption by registering the difference between fuel delivered to the engine and fuel returned to the tank. Their configuration, shown in Figure 4, enables highly resolved measurements that are minimally affected by vessel motion or vibration. Capacitive sensors, shown in Figure 5, translate changes in fuel height into volume through a calibrated height-to-volume relationship. Although somewhat less accurate due to sensitivity to impurities and vessel movement, these sensors provide a cost-effective alternative for vessels where the installation of flow meters is impractical. Flow meters can achieve accuracy below 1% under stable conditions, while capacitive sensors typically maintain accuracy within 2–5%, depending on tank geometry and vessel movement [35]. Vessels with similar characteristics were equipped strategically with either both devices for cross-validation or only the more economical option, ensuring optimal coverage of the research fleet.

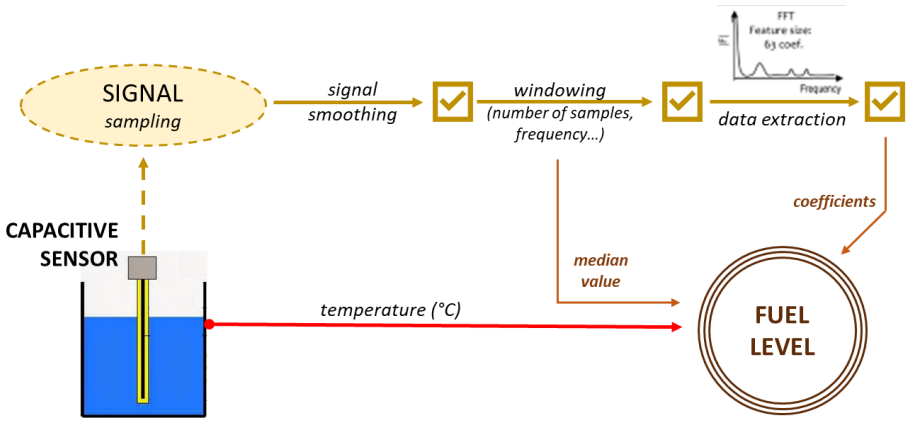


Figure 5. Fuel level sensors [35]

In 2024, the devices were installed on 12 fishing vessels, 10 purse seiners and 2 trawlers, operating in the Adriatic Sea. Their technical characteristics are presented in Figure 6 and example of the installed device is presented in Figure 7. Each device is connected to a central server immediately after installation, enabling remote transmission of fuel consumption, fuel temperature, vessel position, and other relevant parameters [32, 33]. The MAPON application is used as the primary digital interface for data collection, providing real-time GPS tracking, fuel-use reporting, and synchronization of all incoming signals [38]. These visualizations confirm the ability of the system to capture specific fishing behaviours, such as circling during purse-seine net setting, which are critical for segmenting the operational profile.

Vessel												
Main engine	370 kW		477 kW		302 kW		537 kW		526 kW		242 kW	
Auxiliary engine (number of engines/power)	1	130 kW	1	137 kW	1	56 kW	2	126 kW	1	90 kW	1	1 kW
	1	70 kW							1	50 kW		
	1	30 kW	1	60 kW	1	56 kW						
Vessel												
Main engine	221 kW		480 kW		450 kW		220 kW		223 kW		386 kW	
Auxiliary engine (number of engines/power)	2	50 kW	2	185 kW	2	100 kW	1	14	1	35 kW	1	35 kW
							1	1				

Figure 6. Investigated fishing vessels from the Croatian fishing fleet [34]

The collected data streams were integrated into a structured research database developed specifically for the purpose of this research. The database stores fuel use data, vessel trajectories, engine-related parameters where available, and CO_2 emissions (Figure 8). All data is time-synchronized to ensure compatibility during analysis and allow reconstruction of entire fishing cycles: steaming, searching, setting, hauling, and returning to port. Validation of the measurement system is performed by comparing real-time measurements with fishermen's estimates, annual fuel-delivery records, and known tank-level changes. The results showed a high level of data correspondence and verified that the deployed equipment offer accurate and

reliable measurements [34]. These early results underline the system's capability to support high-quality assessments of operational efficiency and to identify periods in the fishing cycle that contribute disproportionately to energy use and emissions.

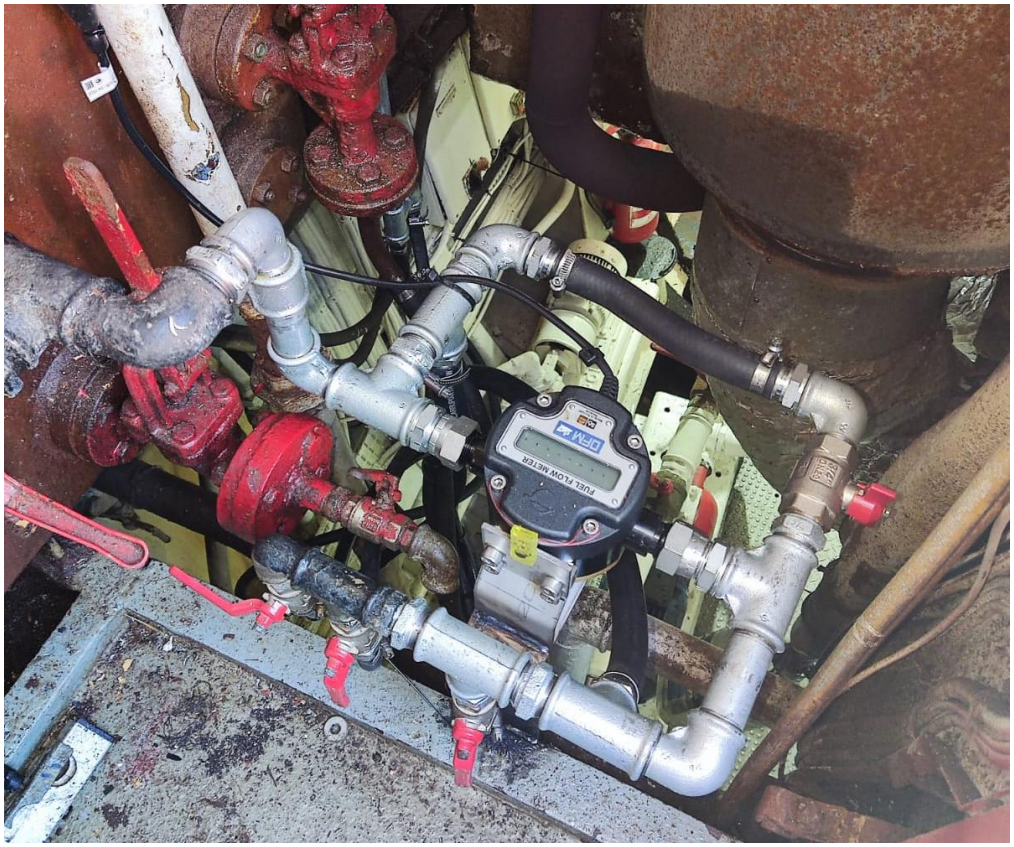
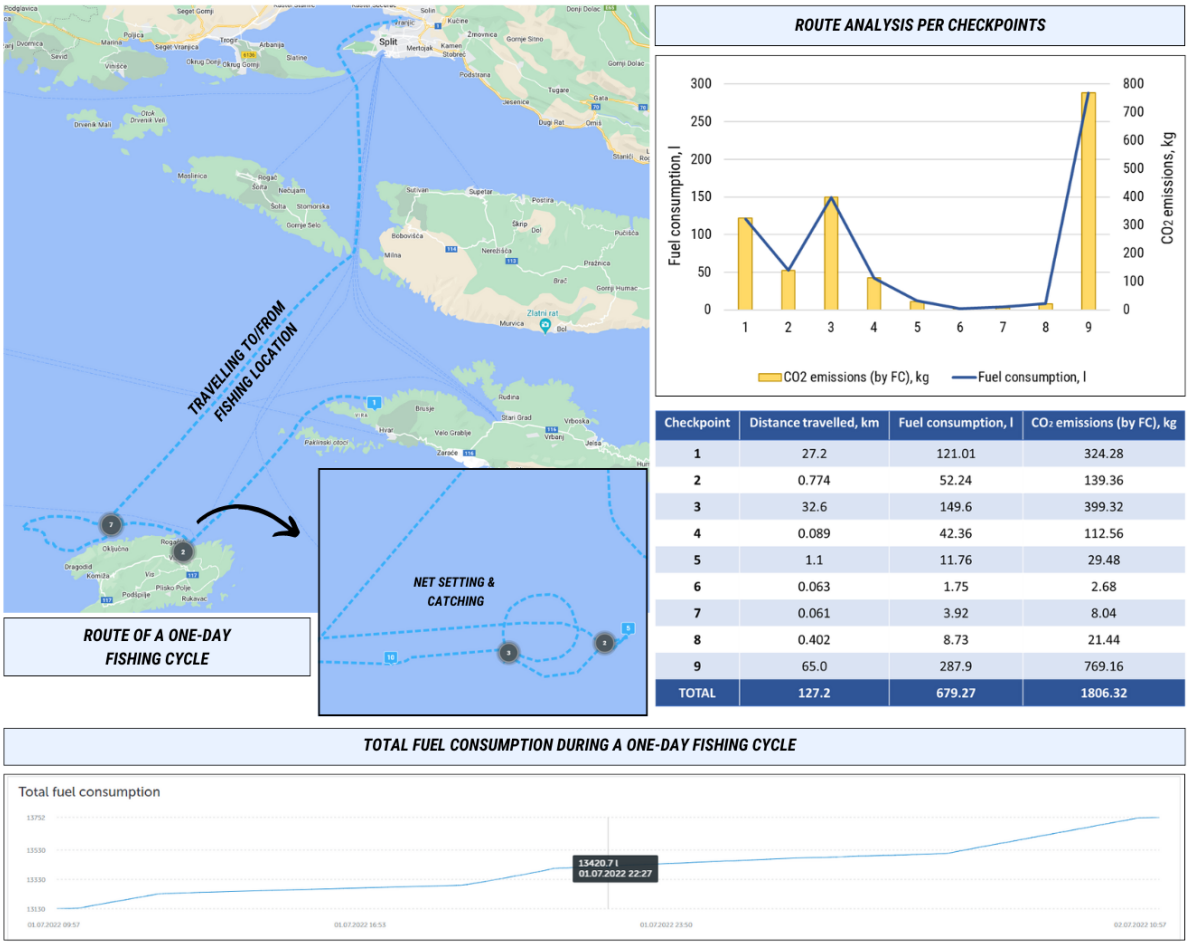


Figure 7. Differential Fuel Flow Meter (DFM) installed onboard a purse seiner

The establishment of this monitoring system and the associated database represents a critical step for subsequent stages of the research. High-resolution fuel use data not only allow detailed characterization of vessel operating profiles but also enable realistic modelling of alternative fuels, hybridization, biofouling impacts, and long-term decarbonisation strategies. By replacing uncertain estimates with robust empirical measurements, the system ensures that all further analyses, from environmental assessments to techno-economic evaluations, are grounded in accurate and vessel-specific operational evidence.



Checkpoint	Distance travelled, km	Fuel consumption, l	CO_2 emissions (by FC), kg
1	27.2	121.01	324.28
2	0.774	52.24	139.36
3	32.6	149.6	399.32
4	0.089	42.36	112.56
5	1.1	11.76	29.48
6	0.063	1.75	2.68
7	0.061	3.92	8.04
8	0.402	8.73	21.44
9	65.0	287.9	769.16
TOTAL	127.2	679.27	1806.32

Figure 8. Fuel consumption monitoring [33]

2.2. Energy Efficiency Index (EEI) for fishing vessels

The establishment of a reliable Energy Efficiency Index (EEI) is essential for evaluating and comparing the environmental performance of fishing vessels whose operations vary widely in duration, routing, engine loading, and catch volume. Unlike merchant shipping, where the EEDI, EEXI, and CII provide standardized benchmarks, fishing vessels are not fully covered by IMO's mandatory measures, creating the need for indices tailored to their operational profiles and function. The development of an EEI in this research is therefore grounded in real-time measurements of fuel consumption, vessel activity, and catch performance, enabling an assessment that reflects both energy use and the productive output of fishing operations [34].

The methodological starting point comes from the observed limitations of traditional fuel-based metrics, which are often based on annual averages or estimates collected through manual reporting. The assessment methodology is described in Figure 9. The high-resolution data

collected in this research allow a more accurate calculation of energy needs associated with steaming, searching, net setting, hauling, and returning to port, which directly influence total emissions and operational efficiency. Previous research on the Adriatic fleet demonstrated that trawlers and purse seiners differ considerably in operational energy distribution and in fuel consumption per tonne of landed fish, making a unified, catch-related indicator suitable for cross-vessel comparison [18, 19, 32, 37].

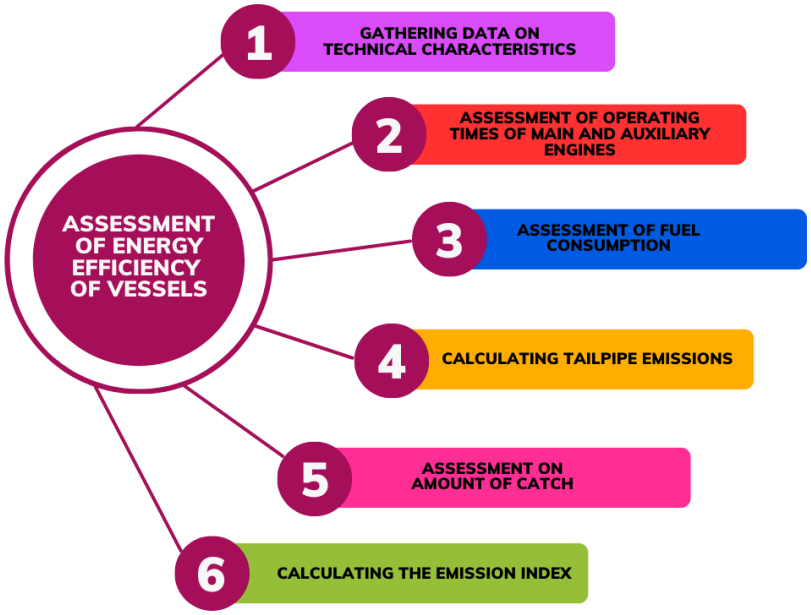


Figure 9. Methodology of developed Energy Efficiency Index (EEI) [34]

The formulation of the index builds on the conceptual foundation established in earlier studies. The environmental footprint is evaluated by integrating fuel-based emission factors with operational energy needs, producing an indicator that expresses environmental impact per unit of landed fish [34]. This approach provides transparency and allows direct comparison between vessel types, seasons, or fishing gears. The developed EEI combines measured energy use with catch data to represent both the environmental load of the vessel *CF* and the societal benefit of its activity, *BS*:

$$EEI = \frac{CF}{BS}. \quad (1)$$

Since fuel consumption is the main driver of CO_2, NO_X, SO_X, and PM emissions, the index serves as a proxy for direct environmental impact. By calculating the Carbon Footprint *CF* ($CO_{2\text{-eq}}$) of a vessel, the index considers the amount of GHGs directly and indirectly caused by an operation and accumulated over time [40]:

$$CF = GWP_{CO2} \cdot E_{CO2} + GWP_{CH4} \cdot E_{CH4} + GWP_{N2O} \cdot E_{N2O}. \quad (2)$$

The Global Warming Potential (*GWP)* indicates how much energy 1 tonne of a given gas traps in the atmosphere over a specific time period relative to 1 tonne of CO_2. The values are presented in Table 1. The emissions of CO_2, CH_4 and N_2O produced during fuel combustion and denoted as E_{CO2}, E_{CH4} and E_{N2O} are calculated by the following equation:

$$E_i = FC \cdot EF_i, \quad (3)$$

where *FC* denotes the fuel consumption in kg and EF_i marks emission factor for different emissions [34], presented in Table 1.

In order to calculate the index at the level of the entire fleet, values of catch and *FC* were obtained [34]. The *FC* can be calculated using the equation (4):

$$FC = P \cdot SFC \cdot t, \quad (4)$$

where *P* stands for total engine power in kW, *SFC* stands for specific fuel consumption, and *t* represents operating time in hours. The operating time is calculated by multiplying the number of annual workdays with the daily operating hours characteristic for each type of vessels. The total installed power consists of main engine power P_{ME} and power of the auxiliary engines P_{AE}. The power of the main engine is taken from the GFCM database [41] and the power of the auxiliary engines is estimated by comparing it with the power of the main engine of each ship and finding the average value of the ratio, which was then used to determine the power of the auxiliary engines of the rest of the fleet:

$$P_{AE_T} = 0.124 \cdot P_{ME}, \quad (5)$$

$$P_{AE_PS} = 0.388 \cdot P_{ME}. \quad (6)$$

There are significant differences in the power systems of purse seiners and trawlers that originate from the differences in their working principles, which is why their engine powers are calculated separately. After determining the engine power, equation (4) is modified to include both the main and auxiliary engines:

$$FC = P_{ME} \cdot SFC_{ME} \cdot t_{ME} + P_{AE} \cdot SFC_{AE} \cdot t_{AE}. \quad (7)$$

SFC of marine engines ranges between 155 and 250 g/kWh. For the main engine *SFC* is set at 215 g/kWh for high-speed diesel engines, while for the auxiliary engines the *SFC* is set at 210 g/kWh [42], because auxiliary engines can work closer to their optimal workload.

Table 1. Emission factors and GWP values [34]

	Emission factor, g emission per kg fuel	GWP (100 years)
CO_2	3206	1
CH_4	0.019	27-30
N_2O	0.142	273

The index developed in this thesis expresses the vessel's measured energy consumption over a defined operational cycle and relates it to the productive output, establishing a direct ratio between inputs and outputs. While the unit choice can vary depending on context, such as MJ per tonne of fish, fuel litres per tonne of fish, or grams of CO_2 equivalent per kilogram of catch, the methodological foundation remains the same: real energy use normalized by catch performance. By relying exclusively on real-time, high-resolution data instead of averages, the resulting EEI captures the true variability of operations and enables comparisons across vessels, gear types, seasons, and environmental conditions. This energy-based indicator also allows the integration of additional factors when required, such as hull fouling impacts, propulsive losses, or technical upgrades.

2.3. Sustainability Index (SI) for fishing vessels

Assessing the sustainability of fishing vessels requires an indicator that integrates environmental performance, economic viability, and operational efficiency into a single, interpretable metric. The Sustainability Index (SI) developed in this research draws directly on the multi-dimensional framework proposed in recent fisheries studies, where environmental, economic, and technical indicators are combined to evaluate how effectively a vessel transforms inputs (fuel, labour, energy) into socially and economically valuable outputs such as catch, revenue, and stable long-term operation [18, 26, 41, 42]. Unlike traditional single-parameter indicators, which focus solely on fuel consumption or emissions, the SI provides a more comprehensive representation of vessel performance and supports comparison across different vessel types, sizes, gears, and fishing seasons.

The methodological framework, presented in Figure 10, starts with integrating the high-resolution operational data collected from the monitoring system with broader economic and environmental parameters. Fuel consumption and operational profiles, recorded in real time, form the base of the environmental component since they directly determine GHG emissions

and overall energy use. Emissions per unit of catch and operational efficiency are derived from these measurements and incorporated into the environmental dimension of the index. The economic dimension of the SI is based on revenue generated by the landed catch, fuel and maintenance costs, labour input, and other operational expenditures, reflecting the economic productivity and resilience of fishing operations. The index integrates concepts similar to those presented in the fisheries sustainability research, where profitability, cost structure, and value generation are essential indicators of long-term economic viability. By linking real catch data with fuel consumption and operational duration, the model evaluates how much economic value is produced per unit of resource used, thereby connecting environmental efficiency with economic output in a simplified manner [28].

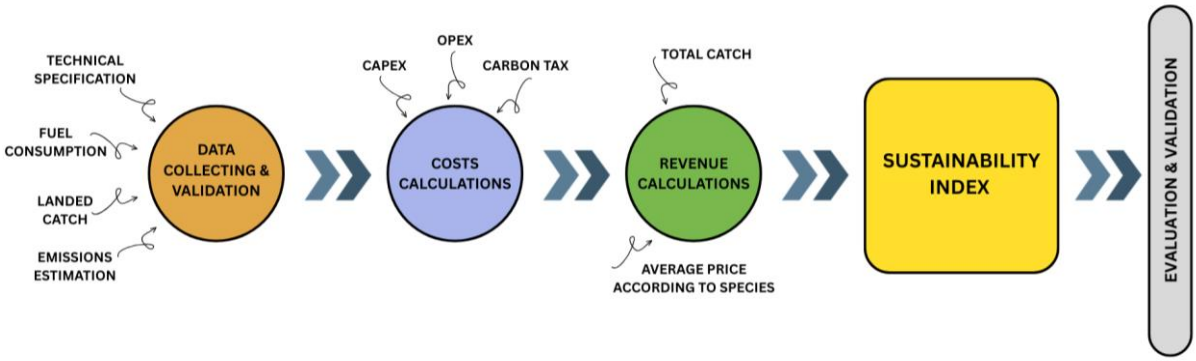


Figure 10. Methodology framework of the Sustainability Index (SI) [28]

The environmental-economic SI is an indicator of the efficiency of fishing vessels, which takes into account capital and operating expenses in relation to revenue, calculated as [28]:

$$SI = \frac{CapEx + OpEx + CA}{Revenue}, \tag{8}$$

where *CapEx* denotes capital costs, *OpEx* describes operative costs and *CA* marks denotes carbon taxation costs. The revenue is calculated using data on catch rate and average price according to species, by the following equation:

$$Revenue = m_i \cdot PR_i, \tag{9}$$

where m_i represents the total mass of the landed species and PR_i denotes the average price of the species. The average price is determined based on the data gathered from the national repository [45]. The prices of several species show a continuous increase in value while others show random fluctuations through the years. Depending on the type of marine organisms, the

price can vary from as low as 0.42 €/kg to much higher prices of 94.20 €/kg [28]. Total capital costs, *CapEx*, refer to the installation of the power system. Considering that the majority of fishing vessels are diesel-powered, the capital costs are calculated by [33]:

$$CapEx = P_{eng} \cdot PR_{eng} \cdot t, \tag{10}$$

where P_{eng} refers to the power of the diesel engine, PR_{eng} marks the cost of the engine of 250 €/kW [33] and t marks the number of years for which the costs are calculated. Capital costs may also include the cost of purchasing fishing equipment, auxiliary equipment and other costs. Total annual operating costs, *OpEx*, consist of fuel costs and maintenance costs:

$$OpEx = FC_D \cdot PR_D \cdot t + EC \cdot PR_{M-D} \cdot t. \tag{11}$$

The data on fuel consumption, FC_D (kg), is gathered by a direct measuring system and the price of fuel, PR_{FC} (€/kg), is determined based on the prices of previous years obtained from public databases. The maintenance cost can include various costs, from the maintenance of the hull of the ship to the repairs of the fishing net, but in this case, only the cost of maintaining the engine is included. The annual maintenance is calculated by multiplying the vessels's annual energy consumption with a conversion factor [12]. The energy consumption, *EC* (kWh), can be obtained by the following equation:

$$EC = \frac{FC_D}{SFC_D}, \tag{12}$$

where SFC_D, in g/kWh, marks the specific fuel consumption of 0.175 kg/kWh, in the case of diesel fuel according to the Fourth IMO GHG Study 2020 [25].

2.4. Environmental-economic assessment of alternative energy systems

Evaluating the feasibility of decarbonisation pathways for fishing vessels requires a systematic modelling framework that incorporates both the technical characteristics of alternative energy systems and their environmental and economic implications across the full life cycle. To complement the operational data collected in earlier sections, this research applies an integrated assessment approach that includes alternative fuels, hybrid power configurations, and full battery-electric systems, and quantifies their performance using LCA and LCCA. The modelling of alternative fuel systems begins with the identification of realistic substitution options for marine diesel, considering fuels such as LNG, biodiesel blends (e.g., B20), methanol, and hydrogen. The technical viability of each option is evaluated by comparing their

chemical properties, onboard storage needs, engine compatibility, and combustion characteristics [12, 37]. These parameters influence both the fuel conversion efficiency and the emissions profile, which are subsequently reflected in environmental and economic performance. The modelling incorporates well-to-pump (WTP) and pump-to-wake (PTW) emission factors based on the LCA frameworks used in a number of studies [2, 44–46], enabling the calculation of CO_2, nitrogen oxides (NO_X), sulphate oxides (SO_X), and particulate matter (PM) over the life cycle of each fuel. This life cycle approach better captures key factors that are often overlooked when evaluating only tailpipe emissions. As seen in Figure 11, LCA evaluates the environmental impact throughout the entire life cycle of a product or system. In case of fuels, the assessment includes raw material acquisition, manufacturing, transport and distribution, operation or use, and waste management. By considering all relevant inputs and outputs across the life cycle, LCA provides a comprehensive framework for quantifying environmental impacts and identifying opportunities for improving sustainability.

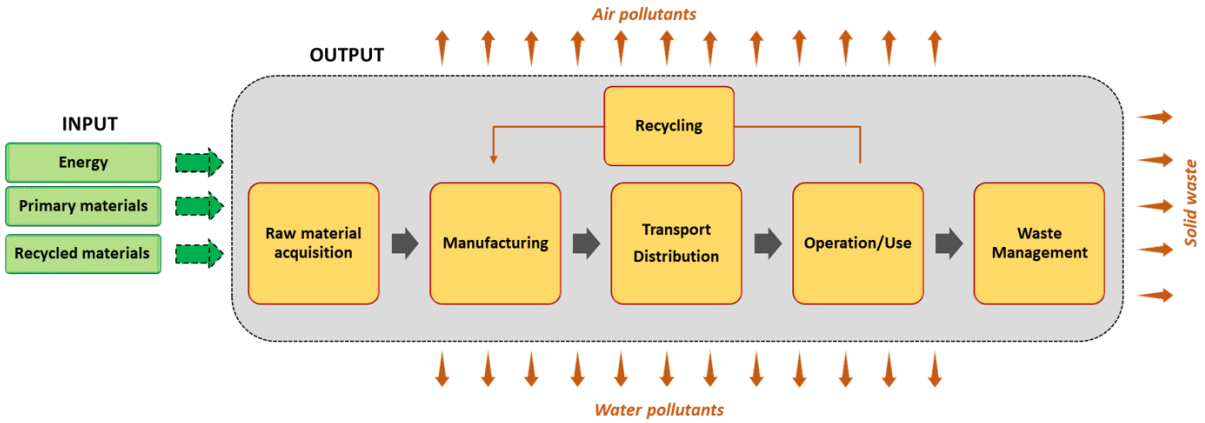


Figure 11. Life cycle assessment of fuels [39]

The environmental performance of each alternative system is evaluated using the LCA methodology, by integrating manufacturing impacts, WTP fuel pathways, and PTW engine emissions. For fuels such as methanol, this includes the upstream production method, renewable share, and distribution logistics, while for electrified systems the emissions depend heavily on the electricity mix or renewable share of the supplying system. In the case of battery-electric vessels, the methodology accounts for battery production, degradation, and replacement over the vessel lifetime [12, 47]. This ensures that the environmental assessment captures the full material, energy, and emissions implications of implementing advanced propulsion systems. The WTP considers fuel production, from the extraction of raw material to the production and

transport of the final product to the refuelling station, while the PTW phase analyses 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 [12]:

$$TE_i = FC \cdot EF_i, \tag{13}$$

where EF_i (g emission/kg fuel) refers to emission factor and i refers to any emissions. The fuel consumption (FC, kg fuel/ kg fish) is calculated according to equation (4). The manufacturing phase (ME), which analyses the emission released during the manufacturing of key elements (e.g. engines, batteries and others), is also taken into account. Finally, the CF accumulated over the life cycle of a product is calculated according to equation (2).

Complementing the LCA, the economic analysis is performed using LCCA, which evaluates total costs of ownership across the life cycle of each alternative energy system, Figure 12. Investment costs include propulsion equipment, battery systems, auxiliary components, and fuel storage modifications. Operating costs include fuel or electricity consumption, maintenance, and periodic component replacement. The referenced studies demonstrate that the cost structure differs substantially across alternatives. For example, battery systems have high capital cost but low operating cost, whereas LNG requires costly storage tanks but offers moderate emissions benefits, and methanol offers potential savings while maintaining manageable storage and engine adjustments [12, 37]. The modelling in this research integrates discounting, fuel price projections, carbon costs, and sensitivity factors, reflecting the economic uncertainties emphasized in the literature [12, 26, 37].

A key advantage of combining LCA and LCCA is the ability to gather and analyse decision-relevant indicators that balance environmental performance with economic feasibility. This dual assessment is particularly important in fisheries, where the profit margins are sensitive to fuel prices and where technology adoption must consider both regulatory pressures and long-term operational viability [26, 32]. By using measured operational data from the monitoring system, the model ensures that each scenario reflects real fuel-use intensity, seasonal demand patterns, and vessel-specific constraints. This enables a more reliable comparison across alternative systems and provides inputs for later scenario analyses regarding electrification, renewable integration, and long-term fleet-level decarbonisation.

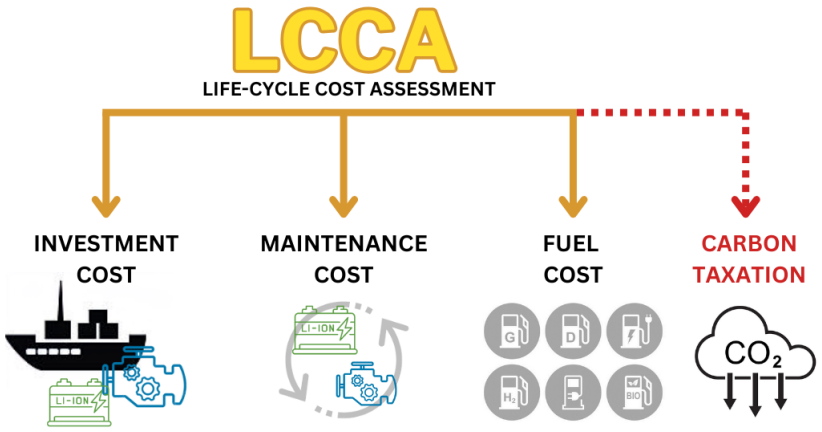


Figure 12. Life cycle cost assessment [28]

Carbon taxation plays an increasingly important role in the economic evaluation of fishing vessels. The CO_2 emissions from maritime operations will progressively fall under regulatory pricing mechanisms such as the EU Emissions Trading Scheme (ETS), which already mandates the purchase of emission allowances for vessels above 5000 GT and will expand its reporting requirements to include CH_4 and N_2O by 2026, with full taxation of their $CO_{2\text{-eq}}$ emissions from 2027 onwards [50]. Although most fishing vessels currently fall below mandatory ETS thresholds, the carbon taxation will be extended to smaller vessels in the future. Following the [51] report, there are three scenarios for determining the carbon tax for 2030, 2040, and 2050:

- Stated Policies Scenario (SPS) – emission reduction according to current regulations,
- Announced Pledges Scenario (APS) – scenario to achieve net zero emissions by 2050 based on current reduction estimations,
- Net Zero Emissions Scenario (NZES) – scenario with guidelines for the global energy sector to achieve net-zero emissions by 2050, with advanced economies achieving net-zero emissions before others.

These values of carbon tax are presented in Figure 13 for each possible scenario including annual values obtained by interpolation. The cost of CO_2 emissions applies only to vessels powered by fossil fuels, and it can be calculated as[48]

$$Carbon\ tax = \sum_{i=1}^{M} E_{CO2} \cdot CA_{sc}. \tag{14}$$

where M is the elapsed time in months, E_{CO2} is the quantity of CO_2 emissions (kg $CO_{2\text{-eq}}$) and CA_{sc} is the value of the carbon tax depending on the scenario.

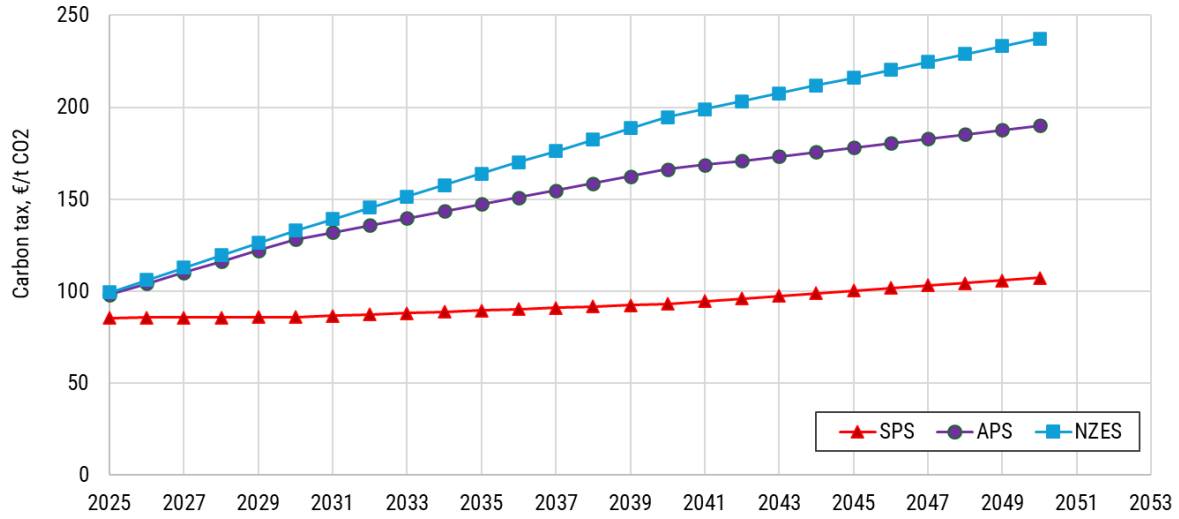


Figure 13. Carbon tax scenarios [52]

Parallel to the modelling of alternative fuels, hybrid energy systems are assessed by incorporating battery storage, auxiliary generators, and possible renewable inputs (Figure 14). By simulating different power system configurations, such as diesel-electric systems, hybrid diesel-battery architectures, and plug-in hybrids, the model evaluates how each configuration affects fuel consumption, operational flexibility, onboard load management, and total energy demand [30]. These simulations provide energy flows, NPC, and operational expenditures, which are essential for comparing scenarios. The modelling of hybrid systems also considers the vessel's measured operational profiles and daily load cycles, ensuring that the output reflects real usage patterns rather than idealized or averaged values.

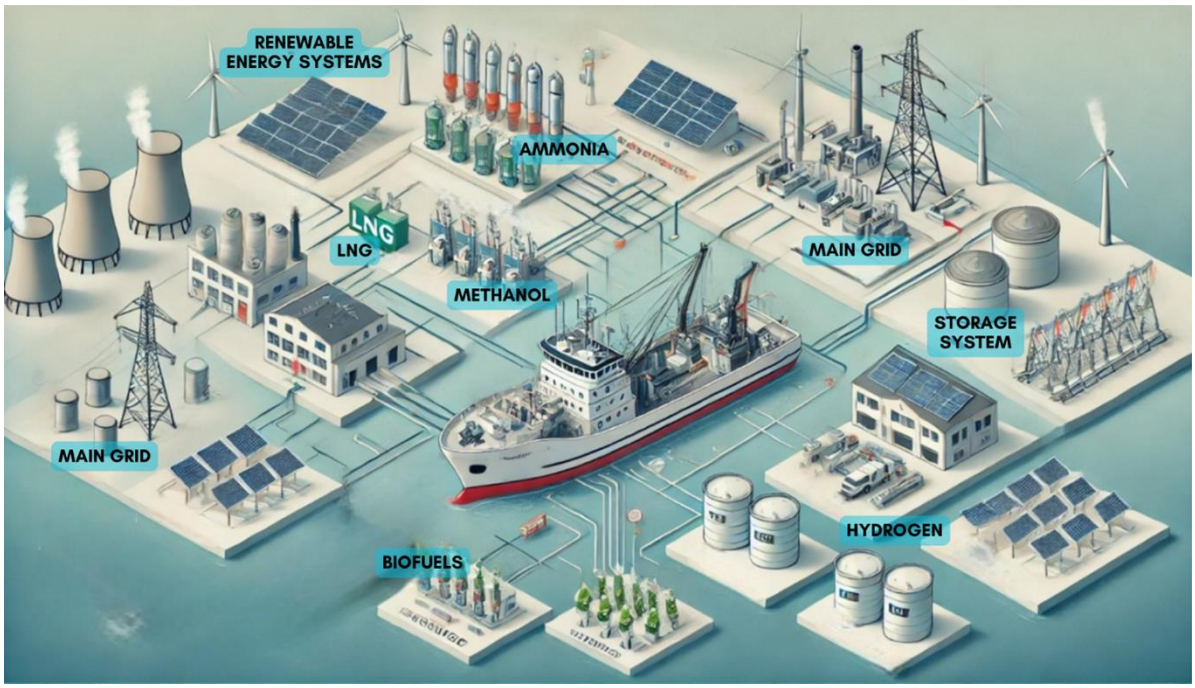


Figure 14. Representation of hybrid energy system in shipping sector [30]

2.5. Integration of electrified fishing vessels into renewable energy system

The integration of fishing vessels into wider energy systems requires a methodological framework that connects vessel-level electrification with the behaviour of national or isolated energy networks. This research focuses on the electrification of fishing fleets within an Isolated Energy System (IES) powered by Renewable Energy Sources (RES) [33], with particular emphasis on island-based fishing port and fully electric purse seiners.

The methodological framework is informed by the EnergyPLAN-based analysis of all-electric purse seiners operating within an island energy system, Figure 15. This approach demonstrates how the hourly electricity demand of fishing ports, derived from real operation profiles and seasonal fishing patterns, can be aligned with locally available renewable resources such as photovoltaic power. By converting real fuel consumption per trip into equivalent electric propulsion needs, and developing hourly demand curves for each season, the model captures the irregularity of fishing activities and their seasonal concentration. The demand distributions are then matched with PV output variability to quantify benefits such as reduced critical excess of electricity production (CEEP), increased renewable utilization, and lower operating and emissions-related costs [33].



Figure 15. Simulation flowchart of an isolated energy system in the EnergyPLAN [33]

Through the localized IES-based modelling approach, the research provides insight into the short-term operational interactions between electrified fishing fleets and RES. By combining real-time operational data, energy demand reconstruction, charging behaviour modelling, and system-wide scenario analysis, the research presents a comprehensive methodology for evaluating how electrified fishing fleets interact with, depend upon, and support integrated RES.

2.6. Influence of hull protection technologies on vessel energy performance

The condition of a vessel's hull has a direct and measurable influence on its energy efficiency, fuel consumption, and emissions. Biofouling begins with microscopic slime accumulation and

quickly progresses to macrofouling communities consisting of barnacles, algae, and other organisms, as presented in Figure 16 [53]. According to the findings, hull fouling can increase vessel resistance by 10% after only one month if no protection is applied, and fuel consumption by 40% while maintaining operational speed [54]. Even relatively thin biofilm layers or initial fouling growth can noticeably raise a vessel's hydrodynamic resistance, leading to increased propulsion power demand and, consequently, higher fuel consumption. Research has shown that slime on the wetted surface can raise resistance by about 1–2% [55]. In addition, a thin slime layer roughly 0.5 mm thick, covering up to half of a ship's hull, may increase GHG emissions by 20–25%, depending on factors such as vessel type, operating speed, and prevailing conditions [56]. The analysis of hull protection technologies within the research therefore focuses assessing the potential benefits of different antifouling solutions through available performance curves, fouling progression data, and fuel-saving estimates.

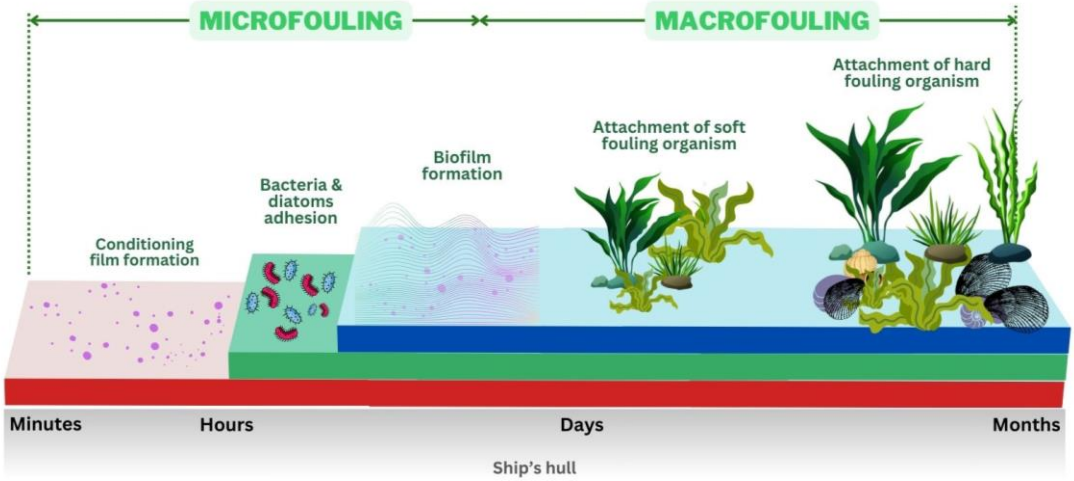


Figure 16. Biofouling formation [53]

To evaluate the role of hull protection in vessel energy performance, this research integrates resistance data with the measured operational fuel consumption obtained from the monitoring system. Since fishing vessels operate under conditions conducive to rapid fouling (slow speeds, long idle times, and frequent port stays), the model incorporates accelerated fouling scenarios to reflect real conditions [52]. Seasonal fouling intensity, water temperature, and fishing time all contribute to variations in hull roughness and must be included when estimating fuel consumption trends over the year. The model expresses total roughness through the Average

Hull Roughness (AHR), which represents the mean roughness height across all elementary surface patches, defined as:

$$AHR = \frac{\sum_{i=1}^{N} Rt_{50,i}}{N}, \tag{15}$$

where N marks the total number of elementary surfaces [57]. Hull roughness arises from four sources: newbuilding roughness, service deterioration, docking-induced roughness, and biofouling. Therefore, it is calculated as:

$$AHR = AHR_{NB} + AHR_S + AHR_D + AHR_{FO}, \tag{16}$$

where AHR_{NB} marks the initial roughness of the vessel hull, AHR_S marks service roughness, AHR_D marks docking roughness, and AHR_{FO} marks biofouling roughness [58]. By applying empirically supported attachment probability (Table 2) and fouling growth rates (Table 3) to the baseline hull condition, the model generates dynamic resistance profiles that evolve over time, allowing simulation of fuel consumption under different maintenance strategies and coating types.

Table 2. The attachment probability in the case of green algae, tube worms, and balanidae in the Adriatic Sea [58]

Type		Green algae, p_1		Tube worm, p_2		Balanidae, p_3	
	Zone	1-3, 7-9, 13-15 Bottom	4-6, 10-12, 16-18 Alongside	1-3, 7-9, 13-15 Bottom	4-6, 10-12, 16-18 Alongside	1-3, 7-9, 13-15 Bottom	4-6, 10-12, 16-18 Alongside
Month	January	1	1	0	0.125	0	0.062
	February	1	1	0.375	0.062	0.062	0.187
	March	1	1	0.562	0.125	0.125	0.500
	April	1	1	0.875	0.312	0.062	0.562
	May	1	1	0.750	0.312	0.187	0.625
	June	1	1	0.937	0.437	0.312	1
	July	1	1	1	0.562	0.312	1
	August	1	1	1	0.812	0.375	1
	September	1	1	0.937	1	0.250	1
	October	1	1	0.750	0.312	0.125	0.250
	November	1	1	0.375	0.250	0.187	0.562
	December	1	1	0.062	0	0.125	0.062

Table 3. Growth rates in the case of green algae, tube worms, and balanidae in the Adriatic Sea [58]

Type		Green algae, r_1, [mm/month]	Tube worm, r_2, [mm/month]	Balanidae, r_3, [mm/month]
Zon	1	0.0375	1.666	0.666
	2	0.0375	1.666	0.500

	3	0.0375	1.666	0.500
	4	0.0375	1.666	0.500
	5	0.0375	1.666	0.166
	6	0.0375	0	0
	7	0.0375	1.250	0.666
	8	0.0375	1.250	0.666
	9	0.0375	2.083	0.666
	10	0.0375	0.833	0.250
	11	0.0375	0	0
	12	0.0375	0	0
	13	0.0375	0.416	0.833
	14	0.0375	0.416	0.250
	15	0.0375	0.416	0.250
	16	0.0375	0.416	0.250
	17	0.0375	0.833	0.333
	18	0.0375	0	0

The dynamics of biofouling can be defined by employing the attachment probability and growth rate of a given species, which depends on the location on the wetted surface and the time of year (e.g., month). Therefore, as seen in Figure 17, the wetted hull surface is divided into multiple zones representing areas with different hydrodynamic conditions and exposure characteristics. These zones account for spatial variations in biofouling accumulation, as certain regions of the hull are more susceptible to organism attachment and growth than others. Consequently, vessels with different hull forms and geometries are expected to exhibit different attachment probabilities and growth rates across the wetted surface.

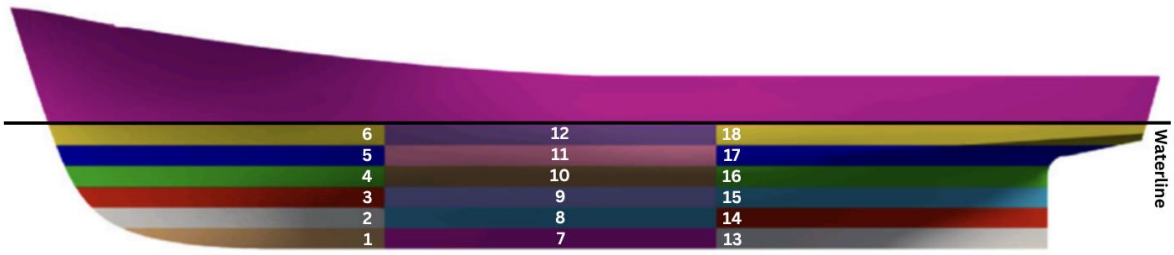


Figure 17. Definition of 18 zones on the wetted surface of a vessel [58]

The efficiency of the antifouling protection is taken into account using the efficiency coefficient defined similarly to the Prandtl tip loss function as:

$$C_{ef} = \frac{2}{\pi} arccos\left[(Ae)^{-\frac{t}{B}}\right], \tag{17}$$

where A denotes the quality of the antifouling protection and B the lifespan of the protection [52]. By combining equation (16) and parameters $p_i(x, y, z, t)$ and $r_i(x, y, z, t)$, the increase in roughness, h_i, on the elementary surface associated with species i equals

$$h_i = \begin{cases} C_{ef} r_i, X > p_i, \\ 0, X \leq p_i, \end{cases} \tag{18}$$

where X marks the uniform random variable between 0 and 1. Thus, the biofouling roughness AHR_{FO} equals:

$$AHR_{FO} = \frac{1}{N} \sum_{i=1}^{N} C_{ef} r_i \Delta t, \tag{19}$$

where Δt marks the time elapsed from a successful attachment (in months) [52].
The increase of the main engine power due to roughness induced by biofouling and deterioration effects equals:

$$\Delta P = \frac{1}{2} \frac{\rho v^3 S \Delta C_F}{\eta}, \tag{20}$$

where ρ denotes the density of seawater, v navigation speed, S wetted surface area, η propulsion efficiency and ΔC_F, the roughness allowance determined as:

$$\Delta C_F = 0.044[1 + k] \frac{AHR_{j+1}^{\frac{1}{3}} - AHR_j^{\frac{1}{3}}}{L_{WL}^{\frac{1}{3}}}, \tag{21}$$

where k is the form factor and L_{WL} is the length at the waterline [59].

In addition to energy performance, the analysis also considers environmental and economic aspects of antifouling technologies. Incorporating these factors into the methodology framework allows estimation of lifecycle impacts, including the frequency of dry-docking, coating renewal costs, and the potential reduction of operational emissions through minimized fuel use. The results enable identifying optimal hull maintenance strategies and quantifying the energy savings that can be realized through the adoption of advanced, environmentally compliant antifouling solutions.

The environmental impact EI of increased fuel consumption are calculated via following environmental footprint [52]:

$$EI = \alpha \cdot GWP + \beta \cdot AP + \gamma \cdot EP, \quad (22)$$

where *GWP* (Global Warming Potential) denotes the potential for global warming, i.e., the impact of CO_2, CH_4, and N_2O emissions. It can be calculated as [52]:

$$GWP = 1 \cdot E_{CO2} + 26 \cdot E_{CH4} + 298 \cdot E_{N2O}. \quad (23)$$

Acidification Potential *AP,* kg $SO_{2\text{-eq}}$, stands for emissions of acidifying gases, SO_X and NO_X, which can negatively affect soil, water, and flora, contributing to a decrease in pH values in the environment. Similarly, Eutrophication Potential *EP*, kg $PO_{4\text{-eq}}$, represents the impact of NO_X emissions, which negatively affect terrestrial and aquatic ecosystems as well as human health through reduction of oxygen levels in water and respiratory diseases [34,60]. These potentials can be calculated as:

$$AP = 1 \cdot E_{SOx} + 0.7 \cdot E_{NOx}, \quad (24)$$

$$EP = 0.13 \cdot E_{NOx}. \quad (25)$$

Weighting factors denoted by *α, β,* and *γ* are determined based on the application area, and in this case, they are taken for the shipbuilding sector [60]. The emissions E_{CO2}, E_{CH4}, E_{N20}, E_{SOX}, and E_{NOX} resulting from fuel combustion are calculated according to equation (3). Due to impact of biofouling, the total fuel consumption considers the power increase of the main engine *ΔP*:

$$FC = (P + \Delta P) \cdot SFC \cdot t. \quad (26)$$

The economic performance of hull protection technologies is evaluated through a life cycle cost framework that captures investment, maintenance, fuel, and carbon tax expenses over a defined lifetime. The economic model therefore couples the technical equations for added resistance and fuel use with detailed cost functions describing both passive and active antifouling systems. Investment costs include the procurement of coating materials or active devices as well as dry-dock handling, labour, and accommodation expenses [52]. For passive systems, the cost of coating *AF* (EUR) is calculated:

$$AF = AF_L \cdot V \cdot n \cdot A_{wet} \quad (27)$$

where AF_L denotes the coating price per liter, *V* is the total required quantity of coating in liters, *n* is the number of coating layers, and A_{wet} is the wetted surface area in m^2 on which the coating is applied [52]. Since passive and active protection methods result in a certain increase in engine power, which further affects the increase in fuel consumption and thus harmful emissions, a

good indicator of the economic impact of passive and active protection is the calculation of fuel costs and the associated carbon tax. The total costs are calculated for a certain period *t* (months) as:

$$LCFC = t \cdot FC \cdot PR_D, \tag{28}$$

where PR_D denotes the price of diesel fuel (EUR/l). The carbon tax is calculated according to equation (14), for the considered carbon tax scenario.

2.7. Assessment of methanol-hydrogen dual-fuel propulsion using modelled operating cycles

The decarbonisation of the fishing sector requires propulsion solutions that significantly reduce GHG emissions while maintaining operational reliability, safety, and economic viability. While full electrification represents an ultimate low-emission solution, its applicability remains limited for a large share of fishing vessels due to range requirements, power demand during fishing operations, and infrastructure constraints [61]. Consequently, transitional technologies based on low-carbon fuels are of specific importance. In this context, methanol and hydrogen have emerged as promising marine fuels due to their potential for reducing emissions, compatibility with renewable energy pathways, and increasing availability within maritime energy strategies.

The application of a methanol–hydrogen dual-fuel marine engine as an alternative propulsion solution extends the research's methodological framework toward advanced fuel-based decarbonisation pathways. The analysis builds upon a detailed energy, environmental, and economic assessment of a dual-fuel engine capable of operating on conventional diesel fuel with partial substitution by methanol and hydrogen. Such a configuration enables gradual decarbonisation of existing and new vessels without requiring full replacement of propulsion systems, thereby offering a more realistic transition option for the fishing fleet [61]. The developed modelling framework evaluates engine performance across multiple fuel substitution ratios, focusing on changes in fuel consumption, thermal efficiency, and exhaust gas emissions. Additional focus is given to CO_2 emissions, as well as NO_X and other pollutants, in order to capture environmental impacts. Beyond direct emissions, the research incorporates LCA by evaluating fuel production pathways and their influence on total environmental impact. The findings indicate that the environmental benefits of methanol–hydrogen dual-fuel operation are

strongly dependent on fuel origin, with renewable methanol and green hydrogen offering the highest emission reduction potential.

A realistic assessment of alternative propulsion systems for fishing vessels requires an accurate representation of their operating cycles, as fuel consumption, emissions, and engine performance are strongly dependent on time-varying load conditions rather than nominal engine ratings [62–64]. Unlike merchant vessels, fishing vessels operate under highly irregular and cyclic regimes that combine transit, fishing operations, auxiliary power demand, and idle periods. Simplified steady-state or design-point analyses are insufficient to capture the realistic environmental and economic performance of alternative propulsion concepts. Therefore, the operating cycle is defined as a sequence of distinct operational modes, each characterised by a specific engine load, duration, and energy demand (Figure 18). These load points represent transit, fishing operations, manoeuvring, and low-load or idle modes, ensuring that the results reflect realistic operational behaviour rather than idealised steady-state conditions. By structuring the vessel's operation in this way, the study captures the dynamic nature of real-life fishing activities and their direct influence on engine behaviour.

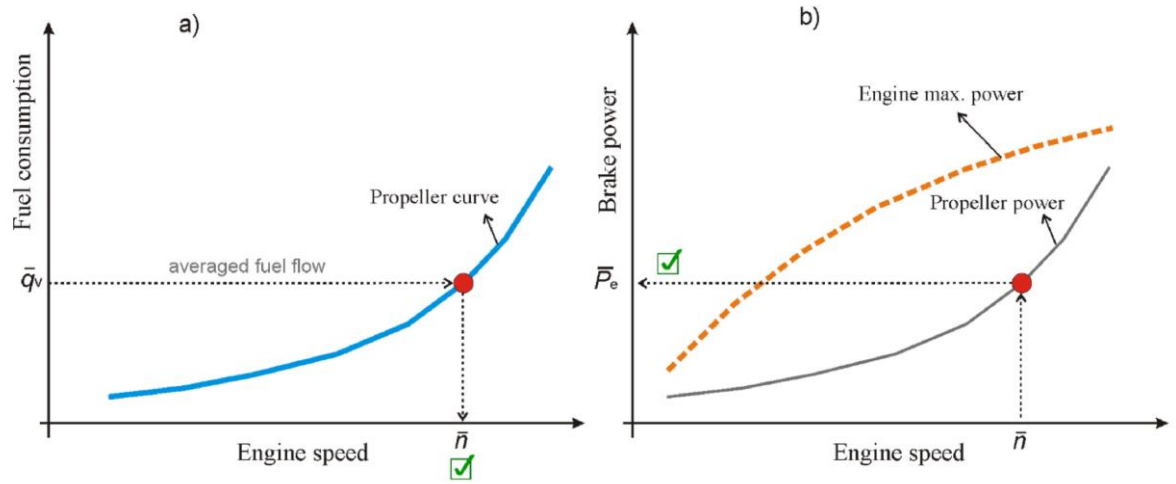


Figure 18. Definition of steady state operating point: a) engine speed definition using the measured fuel flow and propeller curve, b) definition of required engine brake power using a propeller power curve

The operating cycle is constructed using measured data and literature on vessel speed, engine load distribution, and time spent in individual operating modes. Rather than assuming constant operation at a single load point, the cycle is represented as a weighted combination of load

states that together reflect a full fishing trip. This approach enables the calculation of fuel consumption and emissions as cumulative values over the complete operating cycle, providing a realistic basis for comparing different fuel and engine configurations. Within this framework, the dual-fuel engine model is applied to each operating mode separately. For every load point in the cycle, engine efficiency, fuel substitution ratios, and emission factors are determined based on the specific combustion characteristics of diesel, methanol, and hydrogen [61]. The results are then aggregated across the entire cycle, allowing direct comparison between conventional diesel operation and various methanol–hydrogen substitution scenarios. This method highlights how the benefits of alternative fuels are not uniform across the operating cycle but instead depend strongly on load level and mode duration.

3. Selected results with discussion

The complete analysis is carried out on a group of 12 commercial fishing vessels operating in the Adriatic Sea, consisting of 10 purse seiners and 2 trawlers. These vessels represent typical large-scale Croatian fishing units in terms of length, installed power, and gear type, and together cover a wide range of operational profiles, from high-speed steaming to low-speed fishing operations and prolonged idle periods in port. For each vessel, technical characteristics such as length overall (LOA), GT, main and auxiliary engine power (P), fuel type, tank arrangement, and gear type were collected from national registries and technical documentation. The Croatian fishing fleet comprises 7,808 vessels (Ministry of Agriculture, 2023), most of which are smaller vessels: 56.4% are under 6 m LOA and 36.4% range from 6–12 m. Despite their size, the fleet accounts for 5.74% of total Mediterranean fish catches, ranking sixth in capture production within the region [45]. Purse seiners between 24 m and 40 m LOA are the dominant contributors to overall landings, representing 50.5% of all landings in 2020. More broadly, purse seiners form the core of Croatian fisheries, contributing over 90% of the total landed weight and nearly 55% of the total landing [45]. The final phase of purse seine fishing, which consists of hauling and sorting the fish, is shown in Figure 19.



Figure 19. Purse seine fishing - hauling and sorting of the catch

As illustrated in Figure 20, purse seiners and trawlers differ substantially in their technical characteristics. The majority of purse seiners are equipped with engines rated between 150 and 400 kW, whereas most trawlers operate with engines between 150 and 250 kW. A similar difference appears in vessel length: purse seiners have an average LOA of 24 m, compared with 19 m for trawlers. Trawlers also tend to be lighter, with an average gross tonnage roughly half that of purse seiners. When evaluating the environmental and economic performance of the Croatian fishing fleet, it is important to acknowledge its advanced age. The fleet is largely outdated, with an average vessel age exceeding 40 years [41]. As depicted in Figure 21, vessel age correlates with lower engine power, particularly since a large portion of the fleet was built between 1940 and 1960 and typically features engines averaging around 420 kW.

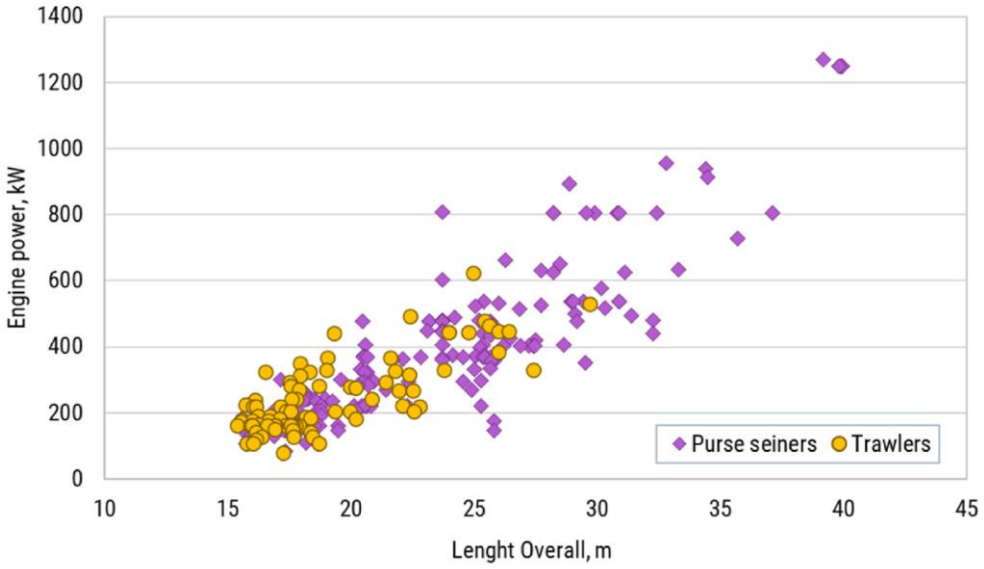


Figure 20. Correlation between engine power and LOA of the Croatian fishing fleet [34]

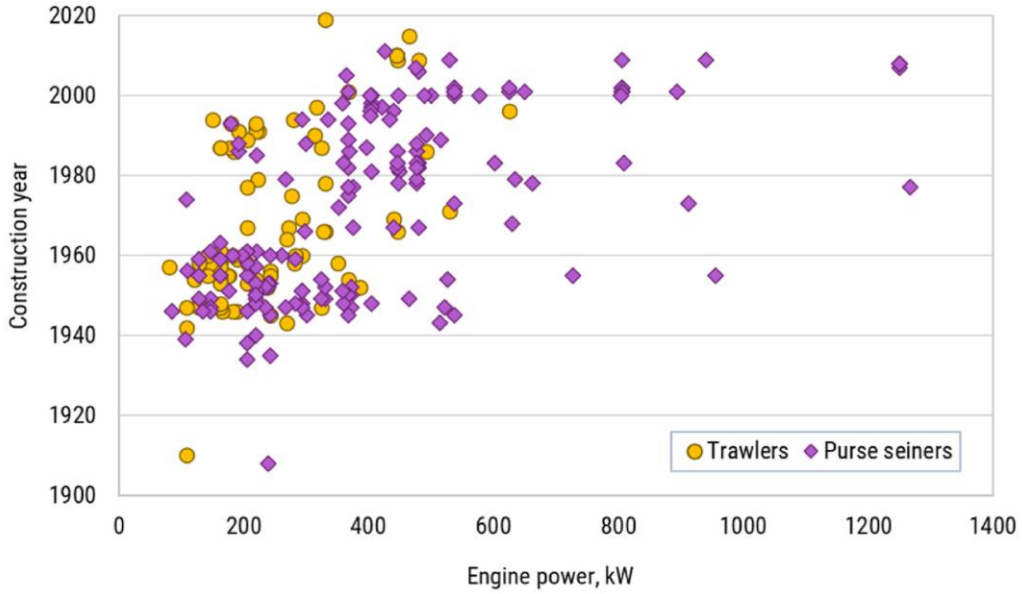


Figure 21. Correlation between engine power and year of construction of the Croatian fishing fleet [34]

The monitoring system installed on these vessels provided a high-quality empirical dataset that captures real operational behaviour. The dataset served not only for descriptive analysis but also as a foundation for validating the modelling approaches developed later in the research. By deriving operational parameters, energy-use patterns, and emission characteristics directly from measurements, the database enabled the implementation and calibration of models intended to be applicable across the entire fishing fleet, regardless of vessel type, operational location, propulsion configuration, fishing gear, or fuel used. In this way, the monitored sample functioned as a representative reference group for developing robust, generalizable modelling tools suited to diverse fleets.

3.1. Definition of the Energy Efficiency Index (EEI)

The assessment of the Croatian fishing fleet revealed clear differences in environmental performance between purse seiners and trawlers, primarily driven by operational characteristics, engine configurations, and scale of fishing activity. Using the Energy Efficiency Index (EEI) calculated according to equation (1), the indices were computed for 163 purse seiners and 82 trawlers based on estimated fuel consumption and catch. The results, presented in Figure 22-23, indicate substantially lower EEI values for purse seiners, with most vessels operating between 0.48 and 0.91 kg $CO_{2\text{-eq}}$ per kg of catch, and an overall range from 0.32 to

2.01 kg $CO_{2\text{-eq}}$ per kg catch. In contrast, trawlers (Figure 24-25) exhibited emission indices approximately four to seven times higher, ranging between 2.08 and 14.11 kg $CO_{2\text{-eq}}$ per kg catch. Several trawlers with low GT and older construction years showed the highest EEI values, confirming the strong influence of vessel size, engine power, and hull age on environmental performance.

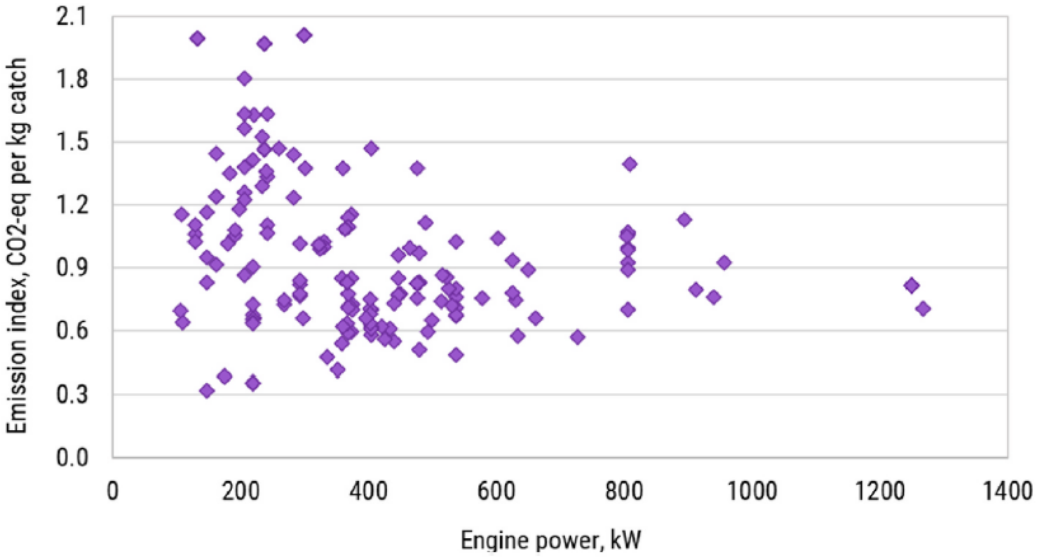


Figure 22. EEI values in relation to engine power – purse seiners [34]

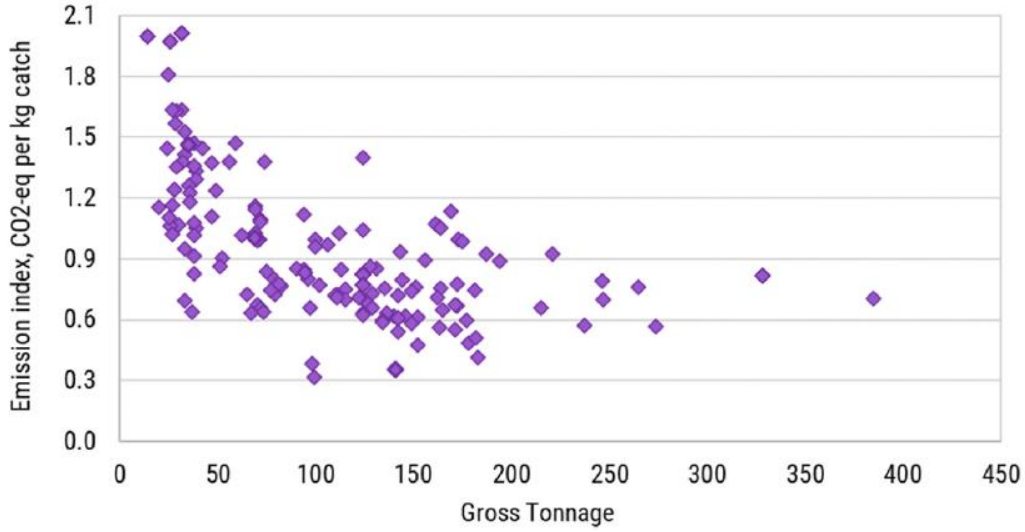


Figure 23. EEI values in relation to GT – purse seiners [34]

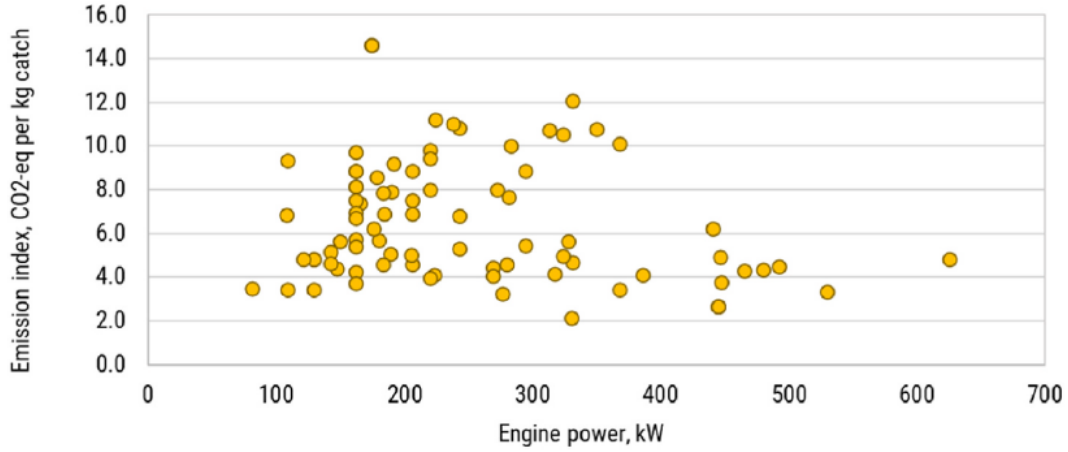


Figure 24. EEI values in relation to engine power – trawlers [34]

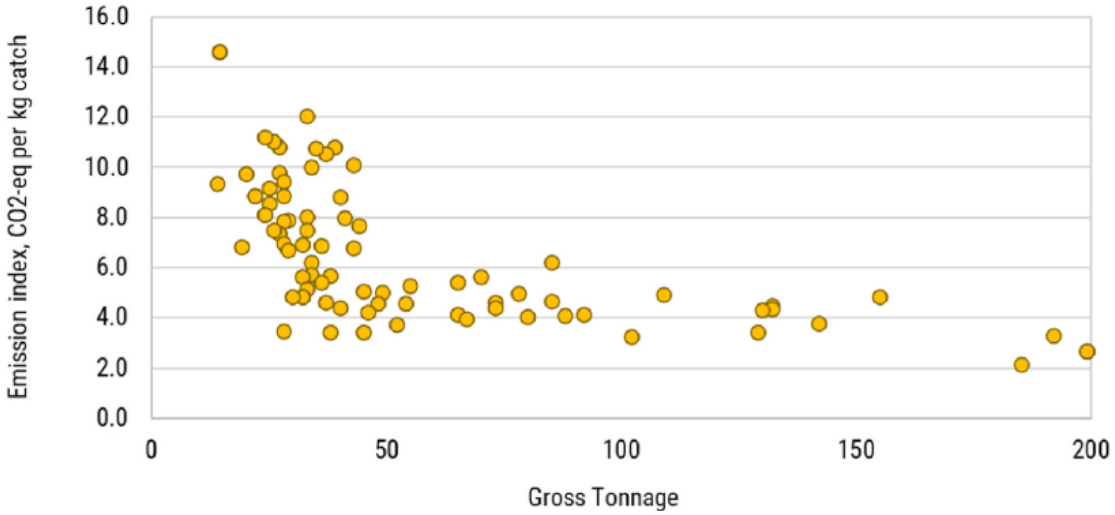


Figure 25. EEI values in relation to GT – trawlers [34]

A validation group of 12 vessels equipped with a real-time monitoring system was used to verify the accuracy of estimated fuel consumption and catch. The validation demonstrated that vessels with measured data resulted in a narrower and more realistic spread of EEI values: 0.15–0.85 kg $CO_{2\text{-eq}}$ per kg catch for purse seiners (Figure 26) and 4.3–7.18 kg $CO_{2\text{-eq}}$ per kg catch for trawler (Figure 27). The comparison highlighted underestimation of catch in smaller purse seiners and deviations in reported engine power due to operational derating practices, both of which affect EEI calculations. The results also showed that the economic context of the catch significantly alters the assessment of efficiency. When the denominator of the index was expressed as economic value instead of mass of landed fish, EEI decreased markedly for all vessels, especially for trawlers targeting higher-value demersal species (Figure 28). This

confirmed that catch quantity alone does not reflect the socioeconomic efficiency of fishing operations, and that species composition, visible in the market price disparities, must be incorporated for an integrated evaluation.

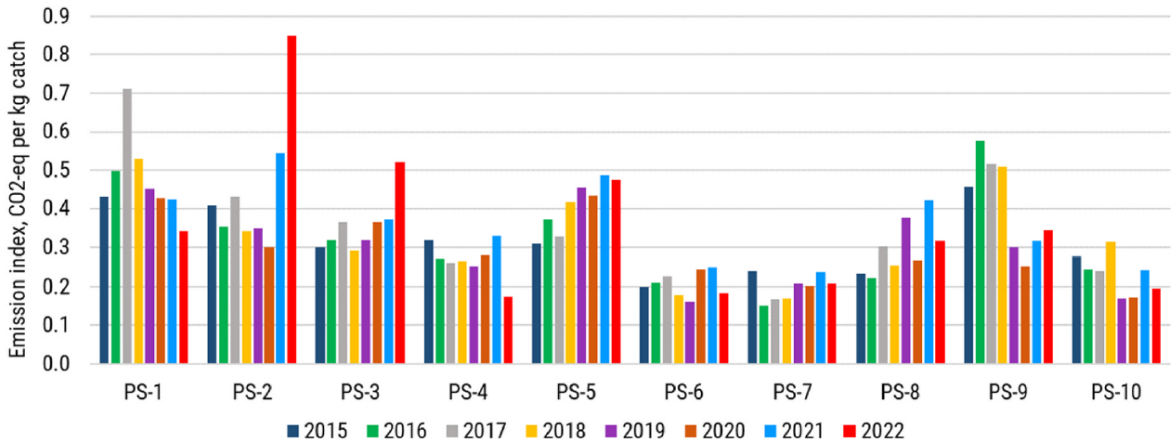


Figure 26. EEI values ($CO_{2\text{-eq}}$ per catch) of the validation group – purse seiners [34]

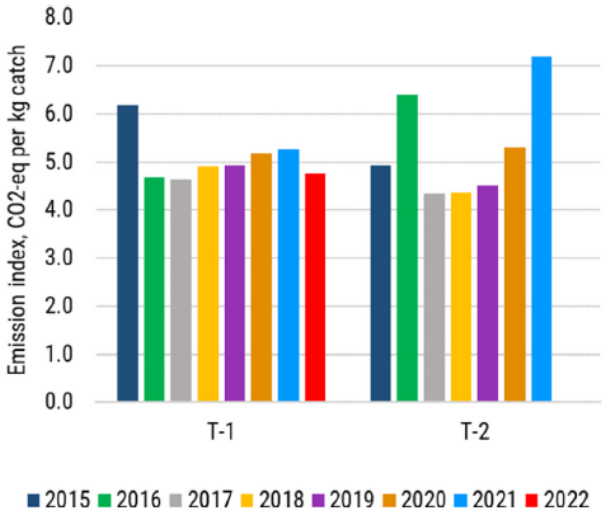


Figure 27. EEI values ($CO_{2\text{-eq}}$ per catch) of the validation group – trawlers [34]

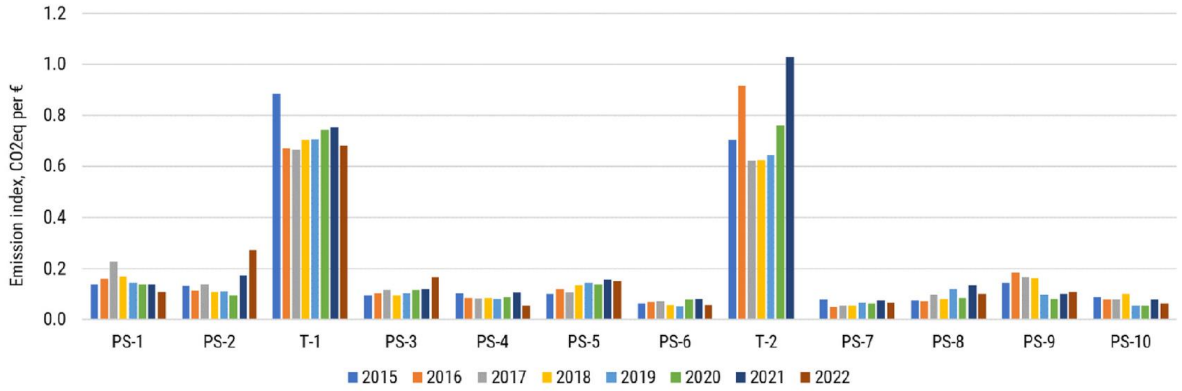


Figure 28. EEI values ($CO_{2\text{-eq}}$ per €) of the validation group [34]

3.2. Definition of the Sustainability Index (SI)

The Sustainability Index (SI) is introduced as an extension of the previously developed EEI in order to capture a broader understanding of vessel performance. While the EEI focuses primarily on the environmental efficiency of fishing operations by relating energy use and emissions to productive output, it does not account for the economic dimension that ultimately determines the viability of fishing activities. To address this limitation, the SI incorporates both environmental impacts and socio-economic factors, including capital and operating costs, revenue from landed catch, and potential carbon taxation.

Under existing conditions without carbon taxation, most vessels operate with revenue exceeding total costs. As illustrated in Figure 29, income exceeded costs by a factor of approximately 1.4–3.4 for the majority of vessels, confirming acceptable economic performance of traditional diesel propulsion. The inclusion of carbon taxation according to the NZES scenario significantly altered this assessment. Only eight vessels remained profitable, while the others recorded SI values greater than 1, indicating unsustainable operation. The vessels with higher engine power and consequently higher fuel consumption showed the greatest sensitivity to taxation. Trawler T1 demonstrated the poorest performance due to low catch and high annual fuel use, resulting in SI values far above 1 in multiple years.

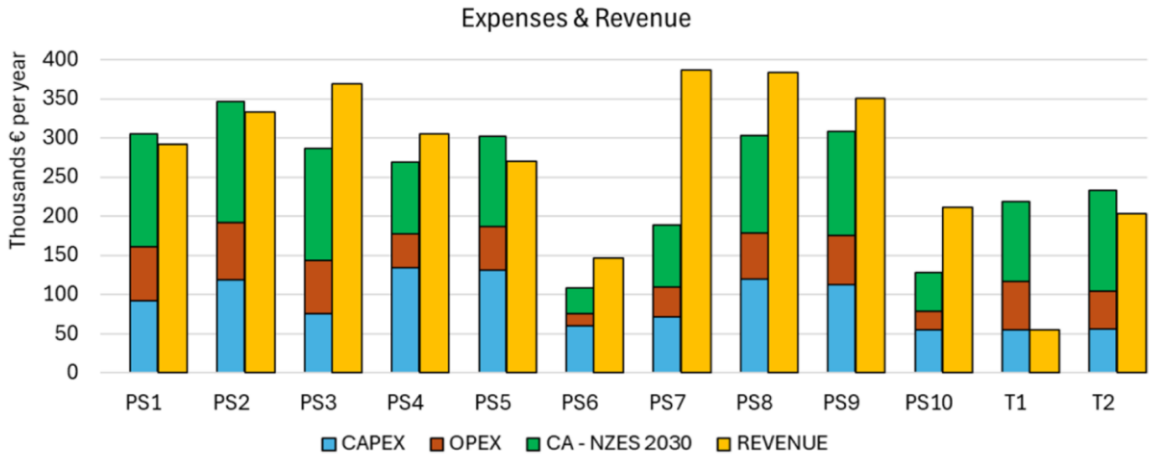


Figure 29. Comparison of average annual total costs and revenue of diesel-powered vessels [28]

Annual SI values for 2015–2022 (Figure 30) ranged predominantly between 0.8 and 1.2 for purse seiners, with four vessels (PS3, PS6, PS7, PS10) consistently achieving SI lower than 1. These vessels combined lower installed power with competitive catch rates, resulting in stable cost-to-revenue ratios. Vessels with higher installed power (e.g., PS4, PS5, PS8) showed occasional SI peaks above 1 during years of reduced catch, demonstrating the strong influence of catch variability on economic sustainability.

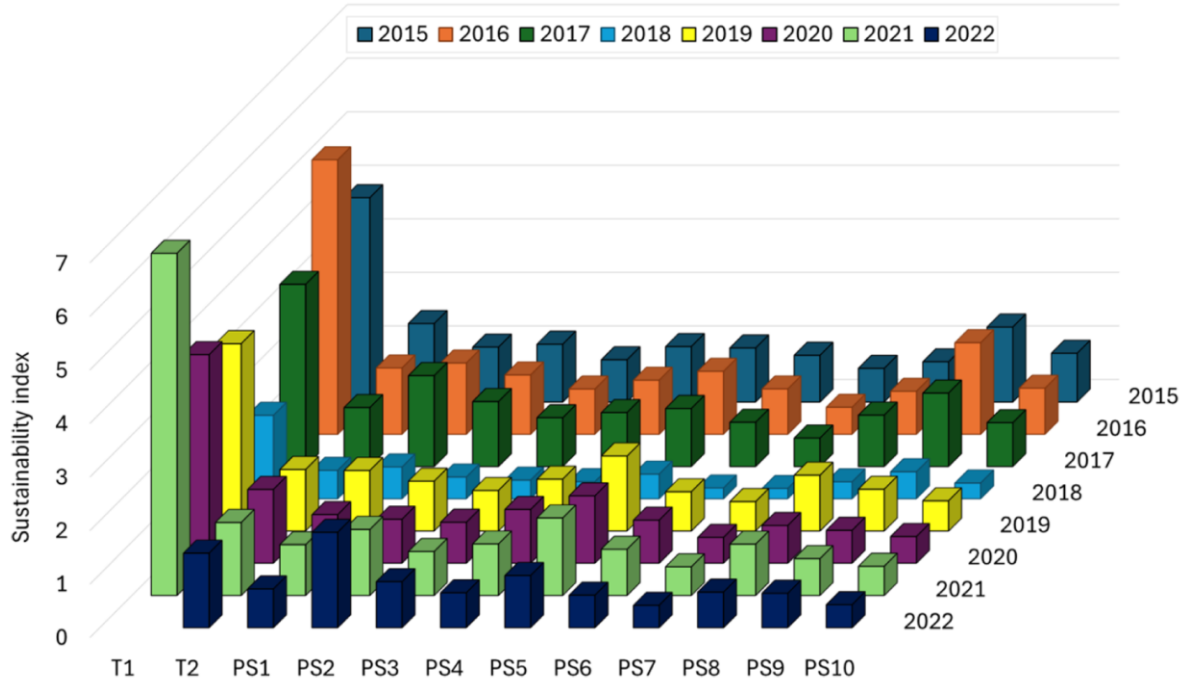


Figure 30. Sustainability indices per year [28]

The analysis of revenue relative to landed weight demonstrated that catch composition plays a critical role in SI outcomes. Although PS1 and PS10 differed by only 22.8 t in total landings, their revenue differed by €15,800, while PS5 generated almost the same revenue as PS10 despite landing 49.2 t less. This highlights the importance of species-specific price variations, confirming that SI is highly sensitive not only to quantity but also to market value of catch. A sensitivity analysis, presented in Figure 31, showed that increases in fuel prices systematically raised the SI for all vessels, indicating worsening sustainability as fuel costs rise. Revenue fluctuations had the opposite effect: decreases in revenue sharply increased SI. Revenue-related sensitivity was more nonlinear than fuel-related sensitivity, suggesting complex market-driven variability in economic performance.

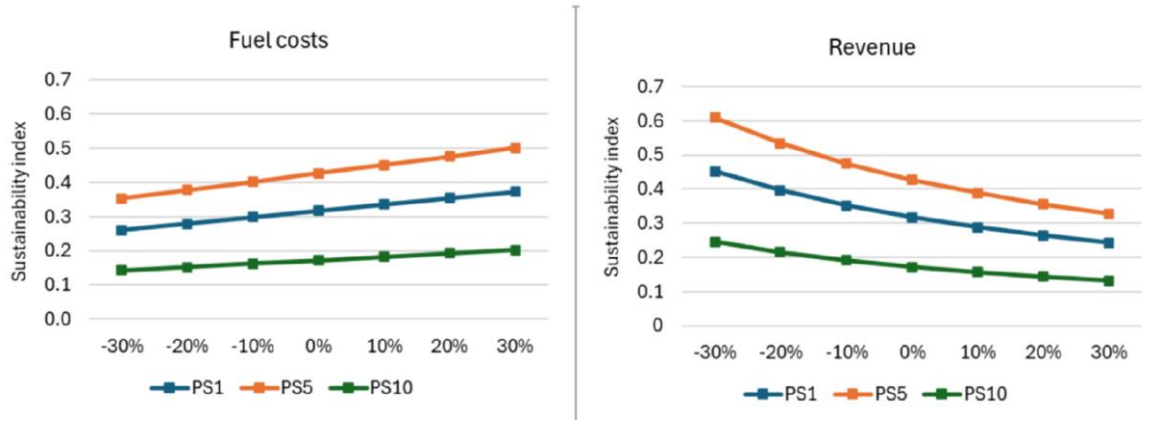


Figure 31. Sensitivity analysis of sustainability index based on fuel costs and revenue fluctuations [28]

3.3. Environmental-economic assessment of alternative power systems

The environmental-economic performance of alternative power systems was evaluated using life-cycle assessments. The assessment combined the operational characteristics derived from real-time measurements with fuel-, electricity-, and technology-specific cost structures described in the studies. Results from analyses performed for hybrid, battery-electric, methanol, biodiesel and conventional diesel systems were used to determine their suitability for fishing vessels under current and projected decarbonisation conditions. The findings presented below are based on the assessment of large-scale purse seiners and trawlers operating in the Adriatic Sea. An example of a trawler is presented in Figure 32.



Figure 32. Trawling in the Adriatic Sea

Diesel propulsion served as the reference scenario for all comparative analyses. The LCA compared several alternative power configurations for a representative Adriatic trawler and demonstrated substantial differences in environmental performance across fuels and technologies, shown in Figure 33. The diesel-powered trawler exhibited the highest share of emissions in the PTW phase, accounting for 90.15% of total life-cycle $CO_{2\text{-eq}}$ emissions, with only 9.80% attributed to WTP processes and negligible manufacturing emissions. For alternative fuels, reductions in total carbon footprint were observed, although the distribution of emissions shifted. Methanol, LNG, and B20 each produced slightly higher WTP emissions than diesel, 14.76% for methanol, 12.58% for LNG, and 11.94% for B20, but delivered reductions in PTW emissions due to cleaner combustion profiles. As a result, all three options achieved lower total $CO_{2\text{-eq}}$ emissions when compared to diesel, confirming their potential to lessen environmental impact while utilizing engines of similar construction. A contrasting trend was observed in the case of ammonia and hydrogen. The ammonia-powered configuration resulted in WTP emissions 99% higher than diesel, giving it the highest life-cycle footprint of all examined fuels. Hydrogen showed WTP emissions up to eight times higher than diesel due to energy-intensive upstream production, but because hydrogen produces zero PTW emissions,

its overall carbon footprint was lower than diesel, though still significantly influenced by upstream processes. These findings indicate that hydrogen offers meaningful PTW benefits but remains highly dependent on clean production pathways to achieve true environmental gains. The battery-electric configuration showed a different emissions structure, with 92.50% of total emissions arising from the WTP phase, predominantly due to electricity production under the Croatian energy mix. Manufacturing emissions were higher than for combustion-engine technologies, while PTW emissions were zero. Although total emissions were lower than diesel, the upstream dominance of the footprint indicates that environmental benefits increase only when electricity sources become largely renewable.

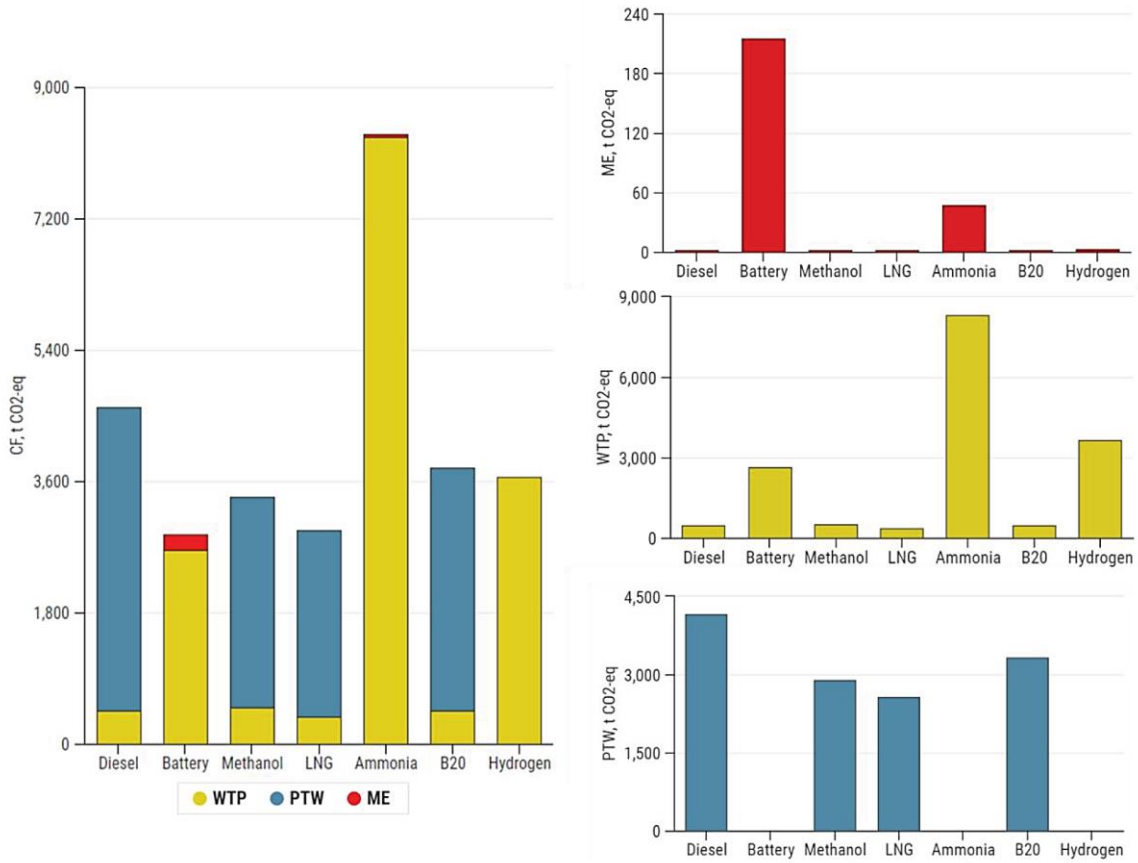


Figure 33. LCA results for a trawler [39]

From an economic standpoint, the result showed that diesel systems remain economically favourable under current regulatory conditions, with the majority of vessels achieving positive sustainability outcomes. For typical purse seiners, total revenue exceeded total costs, indicating economic resilience even when fuel prices fluctuate moderately. However, when carbon taxation was introduced following the NZES trajectory, several vessels, particularly trawlers,

shifted into unsustainable operation due to their high fuel consumption and lower catch volumes. This confirms that diesel vessels are highly sensitive to policy-driven cost increases and that fuel intensity is the main determinant of economic vulnerability.

Battery-electric propulsion is identified as the most environmentally favourable option, with zero operational emissions and no exposure to carbon taxation. However, results consistently demonstrated that high investment costs remain a prohibitive factor, as seen in Figure 34. Capital costs dominated the LCCA due to the large battery capacities required for long fishing trips and the need for battery replacement once during the vessel lifetime. Even though electricity prices are significantly lower than fossil fuel prices, the cumulative lifetime cost of battery systems exceeded those of diesel, methanol, and biodiesel systems for most vessels. Only vessels with low installed power or exceptionally high catch efficiency demonstrated the potential to operate sustainably under a battery-electric configuration.

Methanol propulsion was consistently identified as the most balanced alternative in terms of environmental and economic outcomes. Unlike batteries, methanol systems have relatively moderate capital costs because they rely on dual-fuel engines that are already commercially available. Life-cycle results showed that methanol-powered vessels achieved SI values within ±3% of diesel across the fleet, demonstrating near-equivalent economic performance with a significantly lower environmental footprint [28]. Methanol's lower price relative to biodiesel and its favourable WTP emission profile contributed to cost reductions, despite the presence of carbon taxation. For most vessels, methanol provided overall cost savings or marginal increases in cost that remained within economically acceptable limits. Only vessels with very low catch rates, such as trawler T1, recorded unsustainable outcomes due to insufficient revenue to offset capital and operating costs.

Biodiesel blends presented mixed environmental-economic performance. From an environmental perspective, biodiesel use reduces GHG emissions and carbon taxation when compared to diesel. However, the high fuel price of biodiesel (particularly B50 blends) resulted in significantly higher operating costs. Although the technology requires no major capital investment and integrates seamlessly with existing diesel engines, the elevated fuel cost offsets its environmental advantage. Reducing the biodiesel share in the blend would improve economic performance but increase carbon-related expenditures, indicating a clear trade-off between emissions and cost.

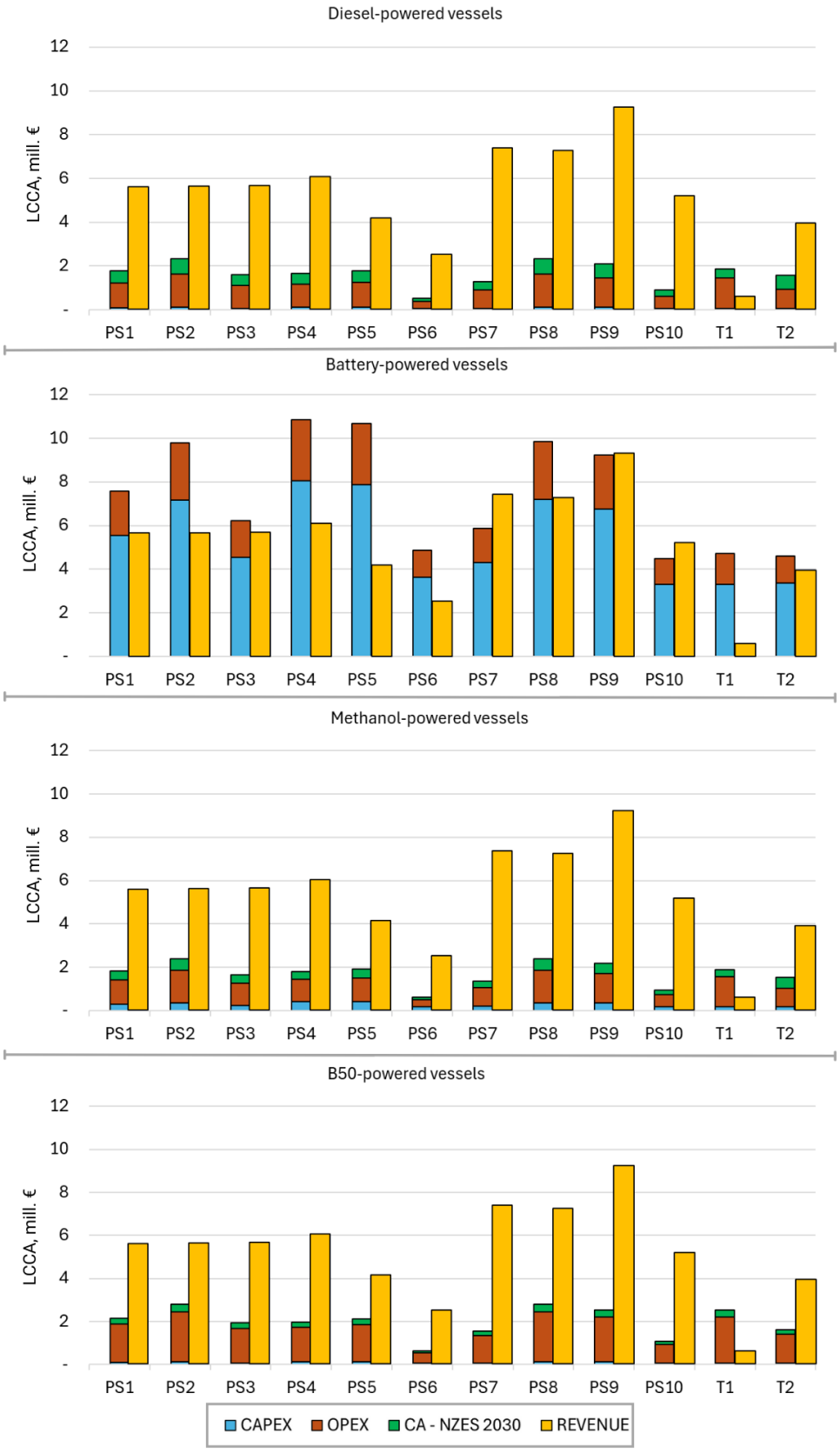


Figure 34. LCCA of different power configurations [28]

Hybrid systems combining diesel engines with battery storage are analysed primarily for energy efficiency and integration benefits. Hybridization demonstrated the ability to reduce fuel consumption through peak-shaving and propulsion support, leading to moderate emission reductions. The assessment of hybrid and plug-in hybrid power systems for purse seiners and trawlers yielded distinct environmental-economic performance outcomes, reflecting differences in vessel size, load variability, and operational profiles. Three configurations were analysed: (1) conventional diesel engine systems, (2) hybrid systems integrating a diesel generator with lithium-ion battery storage, and (3) plug-in hybrid systems capable of charging from the shore grid (Figure 35). The results demonstrate that hybridization is most advantageous for vessels with highly variable operational profiles, such as purse seiners, where batteries effectively reduce fuel use and emissions. For trawlers, hybrid systems are less favourable due to steady engine loading and added conversion losses. Across both vessel types, plug-in hybrid systems provided the most balanced performance, achieving the lowest NPC and the most consistent emissions reductions. Fuel price and carbon taxation were identified as critical determinants of long-term system viability.

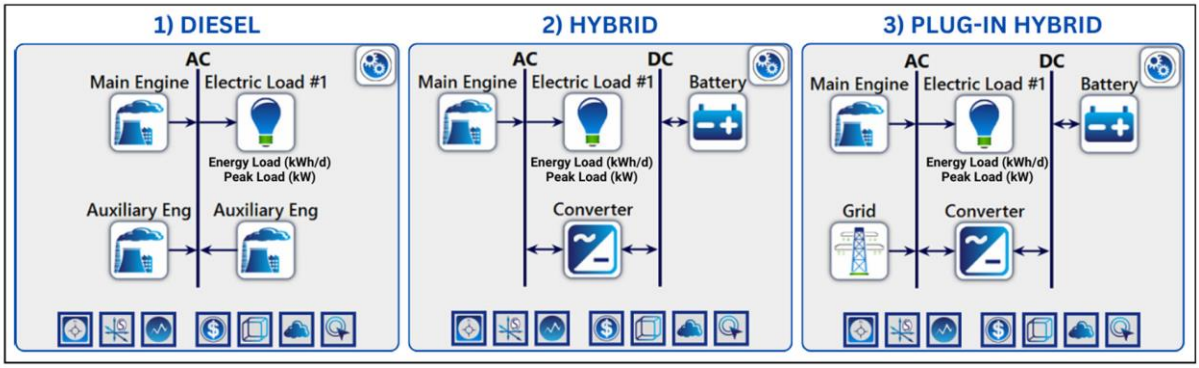


Figure 35. Microgrids designed and analysed in HOMER Pro software [30]

For purse seiners, diesel systems resulted in the highest NPC due to intensive fuel use, while hybridisation reduced fuel consumption and plug-in systems achieved the lowest NPC by shifting energy demand to the electrical grid. In trawlers, the hybrid configuration produced the highest NPC because steady propulsion loads limited battery effectiveness, whereas plug-in systems again achieved the lowest NPC. The comparison between two vessel types is shown in Figure 36. Fuel remained the dominant cost driver for all configurations, with diesel-only systems exhibiting the highest fuel demand and therefore the highest operating costs.

Environmentally, both hybrid and plug-in systems reduced most pollutants compared to diesel, but their performance varied by vessel. Purse seiners benefited from lower CO_2, NO_X and SO_2 emissions under all alternatives, while trawlers experienced increase by 25–39% in CO_2 under hybrid operation due to higher fuel use, although plug-in systems consistently reduced emissions across all categories.

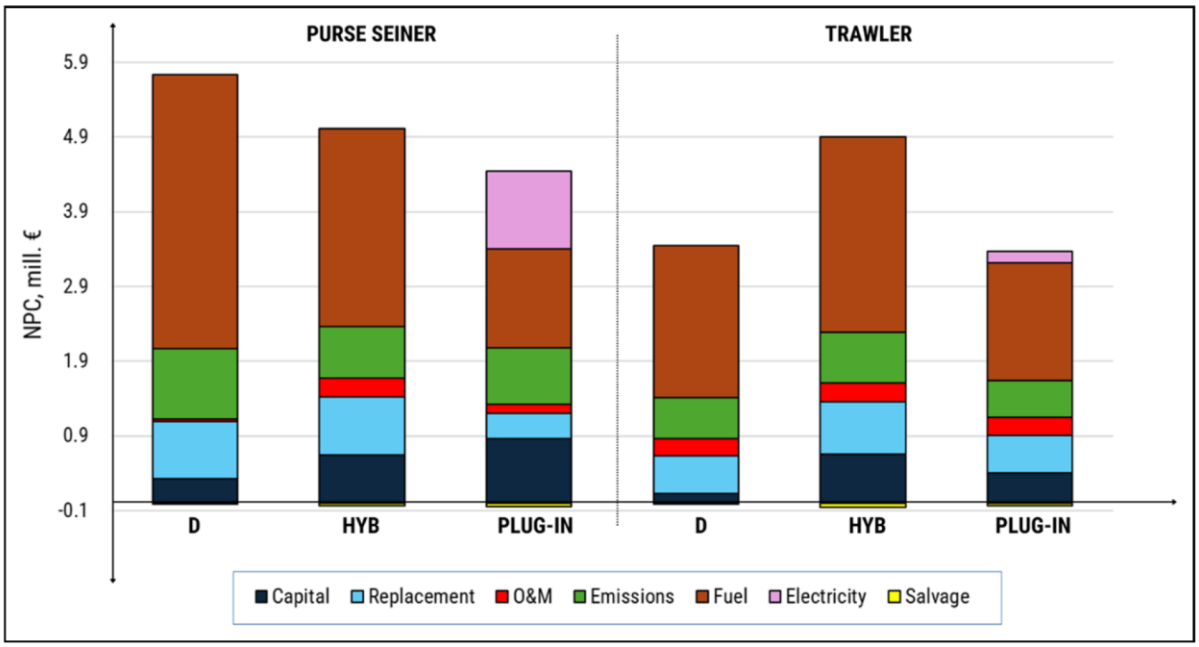


Figure 36. NPC values optimized in HOMER Pro software [30]

Further modelling demonstrated that electrified vessels could integrate efficiently into national and isolated energy systems, with battery charging predominantly occurring during periods of high renewable energy availability.

The analysis of electrifying purse seiners within an isolated island energy system demonstrated that battery-powered vessels significantly influence both emissions reduction and power system behaviour. Hourly modelling of the Island of Cres showed that electrification shifts part of the fishing fleet's energy demand from fossil fuels to PV-generated electricity, reducing diesel consumption by up to 8.69 GWh/year for a 30-vessel scenario. The charging profiles indicated that peak charging occurred during spring (March), with seasonal variability visible across vessel operation modes. The energy demand of the fishing port ranged from 1.65 to 4.96 GWh/year depending on the fleet size. PV generation and fishing-port electricity demand were found to be positively correlated. Months with higher solar irradiation coincided with elevated charging needs, allowing the electric fleet to absorb excess PV production and reduce Critical

Excess of Electricity Production (CEEP), especially in summer (Figure 37). A complete removal of operational fuel emissions is achieved in the electrification scenarios, as the diesel fuel demand of the fishing port fell to zero. In contrast, business-as-usual scenarios emitted up to 2,315 tonnes of CO_2 per year for the 30-vessel fleet. The introduction of electric fishing vessels also reduced IES operating costs due to lower diesel usage, although investment costs of battery systems increased total system expenditures [33].

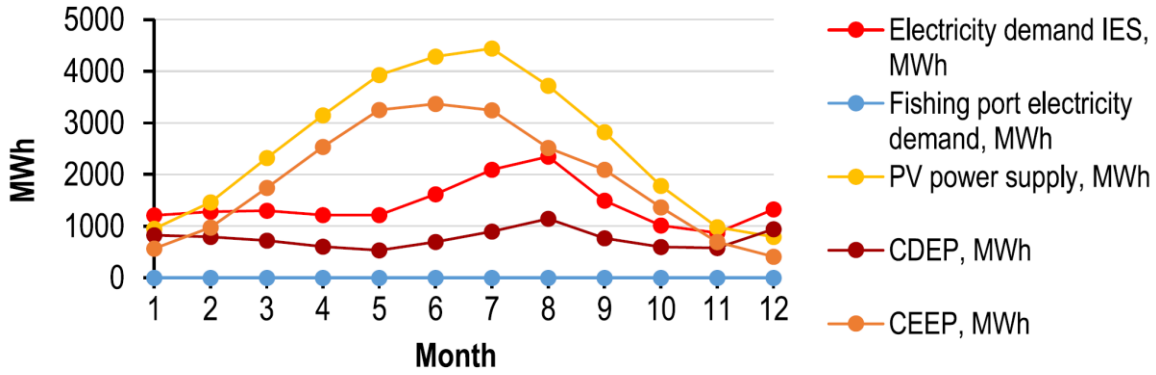


Figure 37. Average monthly values of the electricity demand, electricity supply, CEEP, CDEP, and electricity demand of the fishing port for the BUA 2030 scenarios [33]

3.4. Dual-fuel engine performance under representative fishing vessel operating cycles

The results are obtained using a detailed one-dimensional engine model developed in the AVL BOOST simulation environment, presented in Figure 38. AVL BOOST is employed to model the thermodynamic behaviour of a marine internal combustion engine operating in diesel mode and in methanol–hydrogen dual-fuel configurations. The use of AVL BOOST enables the calculation of in-cylinder processes, fuel consumption, efficiency, and emission formation under varying load conditions representative of real fishing vessel operation [61]. For each operating mode, AVL BOOST calculates brake-specific fuel consumption, engine efficiency, and emissions. The results for individual load points are then weighted according to the duration of each mode within the operating cycle, allowing the derivation of cycle-averaged values. This ensures that operating modes with higher energy demand have a proportionally greater influence on the overall results, consistent with real vessel operation. Following the calibration

of the engine simulation model under steady-state operating conditions, the model was further calibrated for transient engine operation using two representative fishing vessel operating cycles (Figure 39).

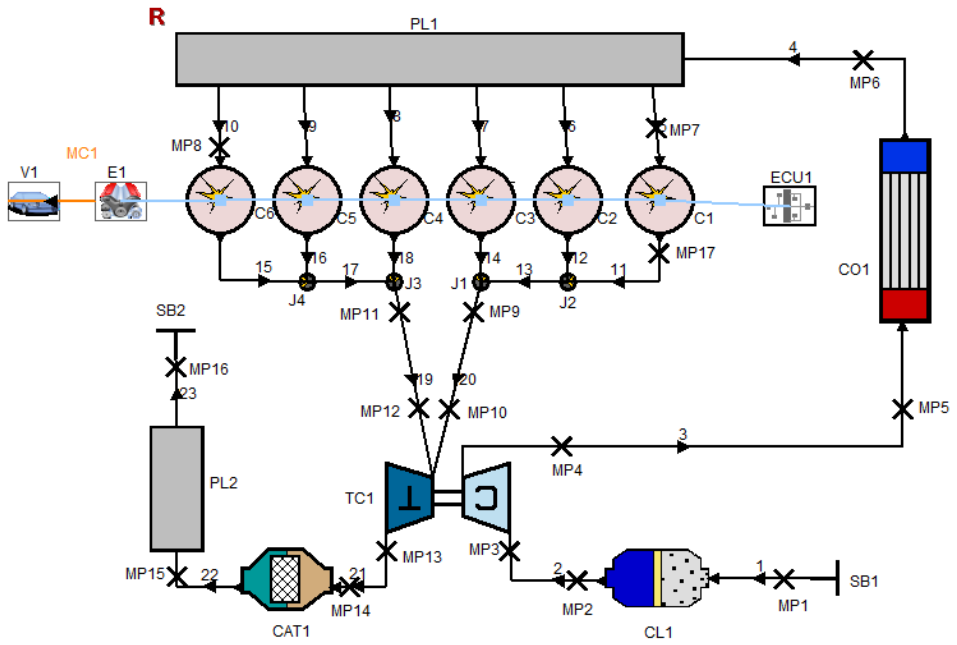


Figure 38. 1D/0D simulation model of fishing vessel propulsion system in AVL Boost™ [61]

The simulation results show that engine load has a dominant influence on both fuel consumption and emission levels. High-load operating modes, which account for the majority of propulsion energy during transit and active fishing, exhibit the highest absolute emissions in diesel operation. Under these conditions, the AVL BOOST simulations demonstrate that methanol–hydrogen substitution leads to significant reductions in CO_2 emissions, primarily due to the lower carbon content of methanol and the zero-carbon combustion of hydrogen. These operating modes, therefore, contribute most strongly to the overall emission reductions.

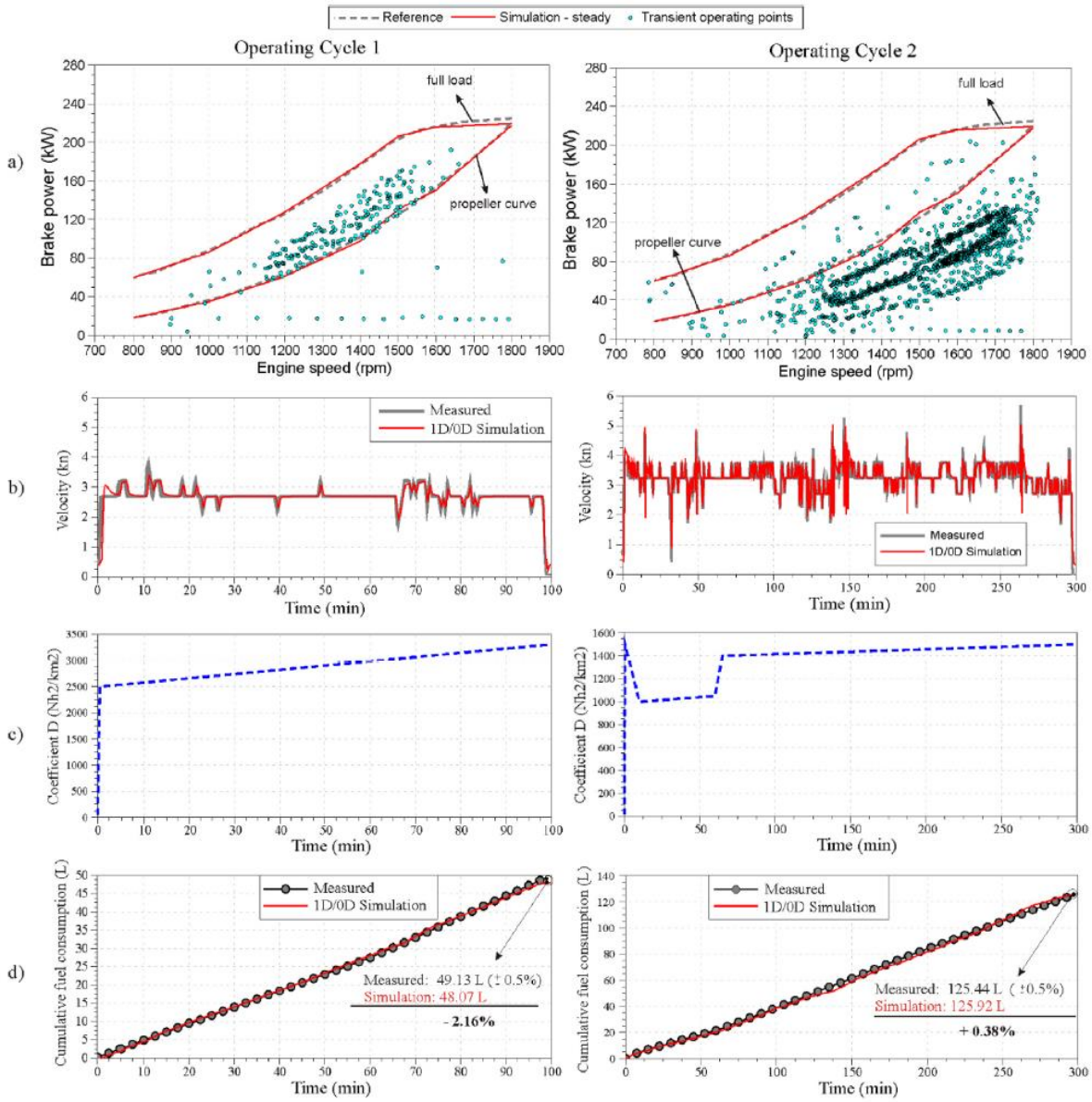


Figure 39. Validation results over two operating cycles – a) positions of engine operating points, b) comparisons of fishing vessel velocity, c) adopted drag coefficient and d) cumulative fuel consumptions [61]

At lower engine loads, the results indicate reduced engine efficiency and smaller relative emission benefits from fuel substitution. In some low-load regimes, efficiency penalties are observed due to less favourable combustion conditions in dual-fuel operation. However, because these low-load regimes represent a smaller share of total energy consumption over the operating cycle, their impact on cumulative emissions and fuel consumption remains limited. The largest emission reductions are achieved during operating modes with medium to high engine loads, which typically dominate the total energy consumption of fishing vessels during

transit and active fishing. The approach based on operating cycles reveals trade-offs that would remain hidden in simplified analyses. This finding further confirms the importance of evaluating alternative fuels over the full operating cycle rather than focusing on isolated load points. When accumulated over the entire operating cycle, the simulations confirm that all analysed dual-fuel scenarios achieve lower total CO_2 emissions compared to conventional diesel operation. The level of the reduction increases with higher methanol to hydrogen replacement ratios. It is important to note that the average engine efficiency over the cycle remains comparable to that of diesel operation, indicating that the emission reductions are achieved without compromising overall propulsion performance.

As seen in Figure 40, the results clearly demonstrate that conventional diesel operation results in the highest total CO_2 emissions, reflecting the dominance of medium- and high-load operating modes within the cycle. These operating modes account for the largest share of energy consumption and therefore govern the overall environmental impact of the vessel. The introduction of methanol–hydrogen dual-fuel configuration results in a substantial reduction in CO_2 emissions across the analysed operating cycles. The level of this reduction increases with higher shares of alternative fuels, indicating that the environmental benefit is directly linked to the degree of fossil fuel substitution. Beyond CO_2 emissions, the environmental assessment also indicates favourable trends in regulated pollutants, particularly NO_X. The results suggest that methanol–hydrogen combustion can reduce NO_X emissions under certain operating conditions due to lower combustion temperatures and altered flame characteristics. Nevertheless, the extent of these reductions varies across the operating cycle, underlining the importance of load-dependent emission modelling when assessing compliance with future environmental regulations. From a broader sustainability perspective, the environmental assessment demonstrates that methanol–hydrogen dual-fuel propulsion represents an effective transitional solution for reducing the environmental impact of fishing vessels. While full electrification offers the highest potential for emission reduction, its applicability is limited by operational range, energy storage constraints, and infrastructure availability. In contrast, dual-fuel systems can be implemented within existing vessel designs while delivering significant reductions in greenhouse gas emissions over the full operating cycle.

By combining high-quality engine simulations with an operating-cycle-based approach, the analysis demonstrates that dual-fuel propulsion can provide significant environmental benefits at the vessel level. While differences between fuel configurations at individual load points may

appear moderate, their cumulative effect over the full operating cycle becomes significant. These results form a key input for subsequent life-cycle, economic and sustainability assessments.

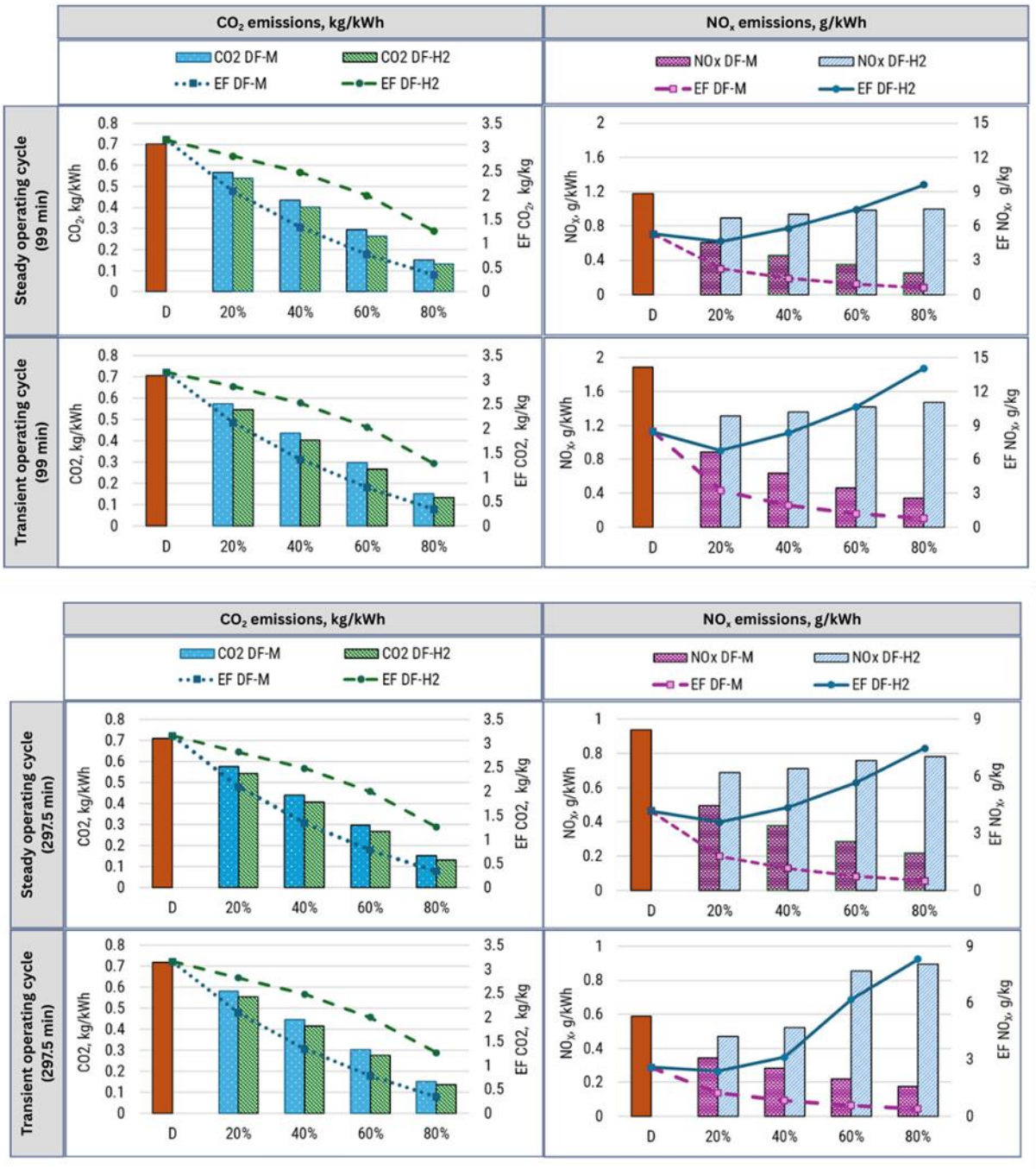


Figure 40. Environmental assessment – relationship between energy substitution level and emission characteristics [61]

3.5. Environmental-economic influence of hull maintenance

Biofouling was shown to substantially degrade vessel performance, with the passive coating system leading to a progressive increase in hull roughness and engine power demand. Modelling of the 54-month biofouling development showed that passive protection led to a continuous increase in hull roughness and engine power demand, with required power rising sharply as fouling intensified; at the highest assessed speed (8 kn), the additional power reached 225 kW, whereas the active ultrasonic system limited the increase to 112 kW, representing roughly a 50% lower power penalty (Figure 41). This higher resistance translated into significantly elevated fuel consumption and emissions, particularly at higher speeds, where the passive system resulted in a 23% higher environmental footprint at 8 kn after the assessment period. Emission differences became noticeable after 18–24 months, with passive protection generating increasingly higher CO_2, NO_X, and SO_X as fouling intensified (Figure 42). Life-cycle cost results highlighted that although passive coatings have lower initial investment costs, frequent maintenance, coating renewal, and dry-docking over the 54-month horizon produced substantially higher cumulative costs. Active systems, despite higher initial installation expense (1,300–8,100 EUR), required minimal maintenance, avoided repeated dry-dockings, and therefore achieved lower long-term costs. Fuel cost analysis at 8 kn illustrated that passive protection increased cumulative fuel costs by 15% after 18 months, rising to 24% after 54 months, relative to active protection. When carbon taxation was included, cost differences became more pronounced. Under the SPS scenario, active protection resulted in 76.6 thousand € lower carbon-related costs after 54 months, which increased to 104.5 thousand € under the NZES scenario. Overall, the results confirmed that active antifouling systems significantly slow biofouling development, reduce power demand and emissions, and offer superior long-term economic performance compared to passive coatings, particularly under higher-speed operation and future carbon-pricing conditions.

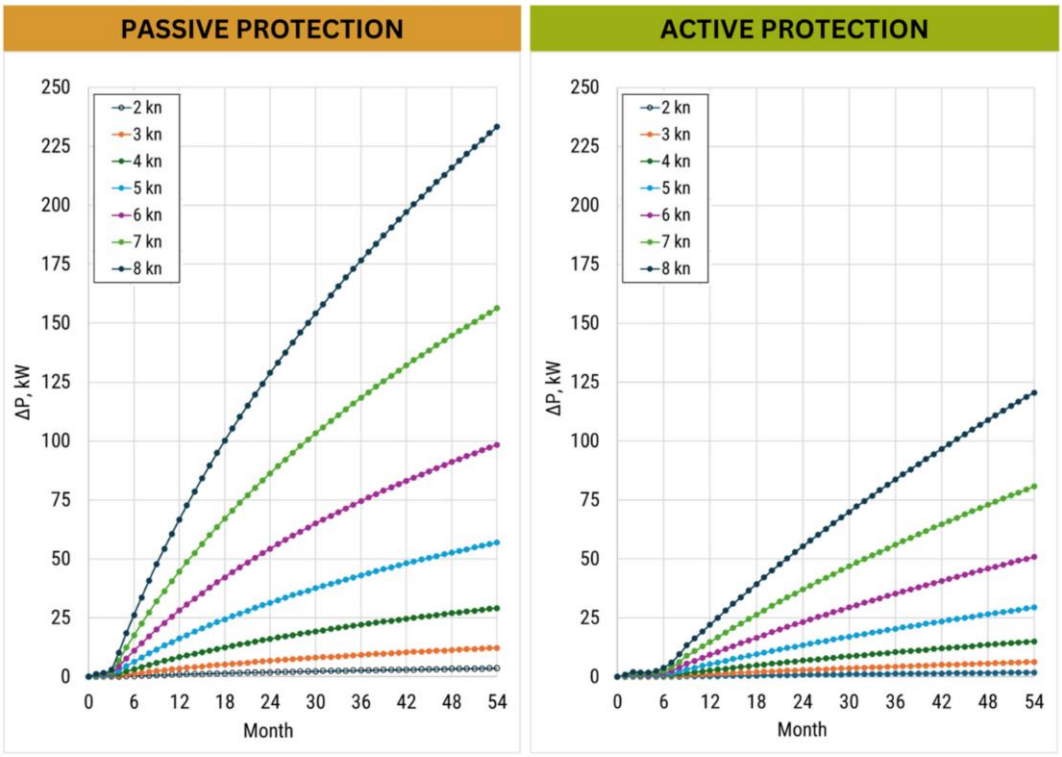


Figure 41. Comparison of passive and active antifouling protection through the power increase in regard to the navigation speed and time period [52]

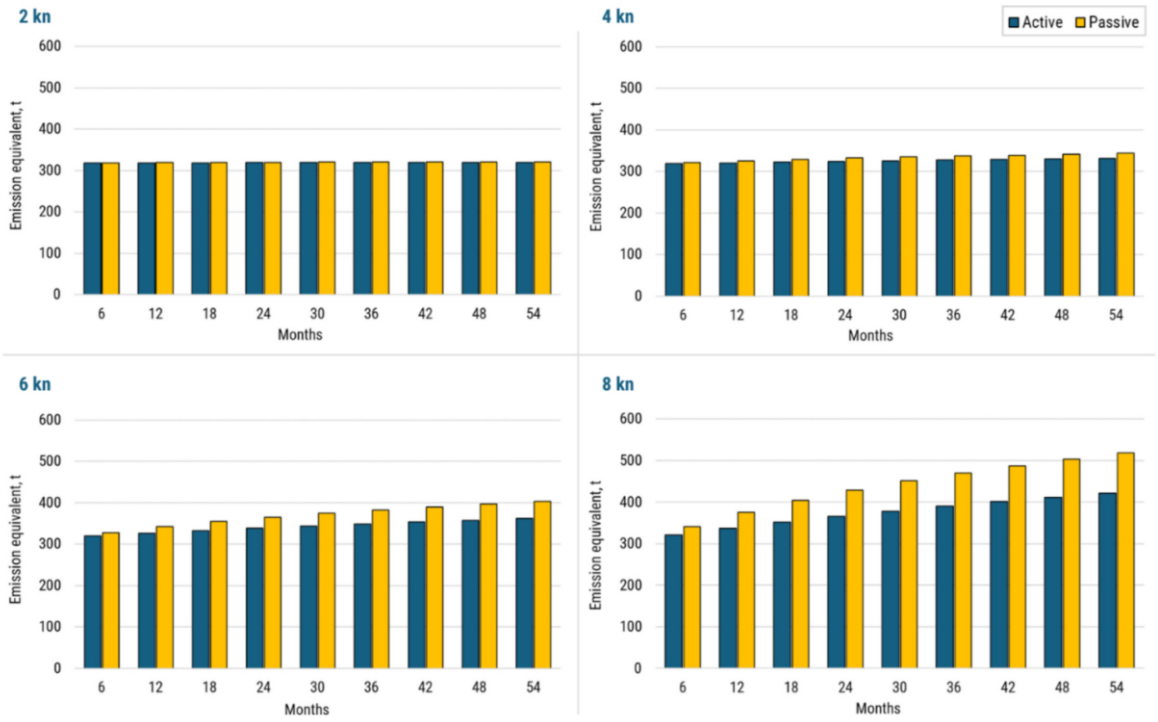


Figure 42. Emission equivalent for active and passive protection through 54 months in case of different speed values [52]

4. Conclusions

The research demonstrated that the improvement of energy efficiency, environmental performance, and economic viability in the fishing sector requires a comprehensive and system-oriented approach. Recent developments, such as the expansion of the EU Emissions Trading System, the findings of the Fourth IMO GHG Study, or the adoption of the IMO Net-Zero Framework, indicate that greenhouse gas emissions from all maritime sectors will be subject to progressively stronger regulatory and economic pressures. Although fishing vessels are currently largely excluded from the mandatory requirements applied to commercial shipping, future decarbonization pathways are expected to increasingly affect the fishing sector through carbon pricing mechanisms, fuel standards, and broader climate policies.

Through the establishment of a detailed monitoring framework, reliable operational data were obtained, enabling a more accurate assessment of vessel behaviour, fuel consumption, and energy use patterns. These insights allowed the development of performance indicators that reflect real operating conditions and reduce the uncertainties typically associated with traditional estimation methods. The data analysis confirms the findings of international studies that identify fishing vessels as highly energy-intensive maritime assets, while simultaneously highlighting their substantial potential for emission reduction through targeted interventions. The results consistently show that the simultaneous application of multiple technical and operational measures offers the greatest potential for improving energy efficiency, reducing emissions, and maintaining economic viability in the fishing sector.

The analysis showed that significant efficiency gains can be achieved when operational data are combined with advanced technological and methodological solutions. The research deliberately focused on a specific segment of the large-scale commercial fishing fleet, primarily trawlers and purse seiners. This focus was methodologically justified by the availability of high-quality technical data and direct operational measurements obtained through onboard monitoring systems, building on approaches developed in previous research projects. While this allowed for robust model development and validation, it necessarily excludes a substantial portion of the fishing sector, particularly small-scale fisheries, which are becoming increasingly important in the context of environmental regulation, socioeconomic resilience, and regional

policy objectives. These fleet segments exhibit far more heterogeneous operational patterns and socioeconomic characteristics, which require dedicated analytical frameworks.

From a technical perspective, the research confirms that conventional diesel-powered systems are increasingly inefficient and environmentally unsustainable under current and future regulatory and market conditions. Hybrid and plug-in hybrid power systems emerge as particularly promising solutions, offering substantial reductions in fuel consumption, GHG emissions, and life-cycle costs when compared to traditional propulsion systems. Full electrification provides the highest environmental benefits but remains limited by investment costs, infrastructure availability, and operational constraints. When supported by RES, these technologies showed the potential to provide both environmental and economic benefits. In addition, hull maintenance and antifouling strategies were shown to play a critical supporting role. The analysis confirmed that biofouling significantly increases hydrodynamic resistance, fuel demand, and emissions, and that both passive and active protection technologies can mitigate these effects. While active systems require higher initial investments, their long-term performance was shown to provide substantial reductions in fuel use and maintenance needs, especially when assessed across the full operational lifecycle of a vessel. These findings underline that propulsion system design, energy storage, fuel choice, and maintenance strategies must be considered jointly rather than each individually.

From an operational perspective, the analysis highlights that vessel efficiency is strongly influenced by fishing practices, operating profiles, and catch characteristics. The results demonstrate that operational measures, such as optimized fishing patterns, reduced non-productive steaming, and improved energy management, can significantly enhance the effectiveness of technical solutions. However, their impact varies considerably across vessel types and fisheries, reinforcing the need for tailored, data-driven assessments. The developed Energy Efficiency Index (EEI) and Sustainability Index (SI) successfully capture these relationships by linking real-time measured fuel consumption and emissions to societal benefit in terms of landed catch and economic value.

When EEI was recalculated using revenue instead of catch mass, vessels targeting higher-value demersal species improved their relative standing, demonstrating that “tonnes landed” is an incomplete substitution for socioeconomic efficiency. By incorporating capital costs, operating expenses, revenue, and projected carbon-related costs, the sustainability index allowed a

transparent comparison of different powering options and vessel configurations. The SI confirmed that under current conditions most diesel-powered vessels remain economically viable, with income 1.4–3.4 times higher than total costs. However, when carbon prices consistent with the NZES trajectory were applied, only a minority of vessels remained profitable. High-powered, fuel-intensive vessels, especially older trawlers with modest catches, became unsustainable. The sensitivity analysis highlighted that revenue variability and fuel price increases both strongly degrade SI, but revenue shocks have a more nonlinear and disruptive influence. Its application revealed that some vessels may face reduced economic sustainability under future carbon pricing conditions, while alternative propulsion systems and hybrid solutions may become increasingly competitive.

An important contribution of this research lies in the detailed assessment of alternative propulsion concepts at the engine-operation level, carried out using a calibrated one-dimensional engine model. The model enables a physically based representation of in-cylinder thermodynamic processes, fuel consumption, efficiency, and emission formation for marine internal combustion engines operating in conventional diesel mode as well as in methanol–hydrogen dual-fuel configurations. By combining steady-state calibration with transient validation over two representative fishing vessel operating cycles, the analysis ensures that simulated engine behaviour reflects real operational conditions rather than idealised load points. The operating-cycle-based approach confirms that engine load distribution is a dominant factor governing cumulative fuel consumption and emission levels in fishing vessels. Medium- and high-load operating modes, which account for most propulsion energy during transit and active fishing, were shown to dominate total emissions over the cycle. Under these conditions, methanol–hydrogen dual-fuel operation achieves substantial reductions in CO_2 emissions, primarily due to reduced carbon content and partial zero-carbon energy input, while maintaining cycle-averaged engine efficiency comparable to diesel operation. Although reduced efficiency and smaller relative emission benefits were observed at low engine loads, their influence on cumulative results remains limited due to their minor contribution to total energy demand. In addition, favourable trends in regulated pollutants, particularly NO_X, are observed under certain operating conditions, highlighting the importance of load-dependent emission modelling for future regulatory compliance.

Overall, the research demonstrated that the decarbonisation of fishing vessels is technically feasible and strategically advantageous when approached through a combination of accurate

monitoring, improved operational practices, advanced maintenance monitoring, and carefully selected alternative energy systems. The methodologies developed provide a robust foundation for evaluating future technological choices and support informed decision-making aimed at enhancing the environmental and economic performance of fishing fleets.

5. Future work

The methodological framework developed in this dissertation demonstrates that the decarbonisation of fishing vessels is both feasible and beneficial when supported by accurate monitoring and appropriate technological selection. Nevertheless, several areas for further work emerge from the findings, particularly in relation to scaling, generalisation, and long-term adaptability of the proposed models. Future research should therefore expand and refine the presented approaches to ensure broader applicability across diverse fleets, operational conditions and energy systems

A key direction for future development concerns the expansion of real-time monitoring systems. The monitoring architecture implemented in this work has proven its value, yet its further deployment across a larger and more diverse segment of the fleet would significantly enhance model accuracy and empirical robustness. Extending the system to include multipurpose vessels and smaller coastal units would allow the development of an even more representative dataset that captures the full operational spectrum of the Adriatic and other Mediterranean fleets. In addition, incorporating supplementary measurements, such as advanced emission sensors and long-term hull condition indicators, would support higher-fidelity modelling, improve calibration of fuel consumption models, and enable continuous performance tracking throughout vessel lifetimes.

Further work is needed to advance and generalize the Energy Efficiency Index (EI) and Sustainability Index (SI). Although both indices have demonstrated strong potential for vessel-level and fleet-level comparisons, additional refinements would improve their robustness and adaptability. Future studies should explore dynamic versions of the EI and SI that incorporate seasonal, meteorological, and interannual variability in catch, revenue, and fuel use. Moreover, integrating social dimensions such as employment, community dependence on fisheries, and vulnerability of coastal economies would allow the SI to evolve into a more comprehensive decision-support tool suitable for policymakers, regulators, and fishery managers. The incorporation of uncertainty quantification, stochastic revenue models, and probabilistic fuel price scenarios would further strengthen the indices' predictive capabilities.

Opportunities also arise for advancing the modelling of alternative energy systems and hybrid configurations. The assessment conducted in this dissertation highlights methanol, plug-in hybrid systems, and battery-electric propulsion as promising options, yet their long-term performance under varying operational, technological, and regulatory scenarios requires continued investigation. Future research should analyse degradation trajectories of batteries, real-world performance of methanol engines in fishing applications, seasonal charging limitations in isolated ports, and the impact of emerging carbon taxation schemes on fleet economics. As the share of renewable energy systems in coastal energy systems increases, more detailed coupling between vessel charging profiles and real-time grid behaviour should be analysed, particularly regarding flexibility, peak-shaving potential, and the use of vessels as mobile storage units within integrated energy systems. The results obtained using EnergyPLAN demonstrate that electrified fleets can support system flexibility; however, further work should investigate alternative optimisation approaches. Other methods could capture local distribution network constraints, port-level congestion challenges, and investment possibilities. Long-term scenario analysis that couples fleet renewal strategies with national climate targets would provide valuable insights for policymakers designing future incentive frameworks or regulatory pathways.

At last, maintenance monitoring, i.e. the refinement of biofouling and hull-protection models, also plays an important role in achieving sustainability. The conducted life-cycle analysis confirms the significant economic and environmental impacts of hull degradation, yet future studies should integrate hydrodynamic CFD simulations, long-term experimental measurements, and in-situ roughness monitoring to improve model precision. Assessing the combined effects of fouling, ageing engines, propeller degradation, and irregular maintenance cycles would offer a more holistic understanding of lifetime vessel performance. Additionally, evaluating the interaction between antifouling technologies and hybrid or electric propulsion could yield insights relevant for future decarbonised fleets.

While this thesis provides a solid methodological and empirical foundation, significant work remains before comprehensive fleet-level and policy-oriented decarbonisation strategies can be fully realized. Future research should extend the developed models and indices to the entire fishing fleet, explicitly accounting for greater variability in vessel size, gear type, operating conditions, and economic structures. Moreover, further work should move towards dynamic and stochastic approaches, including scenario-based and sensitivity analyses within life-cycle

cost assessment, to better capture fuel price volatility, regulatory uncertainty, and technological risk. Attention should be given to the safety, reliability, and operational robustness of hybrid and alternative power systems, as well as to the gradual integration of safety-related and, where appropriate, social indicators into the sustainability assessment framework. The methodological framework, based on real-time measurements, and developed indices form a strong basis for future large-scale analyses aimed at supporting evidence-based policymaking and strategic planning for the fishing sector. These next research steps will be pursued within the framework of the recently launched GREEN-FISH project (IP-2025-02-2271), which aims to extend the assessment to fleet-level decarbonisation pathways and to support the development of coherent, realistic, and socially acceptable energy transition policies for fisheries.

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Curriculum Vitae

Marija Koričan was born on 14 May 1994 in Zagreb, Croatia. She completed VII Grammar School in 2013. She obtained her Master's degree in 2019 at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb (UNIZAG FSB), with a specialization in Production Engineering (thesis topic: *The influence of cleaners with corrosion inhibitors for surface preparation on the protective properties of coatings*).

She began working at UNIZAG FSB in August 2020 at the Department of Naval Architecture and Offshore Engineering as a Junior Researcher. In February 2021, she continued her work at the same department as a Teaching Assistant, while simultaneously attending the postgraduate doctoral program. In the same year, she was entrusted with managing the Laboratory for Marine Engineering, which she significantly modernized with state-of-the-art measurement technology. She has participated in numerous projects funded through competitive programs such as Horizon Europe, Interreg, the European Maritime and Fisheries Fund, the European Regional Development Fund, Croatian Science Foundation, Bilateral Croatian-Chinese Scientific and Technological Cooperation, etc. She was also a member of the UNIZAG FSB Committee for International Projects. The involvement in research projects has enabled her to develop strong dissemination skills, resulting in the publication of numerous articles in leading scientific journals, as well as participation in many national and international conferences. Her organizational skills have been strengthened through the implementation of numerous project workshops and events, particularly through the co-organization of the renowned international PRADS conference held in Dubrovnik in 2022, which gathered more than 200 participants from over 40 countries. Among the recognitions associated with her work, UNIZAG FSB was awarded the MedFish4Ever Award, which she received in October 2023 in Malta on behalf of the Faculty. The award was presented by the General Fisheries Commission for the Mediterranean of the Food and Agriculture Organization (FAO) of the United Nations, in recognition of her contributions to projects focused on the decarbonisation of fishing operations.

She is a co-author of more than 60 papers published in a short period in scientific journals and conference proceedings of specialized national and international events, and she serves as a reviewer for several journals and conference papers (https://orcid.org/0000-0001-7480-7411; https://www.researchgate.net/profile/Marija_Korican?ev=hdr_xprf).

List of publications

Article I Alternative power options for improvement of the environmental friendliness of fishing trawlers

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Article III Electrification of fishing vessels and their integration into isolated energy systems with a high share of renewables

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Article IV Lifecycle cost assessment of hull protection technologies considering their effect on the environmental friendliness of fishing vessels

Marija Koričan, Nikola Vladimir, Neven Hadžić, Viktor Ložar. Lifecycle cost assessment of hull protection technologies considering their effect on the environmental friendliness of fishing vessels. *Marine pollution bulletin*, 209 (2024), Part A; 117137, 14. doi:0.1016/j.marpolbul.2024.117137.

Article V Analysis of environmental-economic sustainability of fishing vessels and its improvement by alternative powering options in projected decarbonization scenarios

Marija Koričan, Ailong Fan, Nikola Vladimir. Analysis of environmental-economic sustainability of fishing vessels and its improvement by alternative powering options in projected decarbonization scenarios. *Fisheries Research.* Volume 285, 2025, 107385, ISSN 0165-7836, https://doi.org/10.1016/j.fishres.2025.107385.

Article VI Environmental-economic assessment of hybrid power systems for fishing vessels

Marija Koričan, Nikola Vladimir, Ailong Fan. Environmental-economic assessment of hybrid power systems for fishing vessels. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment.* 2025;0(0). doi:10.1177/14750902251384076.

Article VII Environmental footprint of hydrogen- and methanol-powered fishing vessel under steady and transient engine operation

Momir Sjerić, **Marija Koričan**, Nikola Vladimir. Environmental footprint of hydrogen- and methanol-powered fishing vessel under steady and transient engine operation. *Ocean Engineering.* Volume 345, 2026, 123864, ISSN 0029-8018, https://doi.org/10.1016/j.oceaneng.2025.123864.

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Article

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).

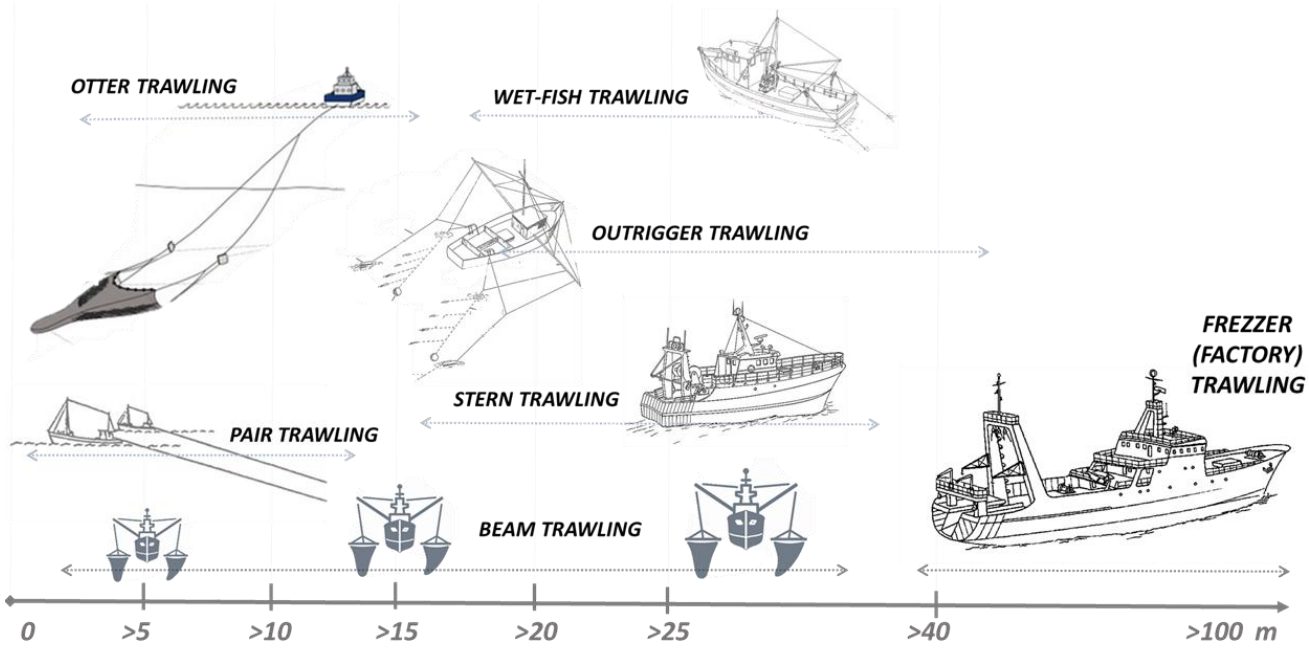


Figure 1. Classification of trawlers by the type of gear and standard length.

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

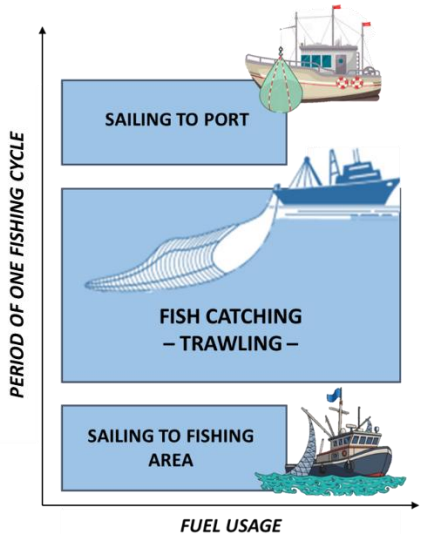


Figure 2. Fishing actions of trawlers.

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.

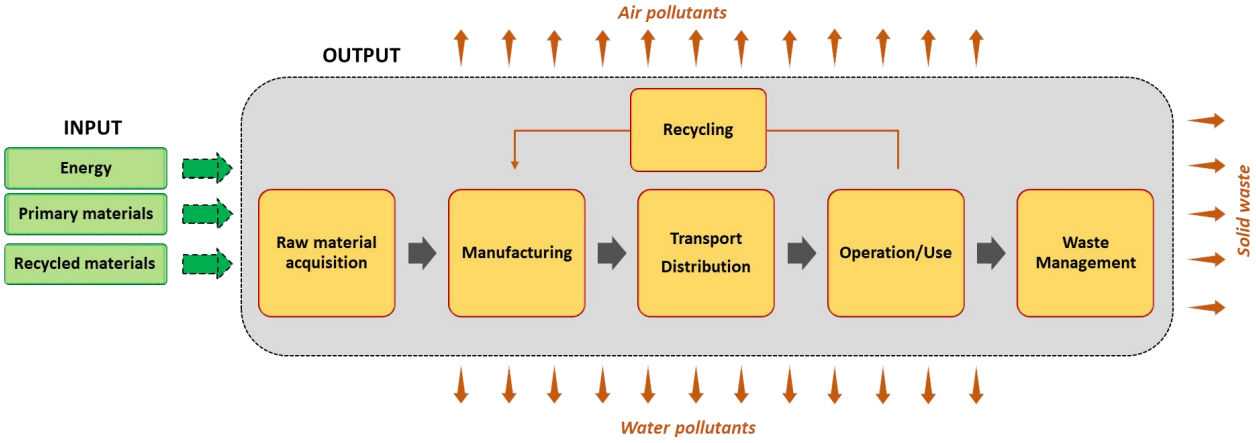


Figure 3. Flowchart of the generalized LCA method.

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]:

$$TE_i = FC \cdot EF_i, \quad (1)$$

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]:

$$FC = EC \cdot SFC, \quad (2)$$

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]:

$$CF = GWP_{CO2} \cdot E_{CO2} + GWP_{CH4} \cdot E_{CH4} + GWP_{N2O} \cdot E_{N2O}, \quad (3)$$

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].

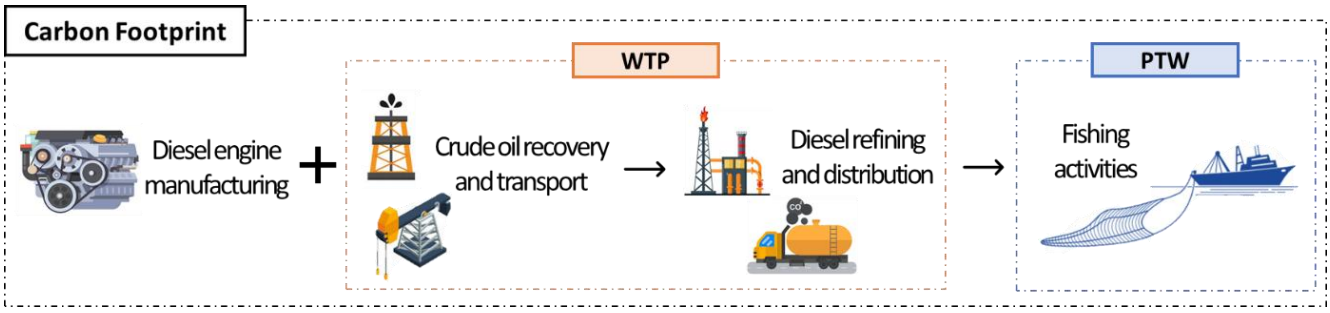


Figure 4. The LCA of a diesel-powered trawler.

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.

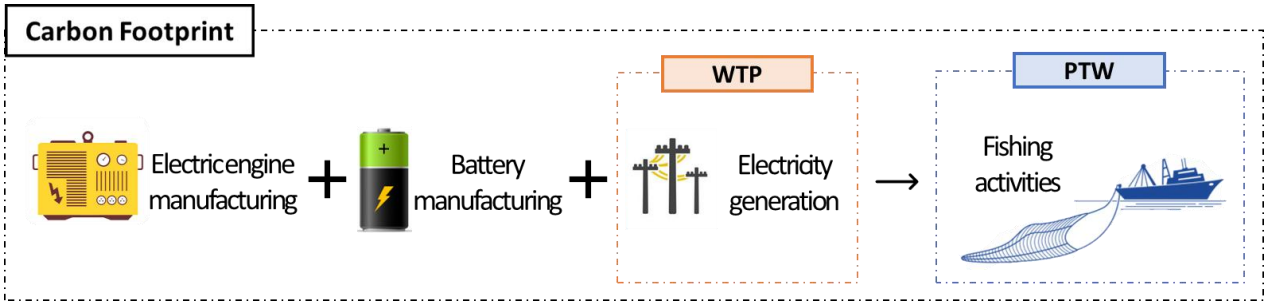


Figure 5. The LCA of a battery-powered trawler.

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]:

$$BC = P_{eng} \cdot t_{daily}, \quad (4)$$

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]:

$$BW = \frac{BC}{BSE}, \quad (5)$$

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.

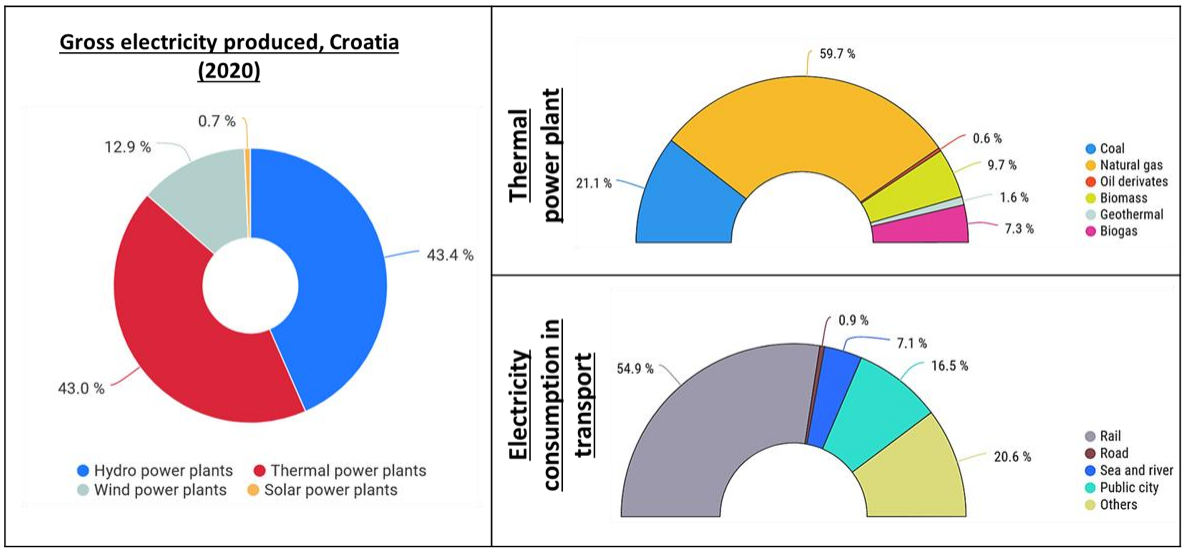


Figure 6. The Croatian electricity mix (2020).

When calculating the fuel consumption of a methanol-powered trawler, the specific fuel consumptions of methanol (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 SFC_M and 10.10 g/kWh for SFC_{P-M} [48]. The following equations are used for calculating the fuel consumption of methanol FC_M and fuel consumption of pilot fuel FC_{P-M} [11]:

$$FC_M = x_M \cdot EC \cdot SFC_M, \quad (6)$$

$$FC_{P-M} = x_{P-M} \cdot EC \cdot SFC_{P-M}, \quad (7)$$

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.

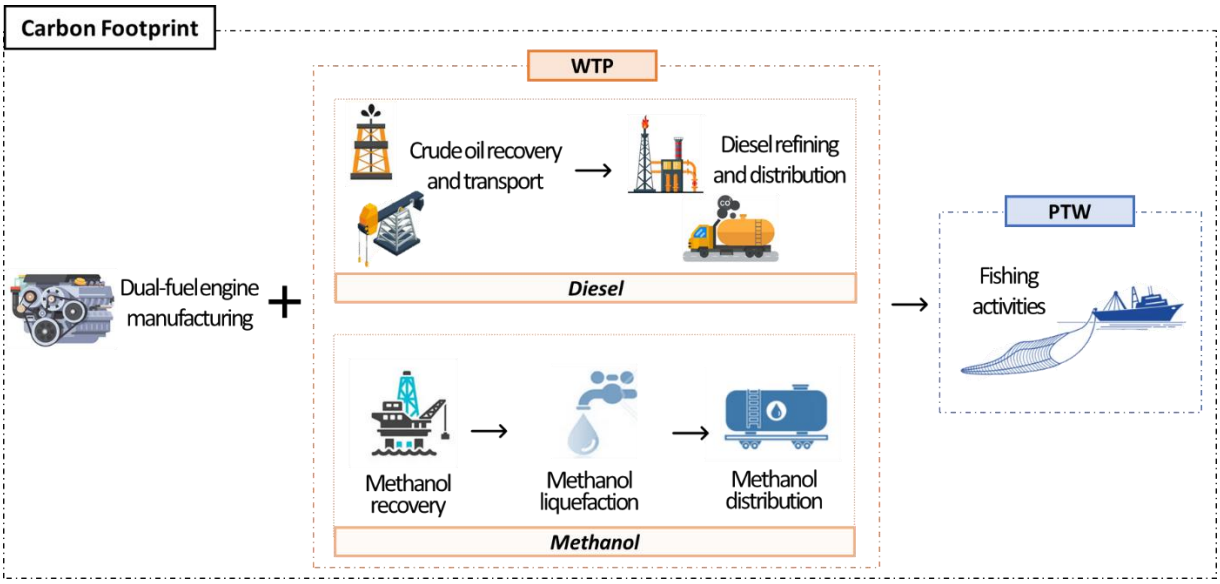


Figure 7. The LCA of a methanol-powered trawler.

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]:

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

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:

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

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:

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

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%.

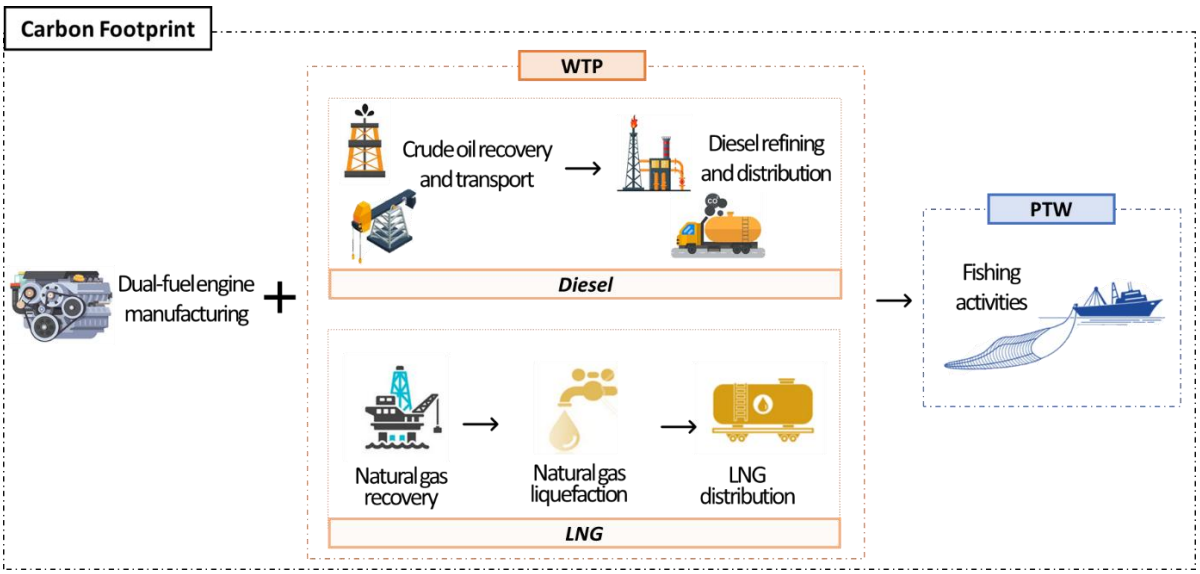


Figure 8. The LCA of an LNG-powered trawler.

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.

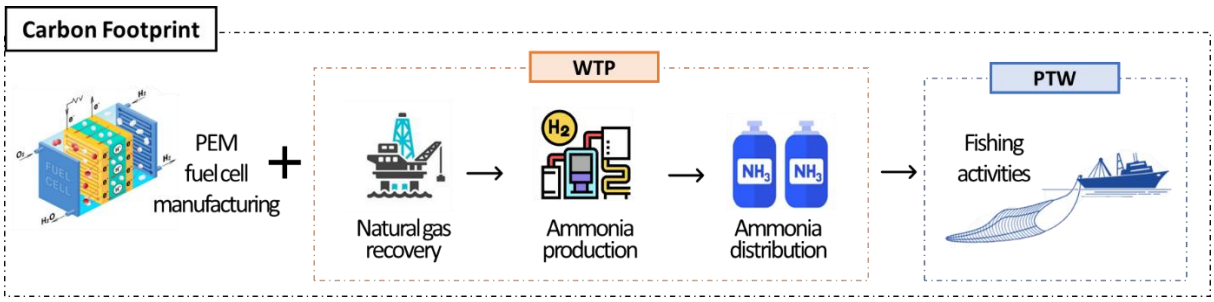


Figure 9. The LCA of an ammonia-powered trawler.

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.

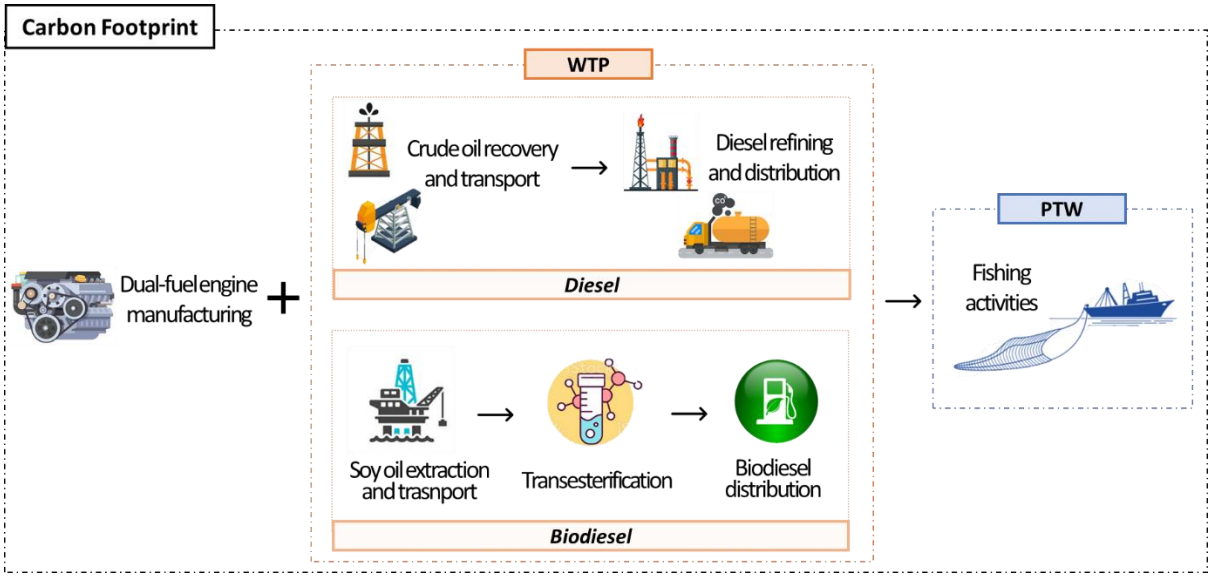


Figure 10. The LCA of a B20-powered trawler.

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:

$$FC_H = \frac{EC_H}{\eta_{FC} \cdot NCV_H}, \quad (12)$$

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].

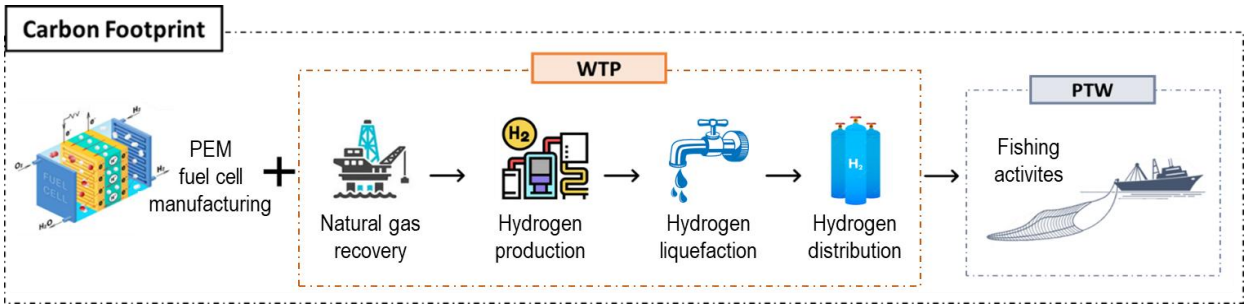


Figure 11. The LCA of a hydrogen-powered trawler.

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:

$$IC_D = P_{eng} \cdot C_{D,eng}, \quad (13)$$

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:

$$LCFC_D = FC_A \cdot PR_D \cdot LT, \quad (14)$$

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):

$$LCMC_D = EC_A \cdot MC_{D,eng} \cdot LT, \quad (15)$$

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]:

$$IC_B = \frac{BC \cdot BP_{2020}}{0.45}, \quad (16)$$

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:

$$LCFC_B = EC_A \cdot PR_{elec} \cdot LT. \quad (17)$$

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:

$$IC_M = P_{eng} \cdot 750. \quad (18)$$

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]:

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

where $FC_{A,\mathrm{M}}$ 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:

$$IC_{LNG} = P_{eng} \cdot 1160. \quad (20)$$

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:

$$LCMC_{LNG} = EC_A \cdot MC_{LNG} \cdot LT, \quad (21)$$

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:

$$IC_{AM} = 1.3 \cdot PR_{PEM} \cdot P_{fc}. \quad (22)$$

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:

$$LCFC_{AM} = LT \cdot FC_{A,AM} \cdot PR_{AM}, \quad (23)$$

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]:

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

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.

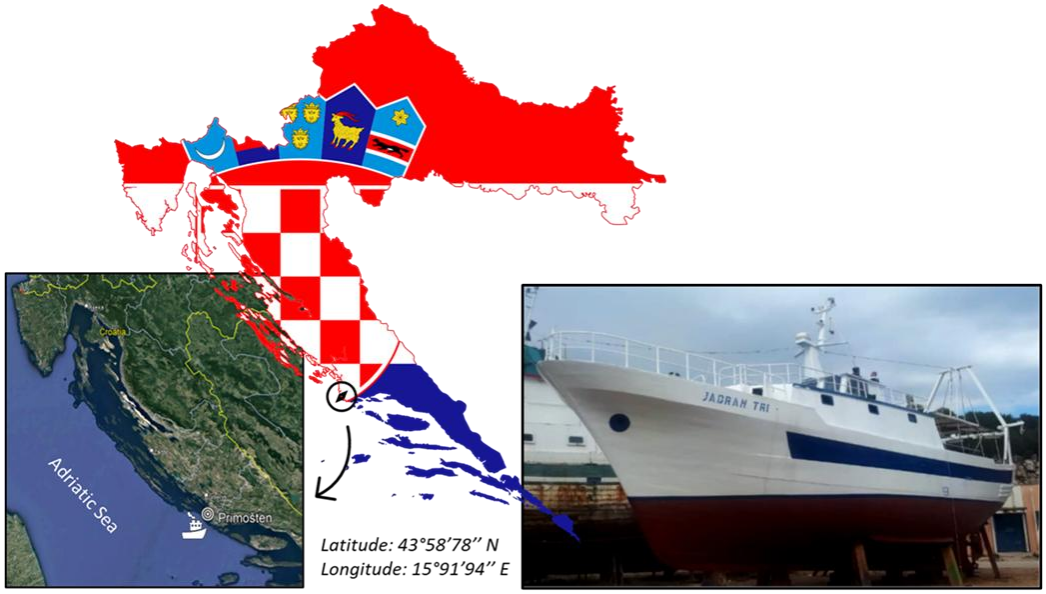


Figure 12. Operating location of the studied trawler.

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.

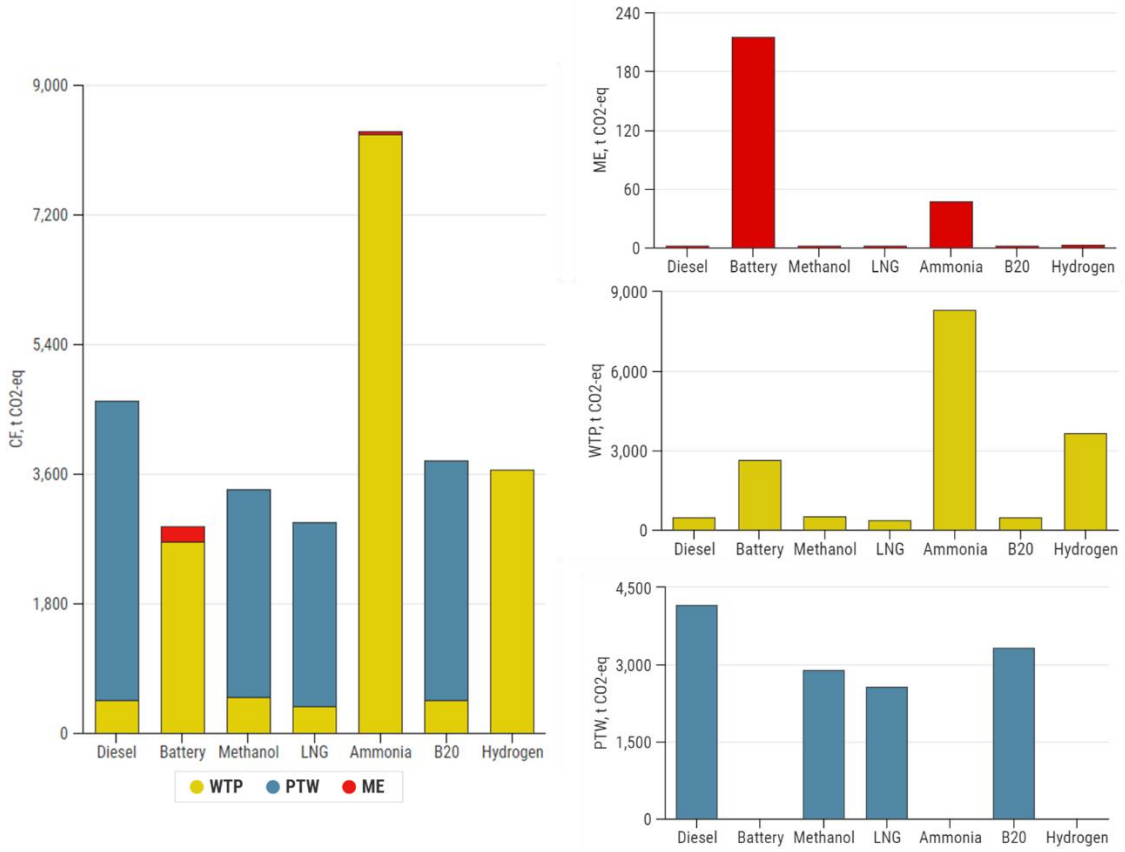


Figure 13. LCA results for a trawler "Jadran III".

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.

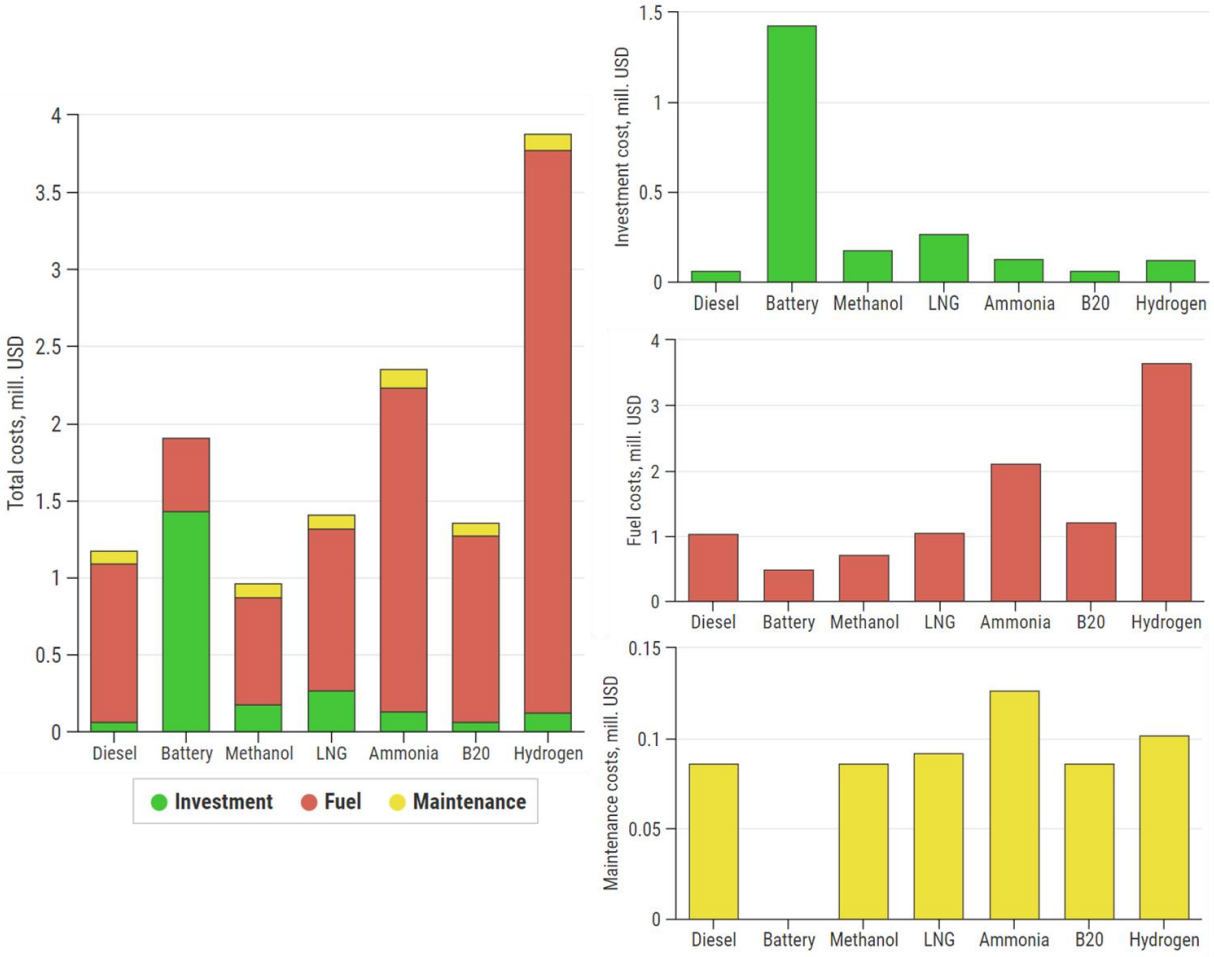


Figure 14. LCCA results for a trawler "Jadran III".

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.

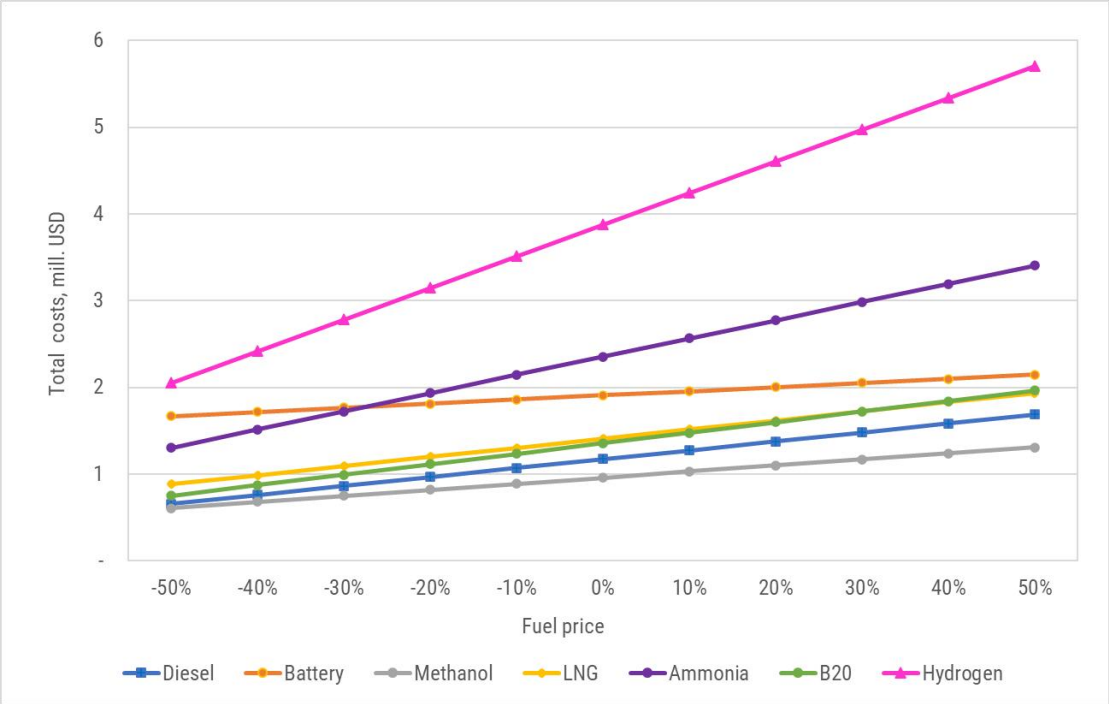


Figure 15. Total costs with respect to fuel price fluctuations.

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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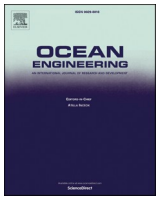
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Investigation of the energy efficiency of fishing vessels: Case study of the fishing fleet in the Adriatic Sea

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ABSTRACT

The reduction of ship emissions is one of the most important and current research topics in maritime sciences. Different technical and operational measures as well as various business strategies are being investigated to reach future decarbonization goals. Fishing vessels generally do not belong to the categories of vessels covered by the regulations of the International Maritime Organization (IMO), but their effect on humans and the environment is very important since fishing operations are mainly performed in coastal waters. Besides, fishing is considered an energy-intensive activity that produces vast amounts of greenhouse gas (GHG) emissions. Most fishing vessels are equipped with aged, low-efficiency diesel engines resulting in relatively high CO_2 indices. This paper investigates the environmental impact of purse seiners and trawlers in the Adriatic Sea, based on their technical and operational characteristics, and taking into account the attained benefit for society. The energy efficiency index is formulated as a tool to compare different fishing vessels from an environmental viewpoint. The technical properties of purse seiners and trawlers operating in the Adriatic Sea are analysed from the relevant databases, and, based on the recorded realistic operating profiles, their energy needs and resulting emissions are assessed. The results show that trawlers have higher emission indices than purse seiners, mainly due to rather high energy needs and lower amounts of landed fish. However, when the income is taken into account, the difference between the emission indices of trawlers and purse seiners is lower.

1. Introduction

1.1. Environmental problems in the marine sector

Global warming is a significant environmental problem, triggered by the high level of anthropogenic Greenhouse Gases (GHGs) in the atmosphere. Fossil fuel combustion is the main source of GHGs and other emissions, such as nitrogen oxides (NO_X), sulphur oxides (SO_X), and particulate matter (PM). The Paris Agreement (UNFCC, 2016), which entered into force in November 2016, sets economic and social measures with the aim of reducing global warming and keeping the global temperature rise below 2 °C above the pre-industrial level and limit the temperature increase to 1.5 °C. The International Maritime Organization (IMO) has made efforts in reducing the maritime environmental impact. In 1997, the Prevention of Air Pollution from Ships (MARPOL) regulation was expanded by Annex VI, which aims to minimize airborne emissions such as SO_X and NO_X. These gases have the potential to alter the ocean pH and disrupt ecosystems (Zhao et al., 2021). MARPOL Annex VI, Chapter IV, introduces two mandatory principles for improving ship design and operations: the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), which are applicable to ships of 400 Gross Tonnage (GT) and above. EEDI is a technical measure that analyses the ships' design and promotes the use of more energy-efficient and environmentally friendlier equipment and engines (International Maritime Organization, 2016). It was first presented as a CO_2 emissions index, representing the ratio of CO_2 emissions per transport work, and over time it evolved into a formula indicating energy efficiency by calculating the ratio of the environmental impact and benefit to society (Deltamarin, 2011). SEEMP is an operational measure for the improvement of ship energy efficiency in a cost-effective manner and encourages ship owners to implement new technologies and practices to optimize the ships' performance (Perčić et al., 2020a).

Recently, the Energy Efficiency Existing Ship Index (EEXI) and the annual operational carbon intensity indicator (CII) were introduced as compulsory amendments that require ships to minimize their GHG

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emissions by increasing their energy efficiency in the short term. The amendments became mandatory from 1 January 2023, and require ships to measure their energy efficiency and to initiate the collection of data for the reporting of CII (International Maritime Organization, 2022). Just like EEDI and SEEMP, these measures tackle only ships over 400 GT, while some other fleets operating in the short-sea sector, like a fishing fleet, remain underregulated. However, decarbonization of fishing vessels is a highly important topic, as can be confirmed from the most recent exploratory opinion of the European Economic and Social Committee (European Economic and Social Committee, 2023), which recognizes the need for an appropriate and realistic decarbonization timetable that includes technological, logistical and legislative developments.

1.2. Types of fishing vessels and their activities

Fishing vessels consume the largest portion of energy and emit high values of harmful gases in the seafood product value chain (Jafarzadeh et al., 2017). According to Kim et al. (2021), GHG emissions of global fisheries increased by 28% from 1990 to 2011, and 179 million tonnes of CO_2-eq emissions resulted from 40 billion litres of fossil fuel consumption by fisheries. The fishing sector itself accounts for 1.2% of global oil consumption, which results in the release of 134 million tonnes of CO_2 emissions into the atmosphere (Basurko et al., 2015).

Fishing vessels can be categorized based on their fishing operations, such as purse seiners, trawlers, gillnetters, and longliners (Kurniawati, 2019). Each type of vessel has a different speed, route, and specifications. Fishing operations fall into three types: towing/dragging the net, encircling, and static operations. Trawlers and purse seiners are both types of commercial fishing vessels, but they use different methods to catch fish. Trawlers employ a cone-shaped net dragged along the ocean bottom or water column, while purse seiners use a net to encircle a school of fish, forming a "purse" around them (Kurniawati, 2019). Fisheries targeting small pelagic species mainly use purse seiners, which have proven to be more efficient than trawlers by consuming only 42% of fuel per tonne of landed fish compared to trawlers (Basurko et al., 2015). As presented in Fig. 1, trawlers usually reach up to 100 m in length, while seiners reach over 200 m (Food and Agriculture Organization of the United Nations, 2008). The technical and operational performances of various trawlers (beam, otter, stern, outrigger, wet-fish, and freezer) and purse seiners (American, European, tuna, drum and seine netter) serve different fishing purposes and differ according to the area of operation, gear, and tonnage (Koričan et al., 2022a), (Food and Agriculture Organization of the United Nations, 2008). A more detailed description of different types of fishing vessels is given by Suuronen et al. (2012) and Koričan et al. (2022a).

Purse seiners are typically used to catch schooling fish such as tuna, mackerel, and herring, while trawlers can operate both in shallow and deep waters and thus catch a wide variety of fish, depending on the location and season. In terms of efficiency, purse seiners can catch large quantities of fish in a single operation, while trawlers may need to make multiple passes to catch a similar amount. However, trawlers can catch a wider range of fish species than purse seiners, whose market value is often higher when compared to small pelagic species caught by purse seiners (Kurniawati, 2019; Koričan et al., 2022a).

Purse seiners and trawlers have significantly different technical characteristics and operational regimes, which highly influence fuel consumption (Vladimir et al., 2021; Koričan et al., 2022b). Purse seining devotes more time and energy to cruising, while trawling spends more time and energy dragging the net, Fig. 2. The intensity of fuel use is well presented by Parker and Tyedmers (2015), confirming that fuel consumption varies considerably between different types of fisheries. Purse seining tuna in tropical waters consumes 56% of fuel during cruising, while trawlers spend 68% of fuel on net dragging, i.e. sailing at a speed of 4 kn (Basurko et al., 2015). Diesel is the most commonly used fuel in fishing vessels, as it provides high energy density and is widely available with mature technology. Fuel consumption is significantly affected by the type of vessel, the fishing gear installed, engine conditions, voyage, targeted species, etc. Therefore, the annual fuel cost varies from 15% to

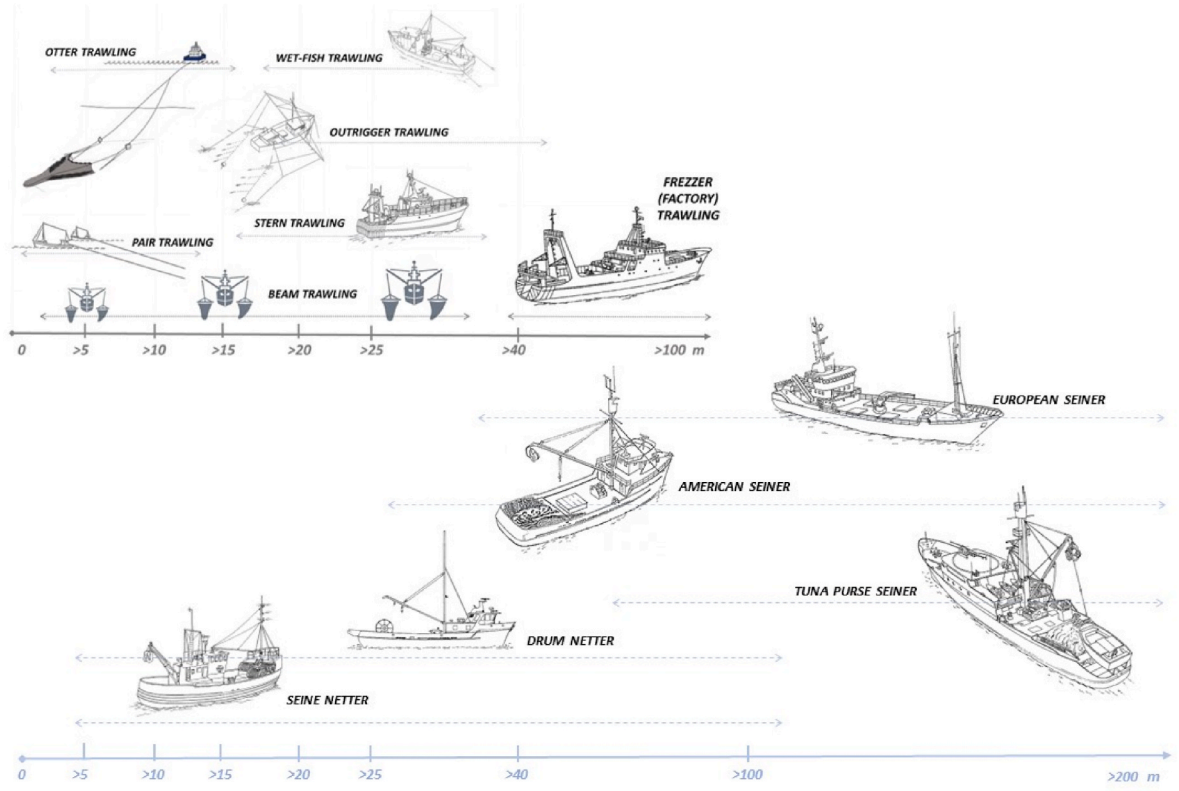


Fig. 1. *Comparison of purse seiners and trawlers by size (adapted from*: Food and Agriculture Organization of the United Nations (2012)*).*

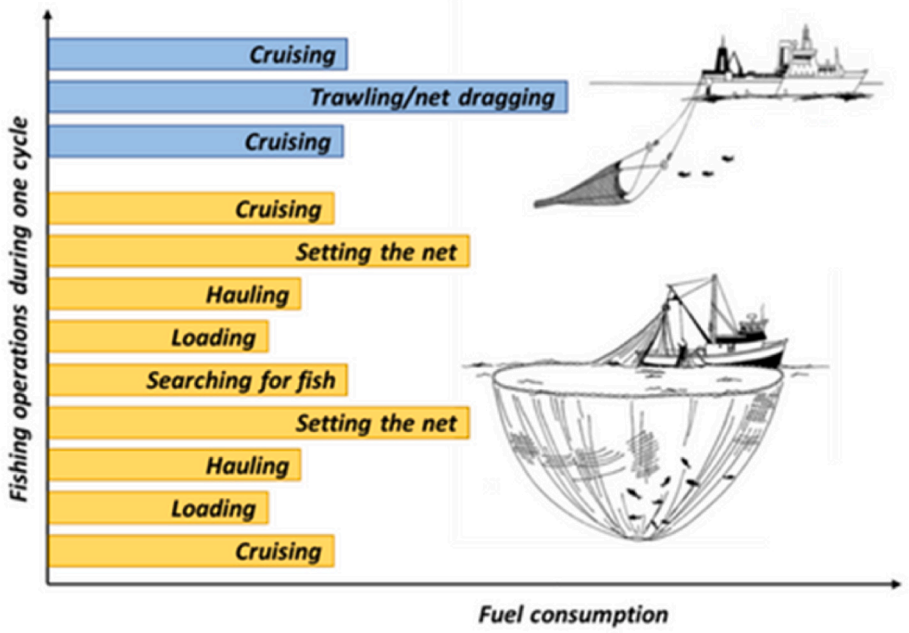


Fig. 2. *Comparison of fuel consumption for various fishing operations of a purse seiner and trawler* (Food and Agriculture Organization of the United Nations, 2012).

70%, depending on the characteristics of the vessel (Basurko et al., 2015). The accurate monitoring of fuel consumption helps to determine the energy efficiency of a vessel and to implement measures to reduce fuel usage and thus reduce harmful emissions such as NO_X, since they are directly related to fuel consumption (Latorre, 2001).

1.3. Research gap and contribution of the paper

To the best of the authors' knowledge, there is a lack of standardized methods for measuring and comparing energy efficiency across different types of vessels and fisheries. Standardized calculations can be found for various ship types such as cargo vessels, passenger ships, LNG carriers, bulk carriers, etc. (Ančić et al., 2018; Vladimir et al., 2018; Trivyza et al., 2020; Perčić et al., 2022) but, given the size of the fleet, fishing is neglected in current policies and is still expected to reduce emissions in accordance with the Paris Agreement. The authors in Deltamarin, (2011) emphasized the significance of harmful emissions released by fishing vessels and performed their EEDI calculations, showing that operating differences have a high effect on the obtained value. The authors calculated the EEDI of RoRo and RoPax vessels using data from the IHS Fairplay database. However, EEDI is applicable only for new ships of 400 GT and above, and fishing vessels are not subject to this regulation, which means that EEDI is not even evaluated. Calculating Fuel Use Intensity (FUI) is another assessment option which considers the fuel consumption needed to catch one tonne of the target species, but focuses more on the economic output that fuel consumption results in Sala et al., (2022). In Sala et al. (2022) the data on fuel consumption were gathered by a monitoring system and used to calculate the fuel-related GHG emissions in 1 h. The CF of the investigated trawl fisheries was shown to be consistent with other findings, as stated by the authors, but the examined trawls were more fuel intensive than most other fisheries. The CO_2 index represents the ratio of harmful emissions and realized benefit (e.g. income or realized catch), thus giving an insight into the socio-economic impact of fishing. Minimizing fuel use and reducing emissions, while achieving higher economic efficiency, would facilitate adaptation to energy-efficient fishing practices and ensure the viability of fisheries (Bastardie et al., 2022). The lack of data on fuel consumption, the quality and quantity of catches, the ratio of expenses and income, etc., is a common issue in research, which is why focus is often placed on monitoring itself, but not on solving the problem of emissions.

Papers that analyse fishing fleets are mainly locally oriented and analyse fleets and catches that are characteristic of a certain climate, thus losing the possibility of a fair comparison with other studies. For instance, Park et al. (2015) aimed to quantify the environmental impact of fishing activities in terms of energy consumption and emissions in the Republic of Korea. Kristofersson et al. (2021) analysed the reduction in GHG emissions in Iceland's demersal fisheries, which was an additional benefit during the establishment of the sustainable use of fish resources. Parker et al. (2018) conducted a more general analysis to present the GHG emissions of world fisheries. The authors presented emissions by region, but even such a division is not sufficient since, for instance, Europe has a large number of seas whose oceanographic features vary considerably, from the Mediterranean to the North Sea.

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

- There are various energy efficiency indicators and performance benchmarks available in the marine sector and they may not be applicable or relevant to all fishing vessels;
- Differences in the operating regime of vessels affect their performance and need to be taken into account when assessing energy efficiency;
- More research is needed to develop standardized methods for assessing energy efficiency in fishing vessels, taking into account the diversity of vessel types and operating conditions;
- There is no clear insight into the energy efficiency of fishing vessels in the Adriatic Sea;
- The deficiency of data on fuel consumption and catches for certain types of vessels limits the scope and accuracy of energy efficiency assessments.

The aim of this work is to assess the energy efficiency of fishing vessels operating in the Adriatic Sea with regard to the emerging decarbonization goals, the lack of environmental regulations for this sector, and the age of the fleet powered by diesel engines, as a basis for defining measures for improvement. As a novelty, the calculation gives an insight into the environmental impact of vessels in accordance with their benefit for society, taking into account the specific characteristics of operational regimes and the quality of the catch. The obtained results are validated taking into account 12 ships, which were equipped with

dedicated monitoring systems. Given that the value of the fish itself ranges widely, depending on the species, the emission index is also calculated in relation to the realized income and is compared for two types of fishing vessels. The development of such an emission index represents the first step towards the application of global measures from which fishing vessels are currently exempted.

2. Methodology

This paper presents a bottom-up approach for calculating the energy efficiency of fishing vessels, with the assessment methodology presented in Fig. 3. The first step is gathering data on the technical characteristics of fishing vessels and estimating the operating times of the main and auxiliary engines. The obtained data enable a further estimation to be made of fuel consumption and the calculation of tailpipe emissions for each vessel in the fleet. After collecting the data, it is possible to calculate the emission index and estimate the share of $CO_{2\text{-eq}}$ in relation to the benefit for society.

2.1. Technical characteristics of the considered fishing vessels

The "General Fisheries Commission for the Mediterranean (GFCM) authorized vessel list" is used to obtain information on fishing vessels longer than 15 m Length Overall (LOA) authorized to fish in the GFCM area of application (General Fisheries Commission for the Mediterranean, 2023). The GFCM dataset includes data on 163 purse seiners and 82 single boat bottom otter trawlers, with general information such as vessel name, registration number and various technical characteristics. The technical characteristics include LOA, GT and engine power. All calculations and estimates are based on this group of vessels. In order to check the data accuracy, in this paper a database obtained by direct measurement on 12 fishing vessels is used. The validation group with technical characteristics of their power system is presented in Fig. 4.

Fishing vessels have a main engine or engines used for propulsion and regularly one or several auxiliary engines for powering support systems, e.g. lighting, ventilation, heating, refrigeration, etc. For the group of 12 vessels, the number and power of individual auxiliary engines are known and are used in this paper. The total power of the auxiliary engines was compared with the power of the main engine of each ship and the average value of the ratio was found, which was used to determine the power of the auxiliary engines of the rest of the fleet.

2.2. Determination of the operating time of the considered fishing vessels

Data on operating time is essential for assessing the energy efficiency of purse seiners and trawlers. The working time of vessels is estimated based on the data gathered through direct monitoring and is analysed separately for the main and auxiliary engines. The group of vessels is equipped with fuel monitoring systems, a GPS system and accessory switches that provide information on the activation/deactivation of a specific engine. The monitoring system is connected to the software "MAPON", which provides real-time data on the route, operating time, specific location and many other outputs (Koričan et al., 2022b; MAPON, 2023).

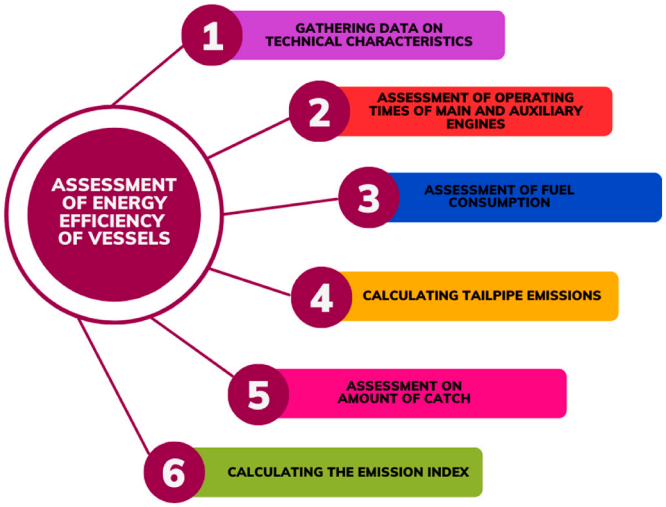


Fig. 3. Schematic display of the emission index assessment.

The cycle is analysed from the preparation of the vessel for fishing activities (starting the engine) until returning to port and unloading (turning off the engine). For the above-mentioned 12 vessels, a two-year measurement campaign was carried out. It was determined that during one work cycle the average operating time of the main engines for purse seiners is 4 h and of the auxiliary engines 15 h. For trawlers, the average operating time of the main engines and auxiliary engines is approximately the same, around 10 h. Due to the legally determined ban on fishing, the co-financed suspension of fishing due to the restoration of the fish stock (Ministry of Agriculture of Republic of Croatia, 2023) and the limited work quota of 20 days per month, there are approximately 200 workdays in a year (in the case of the Croatian fishing fleet), which is used for calculating the annual working time of both types of vessel.

2.3. Catch assessment of the considered fishing vessels

For assessing the values of the catch per ship for the entire fleet, the data on the GT of each ship are used. According to the Food and Agriculture Organization (2023), GT is one of the most important characteristics to express fishing capacity. The value of the catch was taken as a reference measure for the benefit to society. By dividing the total GT with the average annual catch of the fleet, the specific catch value per GT was obtained for purse seiners and trawlers, respectively.

3. Mathematical model for the energy efficiency of fishing vessels

After collecting all the necessary data on the technical and operative characteristics of the fleet, the equation for estimating the emission index is quite simple:

$$EI = \frac{CF}{BS}, \tag{1}$$

where CF presents the calculated carbon footprint of a vessel and BS stands for benefit to society, for instance, achieved catch, income, number of employees, etc.

The Carbon Footprint (CF) presents the amount of GHGs directly and indirectly caused by an operation and accumulated over time (Vladimir et al., 2021). The GHG emissions refer to emissions of CO_2, CH_4, N_2O and fluorinated gases, which are some of the major air pollutants released during ship operations. They are expressed in $CO_{2\text{-eq}}$ and are calculated by multiplying the tailpipe emissions with their GWP (Global Warming Potential) over 100 years (Perčić et al., 2020b):

$$CF = GWP_{CO2} \bullet E_{CO2} + GWP_{CH4} \bullet E_{CH4} + GWP_{N2O} \bullet E_{N2O}. \tag{2}$$

GWP represents a measure of how much energy the emissions of one tonne of a gas will absorb over a given period, relative to the emissions of one tonne of CO_2. It allows for a comparison to be made of the global warming impacts of various gases (CO_2, CH_4 and N_2O) – the greater the value, the greater the influence of the gas on global warming (Environmental Protection Agency, 2022). The GWP of different emissions is presented in Table 1. E_{CO2}, E_{CH4} and E_{N2O} mark the emissions released due to fuel combustion and are calculated by the following equation:

$$E_i = FC \bullet EF_i, \tag{3}$$

where FC stands for fuel consumption in kg and EF_i marks the emission

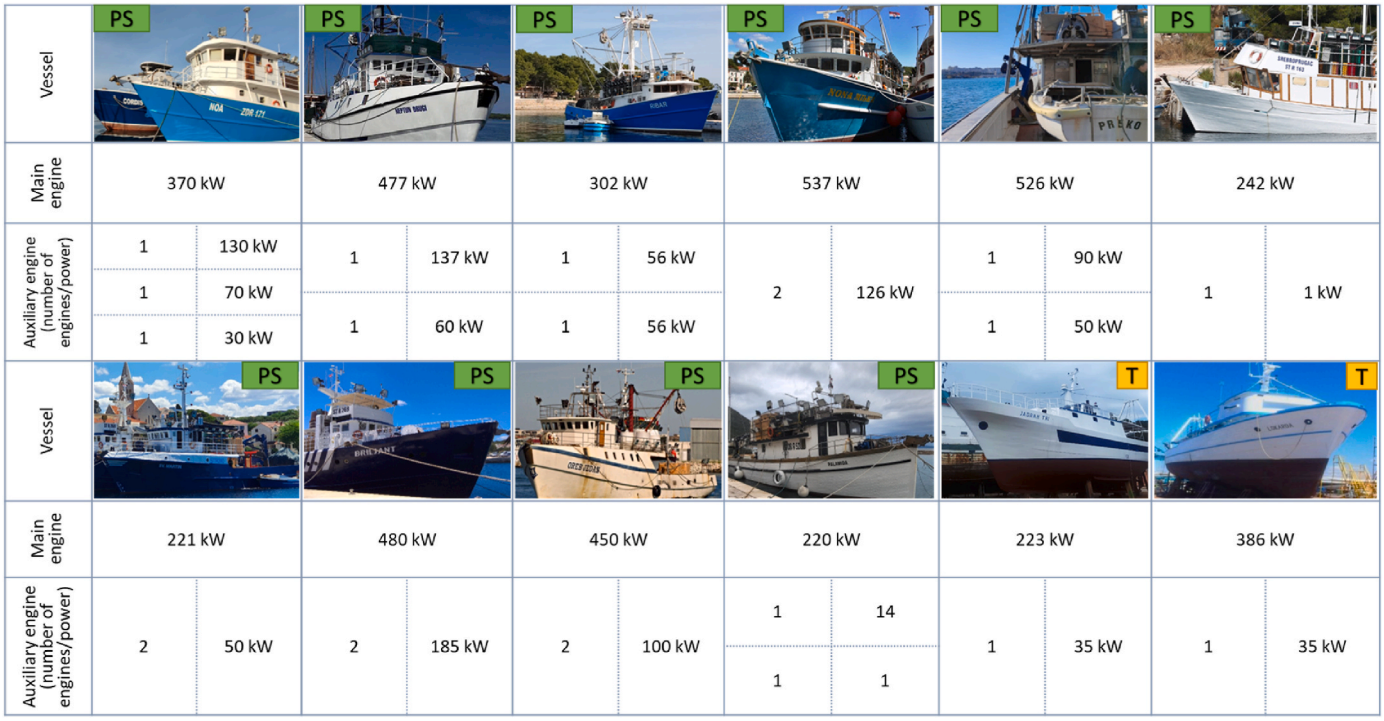


Fig. 4. Main and auxiliary engine power of the validation group.

Table 1
Emission factors and GWP values (Perčić et al., 2020b).

	Emission factor, g emission per kg fuel	GWP (100 years)
CO2	3206	1
CH4	0.019	27–30
N2O	0.142	273

factor for different emissions, presented in Table 1.

To calculate the emission index at the level of the entire fleet, the values of catch and *FC* were obtained. *FC* can be calculated using the equation (4):

$$FC = P \bullet SFC \bullet t, \tag{4}$$

where *P* stands for the total engine power in kW, *SFC* stands for specific fuel consumption, and *t* represents the operating time in hours. The operating time is calculated by multiplying the number of annual workdays with the daily operating hours characteristic of each type of vessel. The total installed power consists of the main engine power P_{ME} and the power of the auxiliary engines P_{AE}. The power of the main engine is taken from the GFCM database and the power of the auxiliary engines was estimated as described in Section 2.1:

$$P_{AE_T} = 0.124 \bullet P_{ME}, \tag{5}$$

$$P_{AE_PS} = 0.388 \bullet P_{ME}. \tag{6}$$

There are significant differences in the power systems of purse seiners and trawlers that arise from the differences in their working principles, which is why their engine powers are calculated separately.

After determining the engine power, formula (4) is modified to include both the main and auxiliary engines:

$$FC = P_{ME} \bullet SFC_{ME} \bullet t_{ME} + P_{AE} \bullet SFC_{AE} \bullet t_{AE}. \tag{7}$$

The *SFC* of marine engines ranges between 155 and 250 g/kWh. For the main engine, the *SFC* is set at 215 g/kWh for high-speed diesel engines, while for the auxiliary engines it is set at 210 g/kWh (Sustainable Ships, 2022), because auxiliary engines can work closer to their optimal workload.

4. Results and validation

4.1. Case study of fishing vessels operating in the Adriatic Sea

The Croatian fishing fleet, described in detail in the Ministry of Agriculture of the Republic of Ministry of Agriculture of Republic of Croatia (2023), consists of 7,808 vessels. The majority of the fleet consists of vessels with an LOA of less than 6 m (56.4%) and vessels between 6 and 12 m (36.4%). A fleet of this size is responsible for 5.74% of the total catch in the Mediterranean area, and is therefore ranked 6th in total capture production for this area (General Fisheries Commission for the Mediterranean, 2023). The catch statistics for the Mediterranean and the Black Sea are presented in Fig. 5.

Purse seiners from 24 to 40 m LOA make the most significant contribution to total landings, with a share of 50.5% in 2020. In general, purse seiners are the backbone of Croatian fisheries with over 90% of landing weight and almost 55% of landing value (Ministry of Agriculture of Republic of Croatia, 2023). As seen in Fig. 6, there is a significant difference between purse seiners and trawlers in the Croatian fleet. Most of the purse seiners have engines with an average power between 150 and 400 kW, while most of the trawlers have engines with an average power between 150 and 250 kW. A difference in LOA is also discernible; purse seiners have an average LOA of 24 m while trawlers are characterized by an average length of 19 m. Trawlers are also smaller than purse seiners in terms of GT, with an average value almost half that of purse seiners.

When performing a detailed environmental and economic assessment of the Croatian fishing fleet, it is important to mention that it is a rather obsolete one with an average age of over 40 years (General Fisheries Commission for the Mediterranean, 2023). As shown in Fig. 7, the older the vessel, the lower the engine power, given that the majority of the fleet consists of vessels constructed between 1940 and 1960 with an average engine power of approximately 420 kW.

The data on the annual catch per species from 2016 to 2021 are

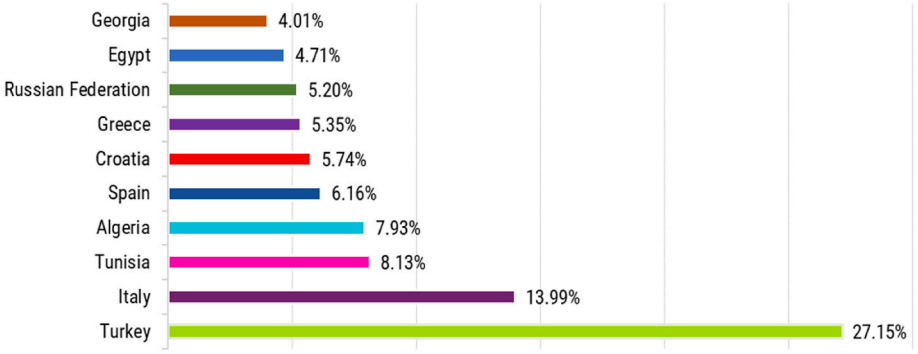


Fig. 5. *Capture production per country in the Mediterranean and Black Sea* (General Fisheries Commission for the Mediterranean, 2023).

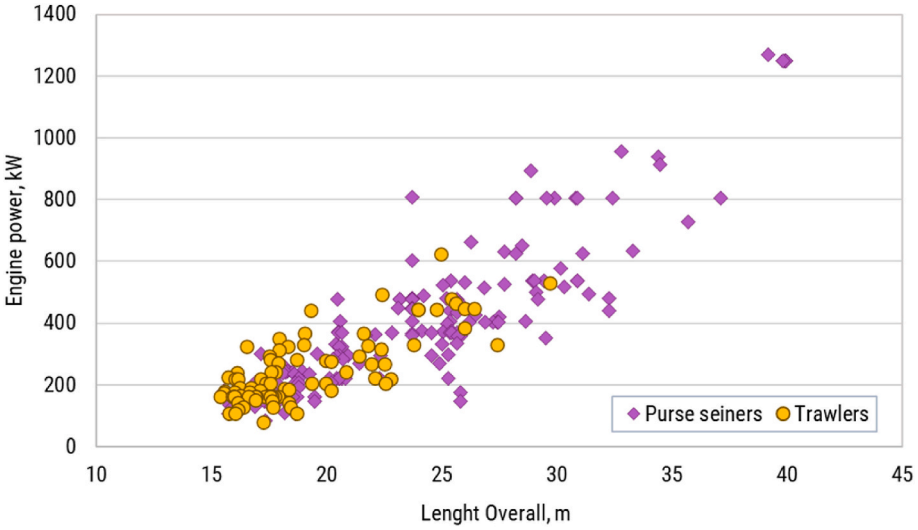


Fig. 6. Correlation between engine power and LOA – Croatian fishing fleet.

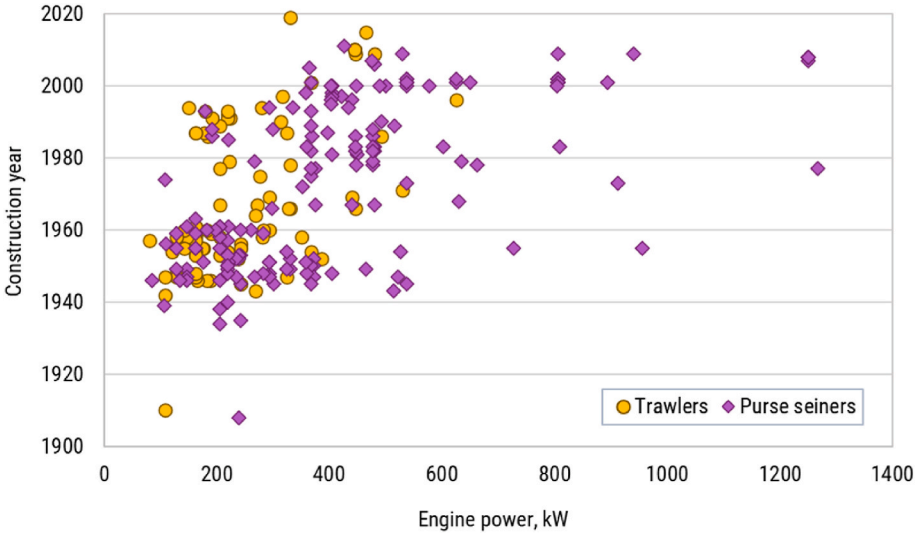


Fig. 7. Correlation between engine power and year of construction of the Croatian fishing fleet.

presented in Table 2 (Ministry of Agriculture D. of F, 2022). The catch of small pelagic species is connected to purse seiners, while data on demersal species are usual for trawlers. It can be seen that purse seiners have on average an over 10 times greater annual catch than trawlers.

4.2. Emission indices of purse seiners and trawlers

The emission indices are calculated according to equation (1) for 163 purse seiners and 82 trawlers. The results are presented in correlation with the engine power and gross tonnage of each vessel. The results for

Table 2
Catch in purse seine and trawl nets from 2016 to 2021 (Ministry of Agriculture D. of F, 2022).

Small pelagic species	Catch in purse seine net, t					
	2016	2017	2018	2019	2020	2021
Sardine	54	48	46	45	45	45
	339.44	400.47	255.56	138.28	138.28	138.28
Anchovy	8	10	13	7	9	11
	232.34	875.09	253.17	997.00	783.13	625.72
Total	62	59	59	53	59	52
	571.78	275.55	508.73	135.28	931.30	129.37
Average – small pelagic species, t				**56 793.65**		
Demersal species	Catch in bottom trawl net, t					
	2016	2017	2018	2019	2020	2021
Total	3	4	4	3	3	3
	988.47	224.54	046.49	962.28	959.81	650.63
Average – demersal species, t				**3 972.04**		

purse seiners are presented in Figs. 8 and 9, while the results for trawlers are presented in Figs. 10 and 11.

The emission indices of the purse seiner part of the fleet showed a range in values between 0.32 and 2.01 kg $CO_{2\text{-eq}}$ per kg catch. Most of the values range between 0.48 and 0.91 kg $CO_{2\text{-eq}}$ per kg catch, with a median of 0.83 kg $CO_{2\text{-eq}}$ per kg catch, which includes vessels with an engine power between 220 and 540 kW. There are three values that were higher than the values of other vessels, with an emission index of 1.97, 1.99 and 2.01 kg $CO_{2\text{-eq}}$ per kg catch. The three higher values belong to vessels with a lower GT, as shown in Fig. 9. When observing the results with respect to the year of construction (presented in Fig. 7), it is clear that older vessels have a lower GT and therefore have a higher emission index.

The emission indices of the trawler part of the fleet showed a range in values between 2.08 and 14.11 kg $CO_{2\text{-eq}}$ per kg catch. The results show 13–15% higher emission index values than purse seiners. The engine power of trawlers mainly ranges between 180 and 300 kW, so the average power of the trawl engine is lower than that of purse seiners. When comparing the GT of trawlers and purse seiners, it is also noticeable that lower values are related to trawlers, between 14 and 199 (with an average of 58.82), while higher values define purse seiners, between 14.39 and 385 (with an average of 110.78). Taking this difference into account, it is clear why the emission indices of trawlers have a significantly higher value.

One emission index has a significantly higher value than the rest of the fleet in the value of 14.11 kg $CO_{2\text{-eq}}$ per kg catch, and belongs to a trawler with an engine of 175 kW power and a GT of 14.44, constructed in 1955. Due to the low GT, the emission index resulted in a very high value. Compared to the mentioned trawler, another ship with a GT of 14, but an engine power of 109 kW, resulted in an emission index of 9.06 kg $CO_{2\text{-eq}}$ per kg catch – approximately 35% lower than the first one. This shows that technical characteristics are not the only influencing parameter in the calculation of energy efficiency.

The calculated emissions are based on estimated catch and fuel consumption values. Considering that fishing operations are influenced by a number of external factors, as described in the introduction, it is reasonable to assume that such a method of calculation hides an error. In order to validate the accuracy of measurements and the range of values, emission indices were calculated for a group of vessels whose annual catch and fuel consumption are precisely known. Information on catch and fuel consumption for the period from 2015 to 2022 is known for each ship, obtained directly from the Ministry of Agriculture of the Republic of Ministry of Agriculture of Republic of Croatia (2023). The value for 2022 is missing for T-2, since the vessel stopped working. The comparison also shows that certain vessels achieved a larger annual catch than expected. As for the differences in technical specifications, some ships have a lower power of the main engine than that initially entered in the ship register. The reason for this is that the fishers themselves limited the power of the engine in order to save fuel. Nevertheless, according to the regulations, the initial values of engine power are entered in the ship registers and they are contained in the fleet data, influencing the final result. This is why there is a difference between the actual and calculated/estimated value of the catch, as shown in Fig. 12, and a difference regarding fuel consumption, presented in Fig. 13.

The emission indices for the validation group are also calculated according to equation (1). The results are presented on a yearly basis, in Fig. 14 for purse seiners, and Fig. 15 for trawlers. Emission indices for purse seiners showed a range from 0.15 to 0.85 kg $CO_{2\text{-eq}}$ per kg of catch, while for trawlers the values ranged from 4.3 to 7.18 kg $CO_{2\text{-eq}}$ per kg of catch.

If the emission indices based on the measured data are compared with the indices based on the estimated values of catch and fuel consumption, for the same group of 12 vessels, some differences can be seen. The reason for such scattering is the error made in the estimation of the amount of catch, shown in Figs. 12 and 13. The difference is especially visible in purse seiners with a small GT, where the estimation yields a smaller amount of catch than can be achieved with more frequent fishing. The value of the catch for trawlers is more accurately determined than that of purse seiners. Another important factor is the value of fuel consumption, which also contributes to the error. Since the

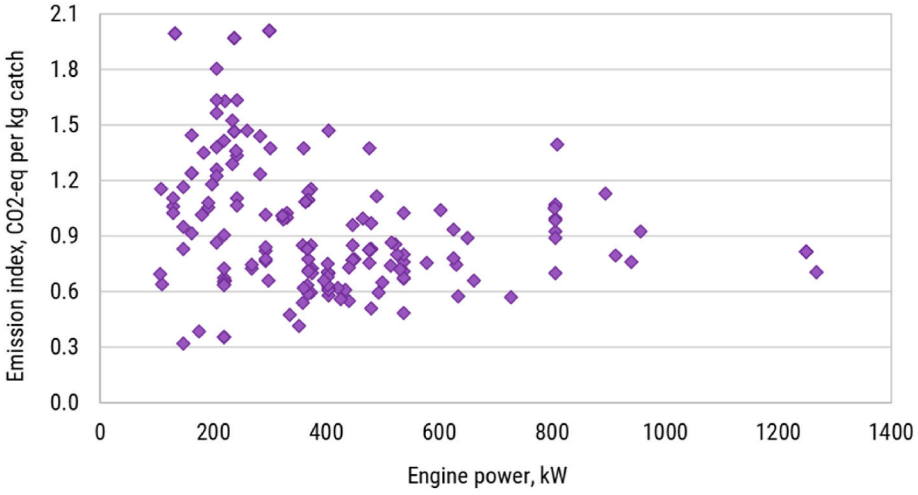


Fig. 8. Emission index values in relation to engine power – purse seiners.

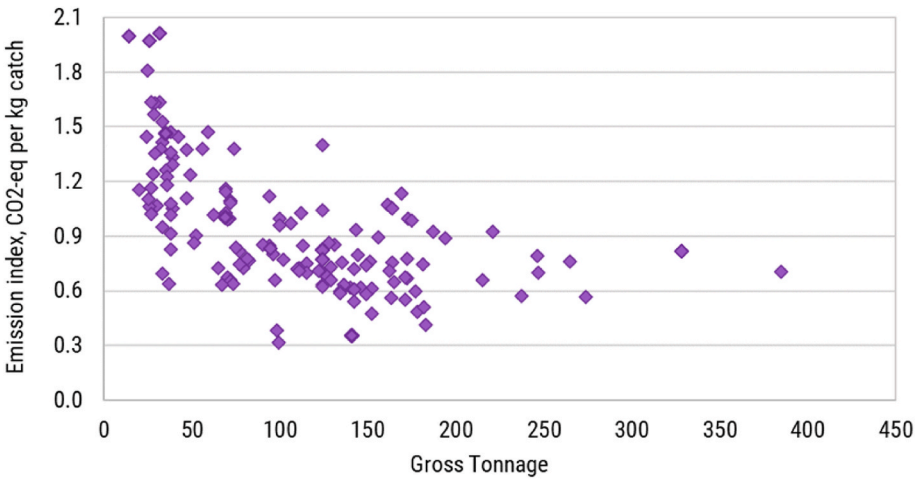


Fig. 9. Emission index values in relation to GT – purse seiners.

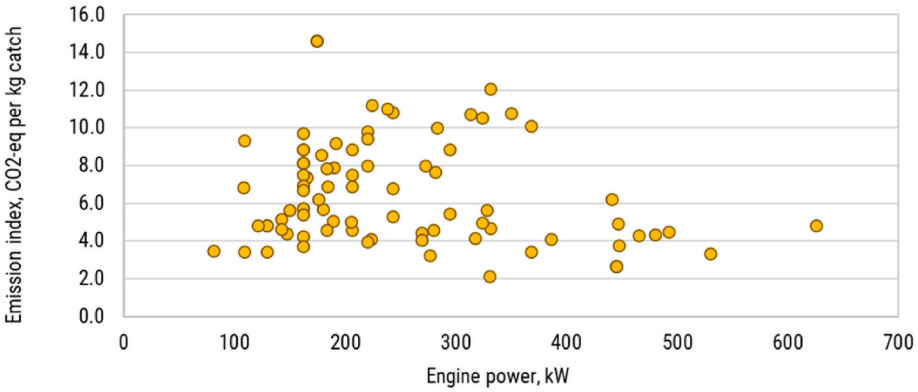


Fig. 10. Emission index values in relation to engine power – trawlers.

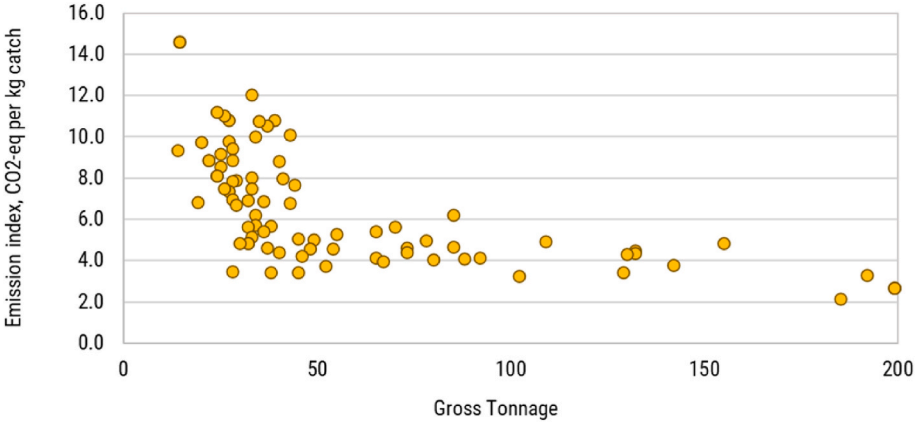


Fig. 11. Emission index values in relation to GT – trawlers.

operating regime is influenced not only by the technical characteristic, but also by the environmental conditions and crew skills, the possibility of inaccuracy of the result somewhat increases.

4.3. Economic assessment of the considered fishing vessels

The previous results showed that trawlers have approximately four times higher emission indices than purse seiners, in the case where the annual catch was chosen as a relevant parameter, i.e. benefit to society. Considering that the quality of the catch varies considerably, especially when it comes to different types of ships, the data on the amount of catch may be an overgeneralized parameter for a good insight into the energy efficiency of the ship. This is reflected in the initial calculation, because two different vessels are being compared. As can be seen in Fig. 16, various types of marine organisms achieve different market prices (Ministry of Agriculture of Republic of Croatia, 2023). Pilchard, anchovy and similar pelagic species achieve lower prices than hake, mullet, seabass and various crustaceans. Tuna and small pelagic species are

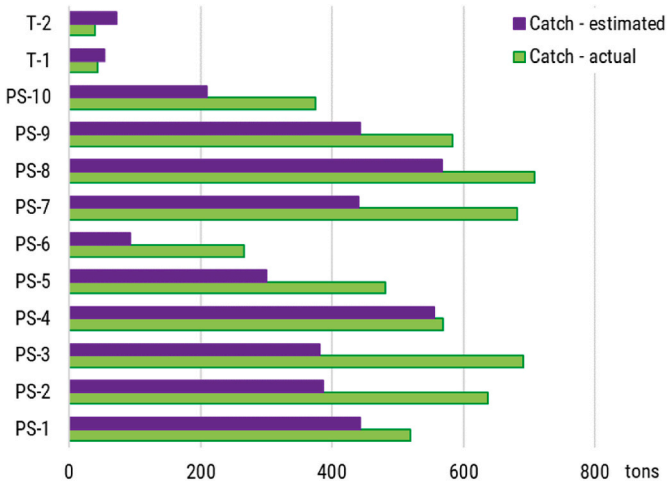


Fig. 12. Comparison of the estimated and actual values of catch.

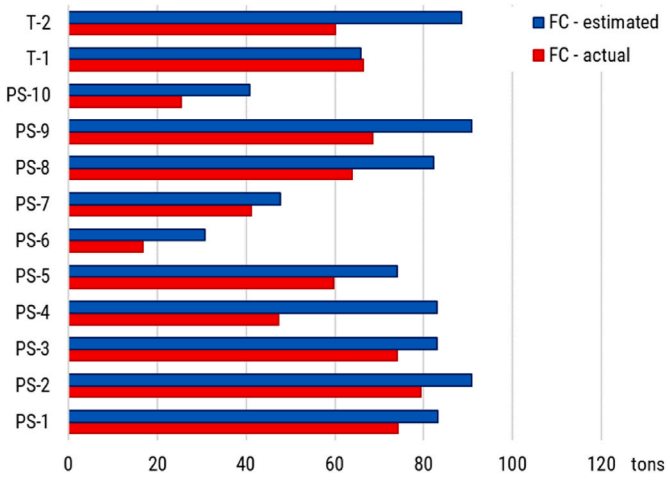


Fig. 13. Comparison of the estimated and actual fuel consumption.

mainly caught by purse seiners, while others will often be found in trawl nets.

If equation (1) is applied, but the realized income is taken as *BS* (obtained as a product of the realized catch and the average price of the corresponding catch group), the emission indices change. The results for the validation group are shown in Fig. 17. All the vessels' emission indices decline significantly, but trawlers undergo the most noticeable change. This directly shows that the quantity of the catch itself is not the most important criterion in determining efficiency, but additional data on the quality of the catch are needed. This is also recognized by Bastardie et al. (2022) who compared the economic efficiency of different species. Bottom trawling of sprat resulted in an efficiency of 3.96 €/l and a low FUI of 0.077 l/kg, crustacean fisheries achieve 3.24–4.78 €/l and an FUI of 1.13–2.15 l/kg, and prawn and mollusc fisheries achieve 25–40 €/l with an FUI of 0.0072–0.0122 l/kg.

5. Discussion

Assessing the energy efficiency of a vessel can be achieved by analysing the FUI. This approach was used in Sala et al. (2022) where the authors stated that energy audits and CF assessments are essential tools for improving energy efficiency and reducing GHG emissions in trawl fisheries. They applied energy audits to a test fleet of 10 vessels, representing three typical Mediterranean trawl fisheries (midwater pair trawl, bottom otter trawl, and Rapido beam trawl). Those fisheries utilize about 2.9 l of fuel per kg of landed fish, although the fuel consumption rate varies greatly depending on the type of gear and vessel size. Their research showed that a single boat bottom otter trawler

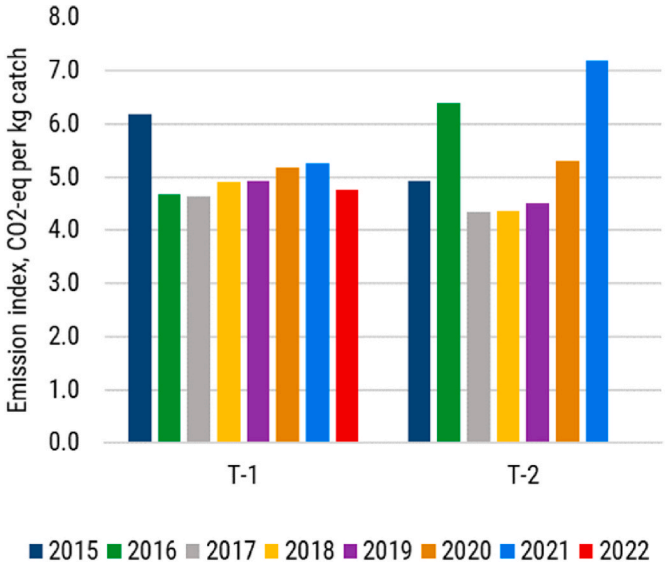


Fig. 15. Emission index values ($CO_{2\text{-eq}}$ per catch) of the validation group, in the period between 2015 and 2022 – trawlers.

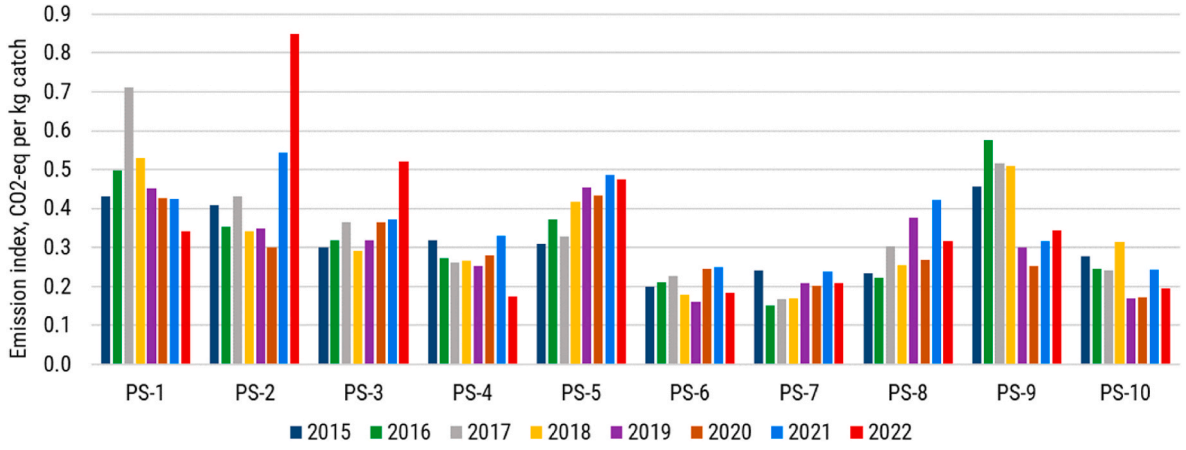


Fig. 14. Emission index values ($CO_{2\text{-eq}}$ per catch) of the validation group, in the period between 2015 and 2022 – purse seiners.

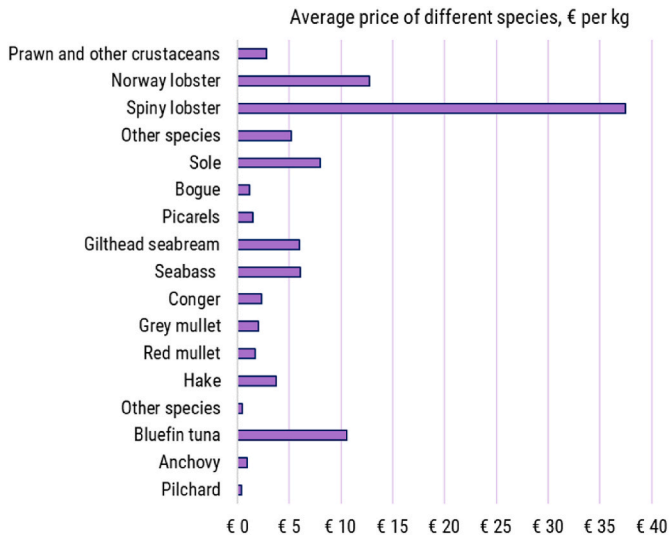


Fig. 16. Average selling price for different species in 2021, Republic of Croatia.

produces around 10,784 kg CO_2 per t fish, a midwater pair trawler 922 kg CO_2 per t fish, and a Rapido beam trawler 7,643 kg CO_2 per t fish. The authors also pointed out that bottom trawlers targeting mixed demersal species and shrimps are more fuel intensive than pelagic trawlers. In this paper, the focus is on single boat otter trawlers whose value varies from 2.08 to 14.11 kg $CO_{2\text{-eq}}$ per kg catch, whose catch and fuel consumption vary in a similar range as the one shown by Sala et al. (2022).

According to Parker and Tyedmers (2015), global tuna-fishing fleets released 179 million tonnes of $CO_{2\text{-eq}}$ into the atmosphere in 2011 while consuming 40 billion l of fuel, or 2.2 kg $CO_{2\text{-eq}}$ per kg of landed fish and invertebrates. Based on the chemical composition of marine fuels, their estimated harvest source of emission can be quantified at roughly 1.9 kg $CO_{2\text{-eq}}$ per kg of landed fish and invertebrates. Compared to the Croatian fleet, which emits 0.32–2.01 kg $CO_{2\text{-eq}}$ per kg catch, the results are a little higher than expected for the tuna-fishing fleet. It must be taken into account that the results from Parker and Tyedmers (2015) are specified only for tuna, while the results obtained for the Croatian fleet are valid for catches consisting of different types of fish.

Even when comparing vessels with similar targeted species and gear, a variation in energy inputs can be noticed. Parker and Tyedmers (2015) stated that purse seining skipjack tuna in the Atlantic results in 26,987 t of landed fish and an FUI of 445 l/t of fish, while in the Pacific the FUI results in 349 l/t but in a much larger catch of 592,451 t. Concerning trawlers, Parker and Tyedmers (2015) stated that small pelagic trawl fisheries burned an average of 92–164 l/t of fish during the harvesting activity, against 280–1,126 l/t of the current study of Sala et al. (2022). Bottom otter trawl fisheries produced 907–1,091 and 1,503–9,685 l/t of finfish and prawn landed, respectively. A comparison of the average fuel consumption of different gear types in EU fisheries is presented by Gabrielii and Jafarzadeh (2020), who stated that beam and bottom trawl consume around 3.3 l of fuel per kg fish, while pelagic trawls consume approximately 6.5 times less. Zaman et al. (2023) conducted research on the hilsa small-scale fisheries in Bangladesh and estimated an absolute FUI of 463 l/t of catch and an average global warming impact of approx. 1.72 t $CO_{2\text{-eq}}$ per t of catch. According to similar principles, Byrne et al. (2021) analysed demersal and pelagic vessels operating in Iceland and stated that the study on fuel intensity in this region is quite poor. The authors noticed a slight decrease in FUI in the demersal fleet, while an increase in the intensity of pelagic segments was noted. In contrast, the annual demersal landing remained stable over the years, ranging between 421,000 and 521,000 t, while the pelagic landings declined significantly, from 1,593,000 to 718,000 t due to a change in targeted species. Avadí et al. (2018) presented a highly fuel-efficient Peruvian trawling fleet, with an FUI of 120 kg fuel per t fish compared to a Chilean trawling fleet with an FUI of 440 kg fuel per t fish. Their research was based on eight trawlers differing in size in general. Surprisingly, the results showed that there is no significant impact on the FUI in regard to the holding capacity – the FUI of the largest vessel was 53% lower than the average of all other vessels. The authors concluded that additional research is needed, especially in the context of gathering data on fuel consumption and vessel performance, to effectively determine the efficiency of vessels of different sizes and operating regimes.

In this paper, the lack of accurate data on fuel consumption for the entire fleet appears as a limitation that must be solved in order to deal with the coming measures. This issue is also highlighted by Fan et al. (2022), who emphasize the importance of accurate fuel consumption models for improving energy efficiency and reducing GHG emissions in the shipping industry. The limitation of data is also visible in the catch analysis, so the emission index cannot be specified according to an individual species. It is also worth mentioning that the emission index values were calculated for the Croatian fishing fleet that uses blue diesel, whose specific characteristic, such as CO_2 conversion factors, are obtained from IMO. Other fishing fleets can use diesel with different carbon content or completely different fuels, which changes the emission index. An important factor is the end user itself, since mixing impurities can change the actual carbon content, as shown by Hasan and Karim (2020). The authors suggest fuel testing as a good way to estimate carbon content, which would improve the accuracy of the results whose calculation is based on fuel consumption.

The efficiency index has been developed on similar principles to the above-mentioned EEDI and EEXI, while the structure of the nominator related to the assessment of environmental impact, and the structure of the denominator related to the benefit to society are adjusted to the power systems of the fishing vessels and their catch, respectively. Expressing benefit to society in this way is particularly relevant from the perspective of fishers and shipowners or fleet managers. If the focus

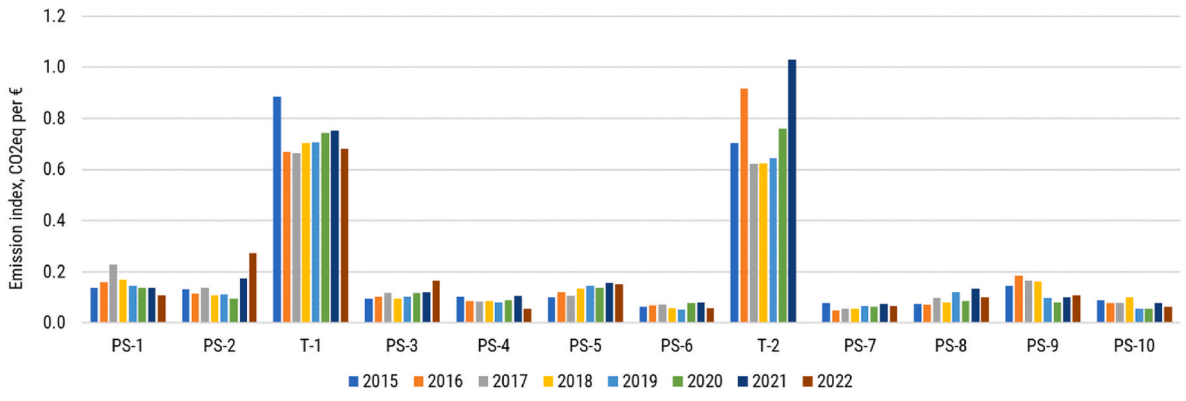


Fig. 17. Emission index values($CO_{2\text{-eq}}$ per €) of the validation group, in the period between 2015 and 2022.

shifts to the consumer, the caloric value of different fish is of much greater importance and can change the values of energy efficiency. For instance, 100 g of pilchard has a caloric value of 152 kcal and costs only €0.44 per kg, while tuna contains 143 kcal per 100 g and costs €10.59 per kg (Food and Agriculture Organization, 1989). Although tuna will make a high profit, there is a greater chance that a large family will buy a larger quantity of pilchards and thus feed the whole family. Considering that there are a number of other species that have a similar caloric value, a much lower price than tuna and a smaller impact on the environment, it is necessary to expand the research and analyse statistical data on sales and see how much the catch of tuna contributes, i.e. whether or not its catch is justified.

6. Conclusions

Fishing vessels continue to consume a significant amount of energy and emit high levels of harmful gases in the seafood product value chain, and are excluded from many of the technical and operational measures provided by IMO. However, some global measures still affect fishing vessels which are expected to adapt accordingly.

This paper provides a detailed analysis of the emission index calculation for the Croatian fishing fleet, specifically for 163 purse seiners and 82 single boat bottom otter trawlers. The emission indices are presented in relation to the engine power and gross tonnage of each vessel. The emission indices calculated for the Croatian fleet are based on the estimated catch and fuel consumption values. Validation of the accuracy of measurements and the range of values was carried out using a group of vessels whose annual catch and fuel consumption are precisely known. A validation group of 12 vessels, 10 purse seiners and two trawlers was used for comparison. The results showed the following:

- The emission indices of the purse seiner part of the fleet range from 0.32 to 2.01 $CO_{2\text{-eq}}$ per kg catch, with most values ranging between 0.48 and 0.91 $CO_{2\text{-eq}}$ per kg catch;
- The emission indices of the trawler part of the fleet range from 2.08 to 14.11 $CO_{2\text{-eq}}$ per kg catch, with 13–15% higher emission index values than purse seiners;
- The emission index values are influenced by factors such as engine power, gross tonnage, and age of the ship;
- The market price can have a great impact on the calculated energy efficiency index, i.e. a smaller catch does not necessarily mean lower profit, and thus the emission index can achieve low values in both cases.

There are different methods to analyse the energy efficiency of a vessel and each has its advantages and limitations. However, certain parameters (catch quantity and fuel consumption) needed to be estimated since there were no public records of these parameters for each individual vessel. In further work, the possibility of supplying these data should be investigated to increase the accuracy of the results. Considering that the emission index values depend on the type of fishing vessel, it would be a good idea to analyse their operational regimes and fuel consumption according to the activity points during one fishing trip. In this way, it would be possible to determine the key periods when the emission of harmful gases is the highest and by using other methods, such as performance monitoring and planning, greater efficiency and lower costs could be achieved.

CRediT authorship contribution statement

Marija Koričan: Data curation, Investigation, Resources, Formal analysis, and/or interpretation of data, Drafting the manuscript, Approval of the version of the manuscript to be published (the names of all authors must be listed). **Nikola Vladimir:** Conceptualization, Methodology, and Design of study, Formal analysis, and/or interpretation of data, Data curation, Drafting the manuscript, Supervision, (revising the manuscript critically for important intellectual content), Approval of the version of the manuscript to be published (the names of all authors must be listed). **Ailong Fan:** Formal analysis, and/or interpretation of data, Data curation, Supervision, (revising the manuscript critically for important intellectual content), Approval of the version of the manuscript to be published (the names of all authors must be listed).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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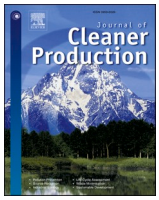
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Electrification of fishing vessels and their integration into isolated energy systems with a high share of renewables

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ABSTRACT

Decarbonization is among the most important research topics in the maritime sector, where different technical and operational measures are being examined to enhance the sustainability of marine operations. Electrification of fishing vessels stands out as a solution towards reducing emissions and operating costs. However, sustainable decarbonization of fishing vessels requires a high share of renewable energy sources (RES) in the power sector. It is also challenging to achieve the sustainable decarbonization of fishing vessels operating in an isolated energy system (IES) in remote areas. The novelty of this study is to demonstrate the opportunities arising from the nexus between fully electric fishing vessels and photovoltaic (PV) power systems in the IES of an island. The study highlights the economic and environmental benefits of integrating all-electric fishing vessels in the IES with 100% RES. The energy modelling of the IES was simulated in the EnergyPLAN. The paper confirms that charging battery-powered electric fishing vessels in the fishing port can reduce the critical excess of electricity production (CEEP), operating IES costs, and the emissions of CO_2. The presented mathematical model is applicable to other ship types and renewable-based IESs if the input data required for such simulations are known.

1. Introduction

In the past decade, significant focus has been placed on environmental protection and emission reduction policies. The shipping industry is being encouraged to adopt low-carbon energy sources to minimize its environmental impact. The Paris Agreement, an international treaty adopted in 2015 under the United Nations Framework Convention on Climate Change (UNFCCC), aims to combat climate change by limiting global warming to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C (UNFCC, 2016). The International Maritime Organization (IMO) has developed a set of technical and operational measures to reduce the environmental effect of the shipping sector (International Maritime Organization, 2020). The most important of these measures are presented in Fig. 1. Both technical and operational measures have their advantages and drawbacks, which is why extended research needs to be conducted prior to their implementation. It has been acknowledged that a particular measure is not equally efficient for different ship types, or for different ships within the same type, since its viability depends on the ship exploitation pattern.

Electrification is an emerging trend aimed at reducing GHG emissions and moving the shipping industry towards a more sustainable and low-carbon future while achieving compliance with marine regulations. It involves the use of electricity as a primary source of power for propulsion and ship onboard systems, replacing or supplementing traditional fossil fuel power systems (Park et al., 2022). There are several options in the market for the electrification of ships, from 100% electric to hybrid-electric and hybrid plug-in ships. Perčić et al. (2020a) compared three types of power systems – diesel engine, battery charged from the grid, and battery charged from the grid and by photovoltaics (PV) on a ro-ro passenger ship. The diesel-engine-powered ship produced 79.74 kg $CO_{2\text{-eq}}$/nm, while the battery options yielded much less, 27.92 kg $CO_{2\text{-eq}}$/nm in the case of a battery-powered and 31.98 kg $CO_{2\text{-eq}}$/nm in the case of a battery-powered ship with PV cells installed onboard. Total costs have been reduced by approximately 40% with the application of a battery-powered system.

Even though the electrification of fisheries has environmental and economic benefits, it requires a proper infrastructure to support charging or battery exchange systems. The infrastructure includes charging stations, grid connection upgrades, and managing the power demands of multiple vessels. These facilities raise a range of issues, from supply safety to ports and payment regulations (Johnson et al., 2022). Due to the low energy density of batteries compared to fossil fuels,

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Nomenclature

Abbreviations

CDEP	Critical deficit of electricity production
CEEP	Critical excess of electricity production
CO_2	Carbon dioxide
EEEP	Exportable excess of electricity production
IDEP	Importable deficit of electricity production
IES	Isolated energy system
IMO	International Maritime Organization
NO_x	Nitrogen oxides
PV	Photovoltaic
RES	Renewable energy sources
SO_x	Sulphur oxides

Variables

D	Annual electricity demand, GWh/year
d	Hourly electricity demand, GWh
E	Annual electricity production, GWh/year
e	Hourly electricity production, GWh
e'	Correction factor
F	Annual fuel demand, GWh/year
FC	Annual fuel consumption, tonnes
SFC	Specific fuel consumption, g/kWh

Subscripts

E	Electricity demand of the isolated region
EFP	Electricity demand of the electric fishing vessels
i	Specific renewable energy source

frequent charging is needed, which is complicated by the irregular operational pattern of fishing vessels. The absence of an electricity grid raises the need to establish a self-sustaining energy system and optimize the recharging of vessels (Spaniol and Hansen, 2021). One option is to establish sea platforms, such as fish farms, offshore cargo terminals, or observation platforms, where electricity could be produced from RES (PV, wind turbines) and supplied to passing vessels (Spaniol and Hansen, 2021). Another option could be isolated energy systems (IESs), such as islands that generate electricity from renewable or non-renewable energy sources to meet the island's energy demands. Charging electric ships requires greater electricity production, so it is necessary to analyse the environmental impact of this production to keep harmful emissions as low as possible (Nuez et al., 2022). A 100% renewable energy sources (RES) energy system, based on PV or wind turbines, and with necessary energy storage (Parlikar et al., 2021), can supply electric vessels and achieve zero emissions, and at the same time also significantly reduce costs (Pfeifer et al., 2020).

1.1. Energy requirements for fishing vessels

When focusing on fishing vessels, Blue Growth is an important aspect of development. Blue Growth refers to the sustainable economic development of marine and maritime sectors, including fisheries, aquaculture, and marine tourism, while ensuring the long-term health and productivity of marine ecosystems (Saviolidis et al., 2020). The fishing sector is responsible for approximately 1.2% of global fuel oil consumption, resulting in around 134 million tonnes of CO_2 emissions annually (Koričan et al., 2022a), and the fuel costs can account for up to 60% of total fishing industry costs (Greer et al., 2019). To reduce the environmental impact of fisheries, traditional fossil-fuel-powered engines are being replaced with electric propulsion systems, which offer several benefits, including reduced GHG emissions, improved energy efficiency, and decreased operating costs (Ling-Chin and Roskilly, 2016; Perčić et al., 2021; Wang et al., 2021). The adoption of a hybrid electric propulsion system in fishing vessels is considered by Kim et al. (2022), who studied combined conventional fuel-based engines with electric propulsion technologies to improve energy efficiency and reduce environmental impact. The results showed a possible reduction in fuel consumption and GHG emissions, although the authors emphasize the importance of analysing the ships' performance and operating profiles.

Purse seining includes cruising to the fishing location (i.e. open sea), searching for the fish, setting the net, hauling, loading, and cruising back to the port (along with unloading the catch), Fig. 2. Cruising takes place at high speed and thus consumes over 50% of total fuel consumption, while the setting of the net and its manoeuvring takes place more calmly, at low speed, in order not to disturb the catch. Fuel use intensity is influenced by the target fish (mainly small pelagic species) and operating conditions (Koričan et al., 2022b).

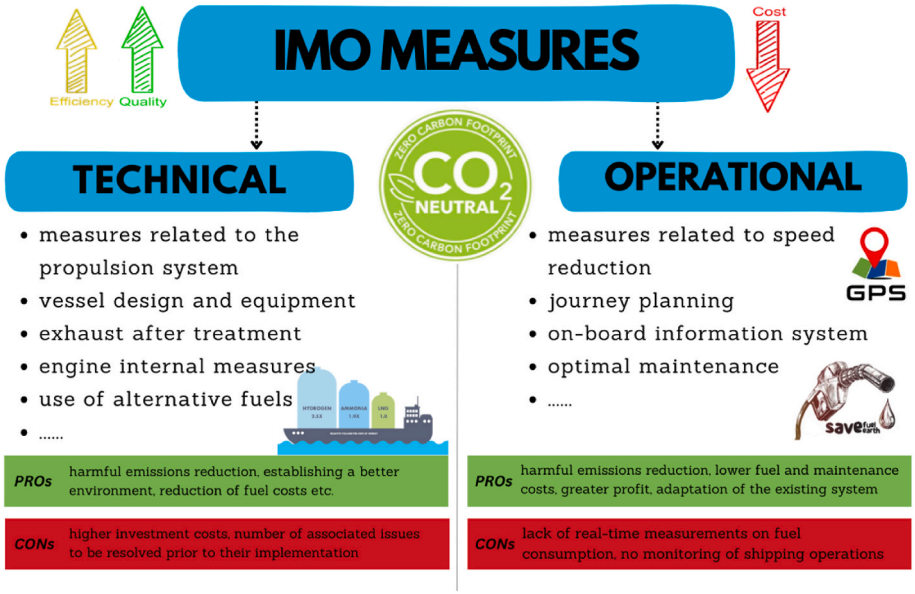


Fig. 1. Technical and operational measures for the improvement of ship energy efficiency (International Maritime Organization, 2020).

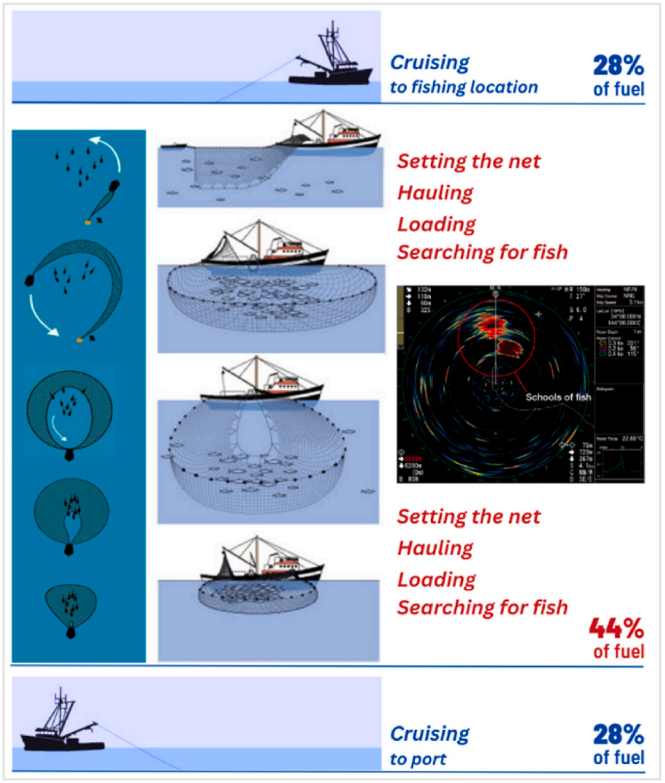


Fig. 2. Typical activities of purse seiners and their fuel consumption.

1.2. State of the art in ship electrification

Since alternative energy sources offer a solution that is acceptable in terms of emissions regulation and meeting the required energy efficiency of a ship, the maritime industry is encouraged to transition to this type of solution (Fan et al., 2021). Several options are being promoted, including lithium batteries, fuel cells, shore-side electricity, solar energy, etc. Perčić et al. (2020b) performed a Life-cycle Assessment (LCA) of alternative fuels in short-sea shipping and showed that electricity-powered ships are the most economically and environmentally friendly solutions. Fan et al. (2021) performed an LCA and a Life Cycle Cost Analysis (LCCA) of inland ship power systems and indicated that the decarbonization potential of battery-powered ships significantly depends on the emissions from the electricity generation process. Therefore, the electrification of ships with batteries can sustainably decarbonize short-sea shipping only if the electricity for powering the ships is generated in the electricity mix with 100% RES.

Batteries are an attractive alternative to traditional marine fuels in the case of ships navigating close to a powering station (e.g. onshore power grid). There are different types of power batteries for electric vessels, where lithium-ion batteries present a superior solution compared to diesel engines, according to environmental and economic indicators (Perčić et al., 2022).

Photovoltaic (PV) power systems have achieved large-scale deployment over the past decade and the prices of the PV modules have fallen by 80%, positioning the technology as the most affordable electricity generation option around the world. For example, the utilization of solar energy by installing PV panels, with an output of 100 WP, onboard fishing vessels could supply 50.52% of the electrical energy needs and provide an IRR of 9%, with a payback period of 8.87 years (Nugraha et al., 2022). Battery storage systems (BSSs) have emerged as an important flexible and reliable option in the electricity mix that is characterized by a high share of PV power systems. The utilization of BSSs together with PV power systems can shift peak demand, flatten solar variability, and partly alleviate network congestion. Peters et al. (2021) investigated the role of BSSs in meeting the PV terawatt challenge and indicated that BSSs represent a straightforward solution for adding flexibility to renewable-based energy systems. The authors concluded that BSSs are an expensive investment that increase the electricity production costs and that energy systems powered by a high share of RES require the integration of advanced complementary storage technologies.

Power-to-Ship technology is an advanced option for renewable-based energy system flexibility and reliability. This option supports aligning the electricity consumption of ships with the available RES power supply, and hence reducing the need for other complementary storage technologies. The nexus between electric ships and PV power systems can help power electric ships with renewable electricity, while improving the economic and environmental performance of the PV power systems. This holistic approach is important, especially in the case of the 100% RES isolated energy system (IES) of islands or other remote areas. Frković et al. (2022) considered the energy planning of an IES characterised by 100% PV power systems in the power sector and battery-powered ferries in the maritime transport sector. It is shown that the synergy between the maritime transport sector and the renewable-based power sector can reduce the excess of electricity production, operating IES costs, and CO_2 emissions (Frković et al., 2022). The electrification of other short-sea shipping sectors can also provide benefits to the IES powered with 100% RES.

1.3. Novelty and contribution of the paper

Increasing efforts have been made to explore the electrification of various shipping modes, but there are still notable research gaps specific to the electrification of fishing vessels, as listed below:

- Research is needed to develop a charging infrastructure that can handle the high-power requirements of large fishing fleets;
- The implementation of RES that can be integrated into the fishing vessel's power system or onshore facilities, such as solar and wind power, needs to be investigated to assess the environmental impact;
- The cost-effectiveness of electrification, including the capital cost, operating costs, and potential revenue streams, needs to be determined.
- Fishing vessels have unique operational requirements, which need to be addressed to maximize energy efficiency and minimize the environmental impact of fishing operations.
- The development of an appropriate charging infrastructure and its integration into existing electrical grids is essential for the wider adoption of electric fishing vessels.

There are number of analyses in the field of emission mitigation technologies in coastal shipping (passenger, cargo) in the literature, but research related to fishing vessels is not yet mature. In order to deal with the above research gaps, this paper includes:

- Considerations on an adequate onshore charging infrastructure, essential for the electrification of fishing vessels, which exploits renewable energy sources.
- Assessing the technical feasibility of implementing electric propulsion systems in different types and sizes of fishing vessels – evaluating the power requirements of purse seiners, energy storage options, and the charging infrastructure.
- Assessing the economic viability of electrifying fishing vessels and establishing an IES, while considering investment costs, operational costs, and potential cost savings associated with reduced fuel consumption (long-term).

The majority of studies focus either on the ship or the IES, while their mutual influence is neglected, and, to the best of the authors' knowledge, there are no publications simultaneously considering the

electrification of fishing vessels and its relation to the IES. Therefore, this paper simultaneously covers the connection between fishing vessels and the IES, considering the specificity of fishing techniques and operating conditions. The study is case specific and deals with the electrification of fishing vessels in the Adriatic Sea, with the island of Cres as an example of an IES. However, the model developed in the paper is universally applicable if the required input parameters are known.

2. Methods

In this study, the EnergyPLAN (Lund et al., 2021) is used to simulate the operation of an IES on an hourly basis, including the power sector and a fleet of fishing vessels. The inputs for the EnergyPLAN simulations include the installed power capacity of the PV power systems, the electricity demand of the island, and the electricity consumption of the battery-powered fishing vessels, i.e. the electricity demand of the fishing port. Additional inputs are the hourly distributions of the electricity demand and electricity supply for modified fishing port scenarios, and the costs of the analysed components, Fig. 3.

Environmental trends and maritime regulation foster the integration of alternative technologies in fishing vessels to ensure environmental and economic benefits. Fishing vessels that operate at low speeds for extended periods are the best candidates for the transition from a diesel engine power system to a battery power system because their diesel engines operate at multiple operating points, making it difficult to sail at the optimal one with minimum fuel consumption.

2.1. Energy demands of fishing vessels

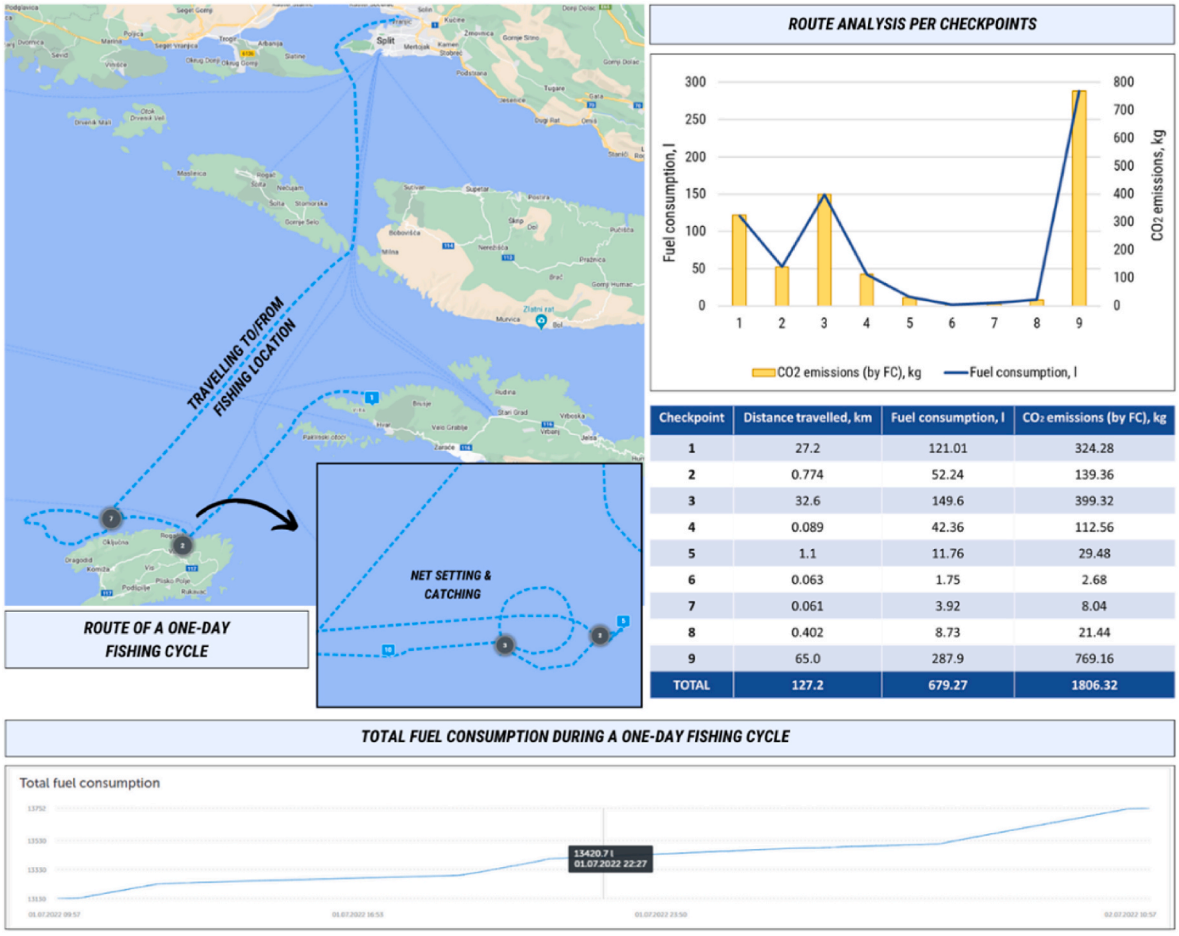
The total energy demand per fishing trip includes the energy required for basic fishing operations, i.e. navigation to the fishing spot, the fish finding procedure, projecting light, the process of pulling out the fish, etc. The basic fishing operations presented in Fig. 2 can be observed through a monitoring system, as presented in Fig. 4. Monitoring systems provide real-time data on the route, operating time, GPS location, fuel consumption, etc. Using various fuel monitoring devices, such as flowmeters and fuel level sensors, as well as accessory switches to denote the activity of the engines, the operating characteristics of a vessel can be measured in real time (Korićan et al., 2022c). The devices are directly connected to a server, which collects data and presents them through "MAPON" software (MAPON, 2023). The data are presented in Fig. 4. As can be seen, purse seiners consume most fuel while cruising, when the greatest distance is travelled. The amount of CO_2 emissions is proportional to the fuel demand/consumption and follows its trendline, as expected. The monitoring system also enables the monitoring of working time. By analysing fishing cycles in different time periods, differences in working time and fuel consumption can be noticed. Given that determining the operating time is important to assess the possibility of battery charging, the hourly energy demand distributions of the fishing vessels are derived by analysing their operation profiles during spring, summer, autumn, and winter.

The total fuel consumption per fishing trip, FC_{FT_l} (l), and the total navigation time per fishing trip, t_{FT} (h), are obtained from the measurements conducted on the specific fishing vessel. The FC_{FT} and t_{FT} are the basic data for calculating the energy demand of the fishing vessels. Moreover, these results vary depending on the operating season, resulting in the different FC_{FT} and t_{FT} of the fishing vessel in spring, summer, autumn, and winter.

The total fuel consumption per fishing trip, FC_{FT_kg} (kg), can be calculated by multiplying the FC_{FT_l} with the marine diesel fuel density,



Fig. 3. Simulation flowchart of an IES in the EnergyPLAN.



Checkpoint	Distance travelled, km	Fuel consumption, l	CO_2 emissions (by FC), kg
1	27.2	121.01	324.28
2	0.774	52.24	139.36
3	32.6	149.6	399.32
4	0.089	42.36	112.56
5	1.1	11.76	29.48
6	0.063	1.75	2.68
7	0.061	3.92	8.04
8	0.402	8.73	21.44
9	65.0	287.9	769.16
TOTAL	127.2	679.27	1806.32

Fig. 4. Example of a route analysis within a fishing cycle (route checkpoints, fuel consumption and CO_2 emissions).

ρ_{diesel} (kg/dm^3), according to Eq. (1):

$$FC_{FT_kg} = FC_{FT_l} \bullet \rho_{diesel}, \quad (1)$$

where ρ_{diesel} is assumed to be 0.845 kg/dm^3 (Ghadamkheir et al., 2023).

The total fuel demand per fishing trip, FD_{FT} (kWh), can be calculated by dividing the FC_{FT_kg} with the specific fuel consumption of the diesel engine, SFC (kg/kWh), according to Eq. (2):

$$FD_{FT} = \frac{FC_{FT_kg}}{SFC}, \quad (2)$$

where SFC is assumed to be 0.215 kg/kWh (Ančić et al., 2018).

The total electricity demand per fishing trip, D_{EFT} (kWh), is calculated by multiplying the FD_{FT} with the marine diesel engine efficiency, η_{diesel} (%), according to Eq. (3):

$$D_{EFT} = FD_{FT} \bullet \eta_{diesel}, \quad (3)$$

where η_{diesel} of the diesel engines on the fishing vessels is assumed to be 42% (Ghadamkheir et al., 2023).

The electricity consumption of the fishing vessel per hour, EC_{FT} (kWh), is the ratio of the D_{EFT} and the t_{FT} and can be calculated according to Eq. (4):

$$EC_{FT} = \frac{D_{EFT}}{t_{FT}}. \quad (4)$$

2.1.1. Sizing the battery capacity for fishing vessels

Fishing vessels have different operation profiles during spring, summer, autumn, and winter. The battery capacity of battery-powered electric fishing vessels, BC_{BEFV} (kWh), needs to be sufficient for each of the operating profiles to meet the required performance specifications throughout the year. Therefore, the BC_{BEFV} is designed to supply electric power for an operation profile of the fishing trip with the highest D_{EFT}. The BC_{BEFV} is increased by 20% due to gradual battery degradation that can reduce the battery capacity by 20% of its initial capacity. The BC_{BEFV} is additionally increased by 20% to maintain the minimum state of charge (SoC) and by 10% to ensure safety during fishing operations. Therefore, the BC_{BEFV} can be calculated according to Eq. (5):

$$BC_{BEFV} = 1.5 \bullet D_{EFT_MAX}. \quad (5)$$

The battery capacity of a battery-powered electric fishing vessel and its operation profiles throughout the year are relevant data for calculating the annual electricity consumption of the fishing vessel fleet, that is, the annual electricity demand of the fishing port, as well as for simulating the operation of the IES.

2.2. Simulations of the IES in the EnergyPLAN

The operation of an IES with a high share of RES can be improved by introducing electric vehicles (EV) as controllable loads and mobile energy storage systems (Vasconcelos et al., 2015). The adoption of advanced centralized EV charging control strategies allows for the integration of a larger number of EVs in the system without the need for grid improvements, as well as for the improved operation performance in an island operation mode and a safe increase in the quantity of variable RES (Lopes et al., 2011). The next stage is to provide a way to gradually extend the electric mobility concept from EVs to vehicles in other sectors. In this study, simulations of the IES were developed to demonstrate the environmental and economic benefits of replacing

diesel engines with lithium-ion batteries on fishing vessels. The PV power system is recognized as an energy source for the development of isolated EV charging stations (Atawi et al., 2021). Therefore, the simulations in this study aim to achieve the charging of battery-powered electric fishing vessels with electricity supplied from the power sector with 100% PV power systems. The calculation of the electricity demand of the fishing port and the development of hourly electricity demand distributions were developed in Excel for each hour of the specific year, i.e. 8784 h.

The total hourly PV electricity production (e_{PV_total}) is the sum of the electricity production from the PV power system in the energy system for a specific hour:

$$e_{PV_total} = \sum_{i=1}^{n} e_{PV,i}. \tag{6}$$

The modelling of PV power system production requires the power capacities of the PV power systems installed in the energy system, as well as the 8784 hourly distribution solar irradiation data set for the specific location of the installed units. The correction factor can be inserted in the EnergyPLAN to modify PV production in such a way that electricity generation remains the same at a time with either no generation or maximum generation, while other values are moderated relatively, according to Eq. (7):

$$e'_{PV} = \frac{e_{PV} \bullet 1}{[1 - FAC_{PV} \bullet (1 - FAC_{PV} \bullet e_{PV})}. \tag{7}$$

The total annual PV electricity production, E_{PV_total} (GWh/year), is the sum of the hourly electricity production from each PV power system for 8784 h:

$$E_{PV_total} = \sum_{x=1}^{8784} e_{PV_total}(x). \tag{8}$$

The total hourly electricity demand (d_{Total}) is the sum of the electricity demand in the energy system for a specific hour:

$$d_{E_total} = \sum_{i=1}^{n} d_{E,i}. \tag{9}$$

The total annual electricity demand, D_{E_total} (GWh/year), is the sum of the annual electricity demand of the IES (D_{E_IES}) and the annual electricity demand of the fishing port (D_{E_FP}), that is, the sum of all the hourly electricity demand of the IES, d_{E_IES} (MWh), and of the hourly electricity demand of the fishing port, d_{E_FP} (MWh) (Lund and Thellufsen, 2019):

$$D_{E_total} = D_{E_IES} + D_{E_FP} = \sum_{x=1}^{8784} d_{E_IES}(x) + \sum_{x=1}^{8784} d_{E_FP}(x). \tag{10}$$

The d_{E_IES} can be obtained from the measurements of the substations that supply electricity to end users in the observed isolated area. The d_{E_FP} requires case-by-case modelling, because it is affected by the number of battery-powered electric fishing vessels in the port, the arrival and departure patterns of the fishing vessels, the operation profile of the fishing vessels for different seasons, the power demand (power capacity of the main and/or auxiliary engines), and the occupancy of the charging stations installed in the fishing port in a certain period (Peng et al., 2020).

An excess or a deficit in electricity production is obtained by subtracting the total electricity demand and the total electricity supply, depending on whether more or less electricity is produced in a particular hour than needed. In this paper, the capacity values of the energy transmission lines were set at zero to simulate the operation of the IES. Therefore, an excess of electricity production is observed as a critical excess of electricity production (CEEP), and a deficit of electricity production is observed as a critical deficit of electricity production (CDEP).

2.3. Investment and fixed operating costs

The existing fishing vessel power system has a diesel engine onboard, which has low energy efficiency and needs to be replaced. Therefore, the *CapEx* of a diesel-powered fishing vessel refers to the purchase of a new diesel engine whose price can be calculated by multiplying the total diesel engine power with the assumed conversion factor of 250 €/kW. The *OpEx* of a diesel-powered fishing vessel includes the maintenance cost and diesel fuel cost. According to the study by Trivyza et al. (2018), the annual maintenance cost is calculated by multiplying the ship's annual energy consumption with a conversion factor of 0.014 €/kWh (EU, 2020). A diesel-powered fishing vessel's annual fuel cost is calculated by multiplying the annual energy consumption, *SFC*, and the Croatian diesel price of 0.78 €/kg.

About 45% of the CapEx of a battery-powered electric fishing vessel refers to the battery price, while the other 55% refers to the costs of additional equipment, such as an electric engine, etc. Therefore, the CapEx of a battery-powered electric fishing vessel can be calculated with Eq. (12):

$$CapEx = \frac{BP}{0.45}, \tag{12}$$

where *BP* (€/kWh) is the battery price and is calculated by multiplying the *BC* (kWh) with the assumed cost of a lithium-ion battery of 200 €/kWh (Perčić et al., 2022). The maintenance cost of the lithium-ion battery power system refers only to the replacement of the lithium-ion battery, that is, to the *BP* and the number of replacements during the lifetime of the fishing vessel. The annual electricity cost is calculated by multiplying the annual energy consumption by the Croatian electricity price of 0.078 €/kWh (Perčić et al., 2022).

The input data for the EnergyPLAN programme cost analysis is the assumed price of light fuel oil of 46 €/GJ for the year 2030. The CO_2 emission costs were assumed to be 180 €/t for 2030 to estimate the benefits of such an ambitious cost level for the integration of batteries onboard of the fishing vessels (Scheelhaase et al., 2021).

3. Case study

The Island of Cres in Croatia is selected as a case study for simulating the integration of battery-powered electric fishing vessels in the IES with 100% PV power systems in the electricity mix. The island is used as a digital laboratory for demonstrating the complementarity of the electricity demand and the PV electricity supply of the IES with the electricity demand of the fishing port.

3.1. Energy characteristics of the Island of Cres

The hourly electricity demand distribution curve of the Island of Cres was obtained from the measurements of the substation Cres 110/35 kV for the year 2018 provided by the Croatian national electricity company HEP Group (HEP d.d. – Hrvatska elektroprivreda d.d.) (HEP d.d., 2018). According to the obtained data, the D_{E_total} of the IES in 2018 was approximately 17 GWh/year (Fig. 5). It is assumed that the hourly electricity demand distribution for 2030 is equal to the distribution in 2018.

The Island of Cres has 2623 h of sunshine per year and it belongs to the islands with relatively high solar irradiation in Croatia. The maximum solar irradiation for the year 2018 reached 1006 W/m^2. Fig. 6 shows the hourly distribution curve of solar irradiation that was derived from the solar irradiation measurements for 2018 taken from the Croatian Meteorological and Hydrological Service (DHMZ - Croatian Meteorological and Hydrological Service, n.d.). According to the projections in one study (Frković et al., 2022), the installed capacity of the PV power systems on the Island of Cres for 2030 was assumed to be 21 MW for 2030.

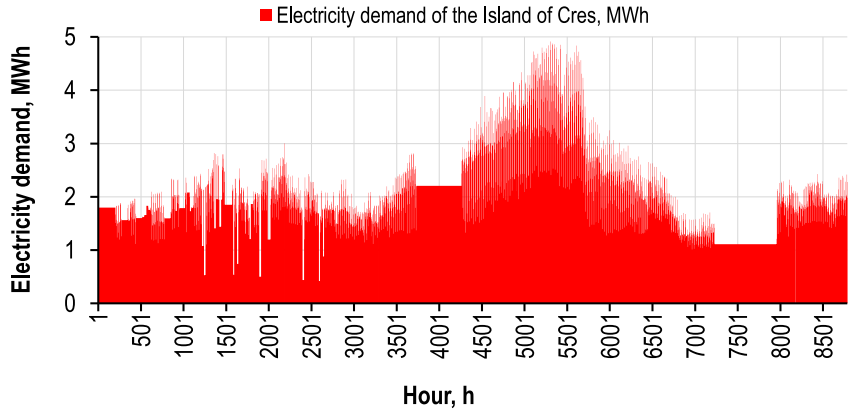


Fig. 5. The hourly electricity demand of the IES (data for 2018).

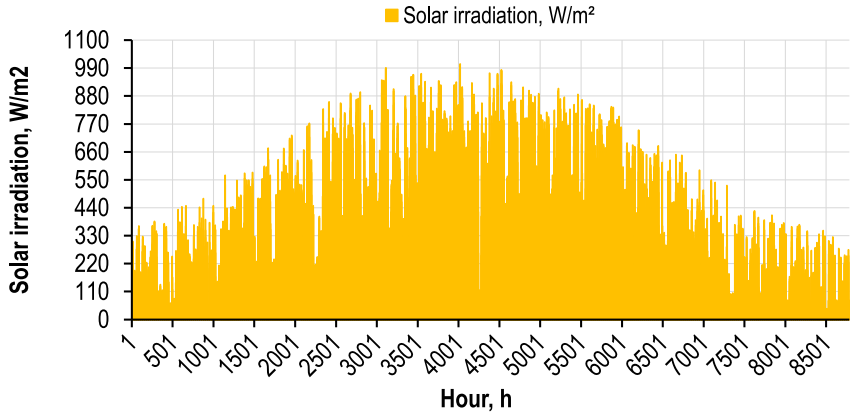


Fig. 6. The hourly solar irradiation distribution for the IES (data for 2018).

3.2. Electricity demand of battery-powered electric fishing vessels

As described in the previous sections, the technical and operating characteristics of the fishing vessels in this research are identified and presented below.

The Croatian fishing fleet consists of 7808 fishing vessels, which are responsible for 5.74% of the total catch in the Mediterranean area (General Fisheries Commission for the Mediterranean, 2023). In Croatia, purse seiners from 24 to 40 m LOA yielded 50.5% of total landings in 2020 and, in general, contribute 90% of landing weight and almost 55% of landing value (Ministry of Agriculture of Republic of Croatia, 2023). Fig. 7 presents the technical characteristics of the purse seiner fleet, and the properties of the vessel selected as the representative one are listed in Table 1.

The characteristics of the closed fishing season and temporary suspension periods are illustrated in Fig. 8.

Table 1
Characteristics of the selected fishing vessel.

Vessel CFR	HRV000001049
Length overall (LOA), m	32.28
Breadth, m	7.4
Gross tonnage (GT)	182
Engine power, kW	480
Diesel generator power, kW	370

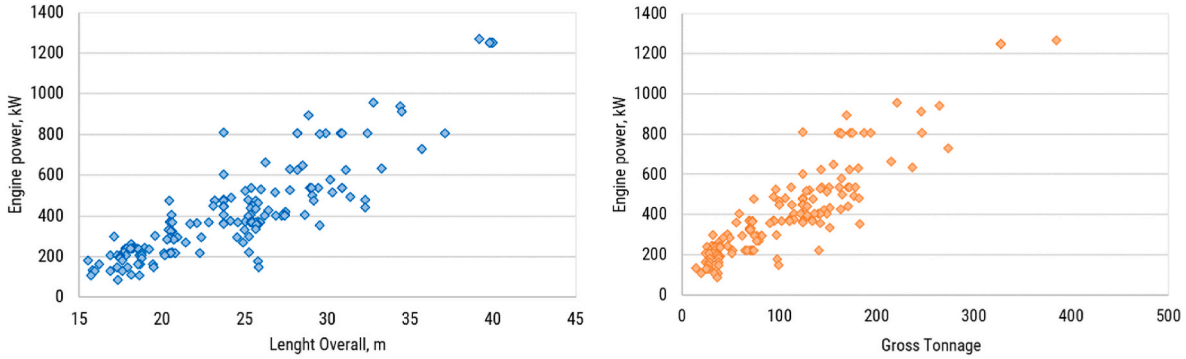


Fig. 7. Technical characteristics of purse seiners in Croatia.

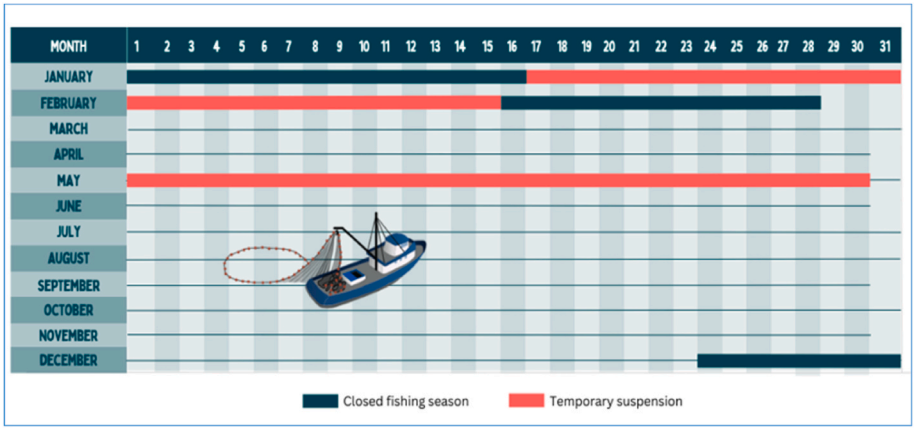


Fig. 8. Fishing activity periods through the year.

Table 2 provides the characteristics of the operation profiles for the selected fishing vessel for each season of the year.

The electricity demand of the fishing vessel and the electricity demand of the fishing port are developed for each weather season according to the operation profile characteristics. The electricity consumption and charging profiles are developed for a two-day period (48 h), as shown in.

Fig. 9. The annual electricity demand of the fishing port was modelled on the arrival and departure patterns of the fishing vessels, whereas the charging of the fishing vessels was set to occur during the daytime, ranging from 10:00 CET to 14:00 CET.

A comparison of the electricity consumption of the fishing vessel per operating season, as well as the electricity demand of the fishing port per operating season, is shown in Fig. 10.

3.3. Overview of the IES scenarios

The scenarios were designed to simulate the operation of the IES, which includes integration of battery-powered electric fishing vessels in the IES powered by 100% PV power systems. The simulations were developed for 2030 for 10, 20, and 30 battery-powered electric fishing vessels. Table 3 shows the characteristics of the 2030 scenarios.

4. Results and discussion

4.1. Business as usual (BAU) 2030 scenarios

The business as usual (BAU) 2030 scenarios were developed for the Island of Cres for the year 2030 in order to consider the integration of new diesel engines on fishing vessels. The total energy consumption of the diesel fuel required for 10 fishing vessels was 2.89 GWh/year, whereas for 20 and 30 fishing vessels it was 5.79 GWh/year and 8.69 GWh/year, respectively. The local PV power system capacity of 21 MW was assumed to be installed in the IES. The average monthly values of the electricity demand of the IES, the electricity supply, CDEP, CEEP, and the electricity demand of the fishing port in the BAU 2030 scenarios were obtained from the EnergyPLAN, Fig. 11.

Table 2
Characteristics of the operation profiles.

Period start	01/03/2030	01/06/2030	01/09/2030	01/11/2030
Period end	30/04/2030	31/08/2030	31/10/2030	25/12/2030
Fuel consumption of the fishing trip, l	1127.4	680.1	735.6	453.8
Total time of the fishing trip, h	32	22	32	13
Required battery capacity, kWh	2791.49	1683.96	1821.38	1123.63

The peak electricity demand of the IES occurs in August, which was expected because during the summer months there is an increased number of tourists on the island. The annual values for the BAU 2030 scenarios are listed in Table 4.

In the BAU 2030 scenarios, there is no electricity demand of the fishing port because the fishing vessels are powered with diesel engines, i.e. fishing vessels consume only diesel fuel. The electricity supply from PV power systems in the IES is not sufficient for the electricity demand of the IES in January and December, because solar irradiation is relatively low. The annual investment costs, diesel fuel costs, and maintenance costs are listed in Table 5.

The analysis of the individual costs indicates that 47%, 30%, and 23% of the total IES costs refer to the CDEP costs, while 35%, 46%, and 51% of the total IES costs refer to diesel fuel costs in S1, S3 and S5, respectively. The share of individual annual costs for the BAU 2030 scenarios are shown in Fig. 12.

4.2. Electrification 2030 Scenarios

The electrification 2030 scenarios were developed to demonstrate electrification of the fishing vessels operating around the Island of Cres. Electricity production from the local PV power systems for 2030 was calculated to be 30.63 GWh/year, while the electricity demand of the island was calculated to be 16.99 GWh/year. A lithium-ion battery with a capacity of 2791.49 kWh is required to ensure navigation of the fishing vessel throughout the year. The total electricity demand of the fishing port was 1.65 GWh/year, 3.31 GWh/year, and 4.96 GWh/year in S2, S4, and S6. A comparison of the monthly values of the electricity demand of the fishing port is shown in Fig. 13.

The peak electricity demand of the fishing port for S2, S4, and S6 occurred in March and was 273.77 MWh, 548.27 MWh, and 823.5 MWh (see Fig. 14). The analysis of the monthly values of the electricity demand of the fishing port demonstrates a positive relation with the electricity supply from PV power systems. Moreover, the electricity demand of the fishing port is relatively low during January and December and relatively high during the summer and autumn. Therefore, the integration of electric ships can reduce the CEEP and increase the penetration of RES in the IES. The average monthly values of electricity demand, electricity supply, CDEP, CEEP, and the electricity demand of the fishing port in the electrification 2030 scenarios were obtained from the EnergyPLAN, Fig. 12.

The annual values for the electrification 2030 scenarios are listed in Table 6.

In the electrification 2030 scenarios, there is no diesel fuel demand of the fishing port because fishing vessels are powered with lithium-ion

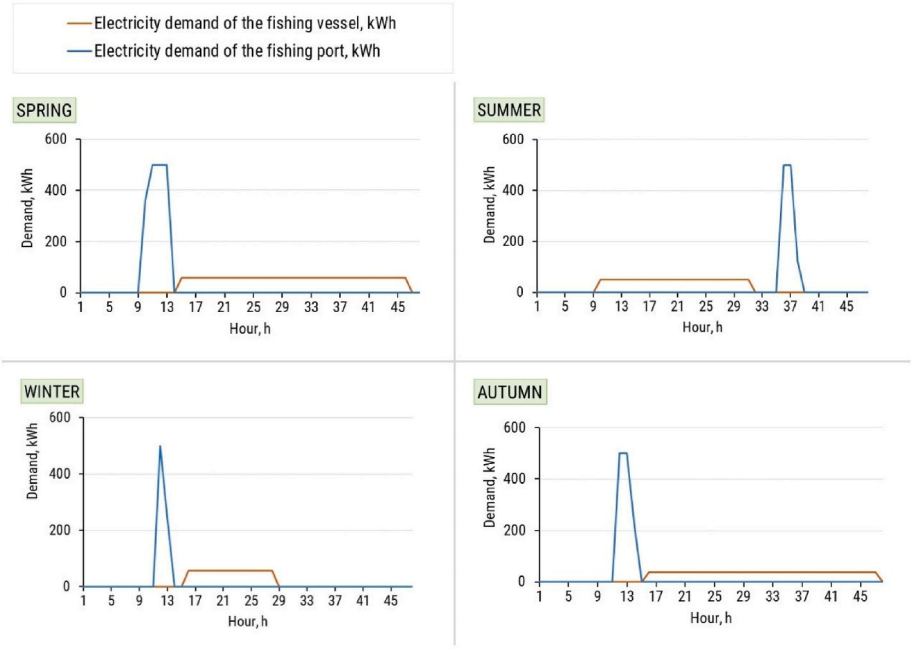


Fig. 9. Electricity demands of the fishing vessel and fishing port.

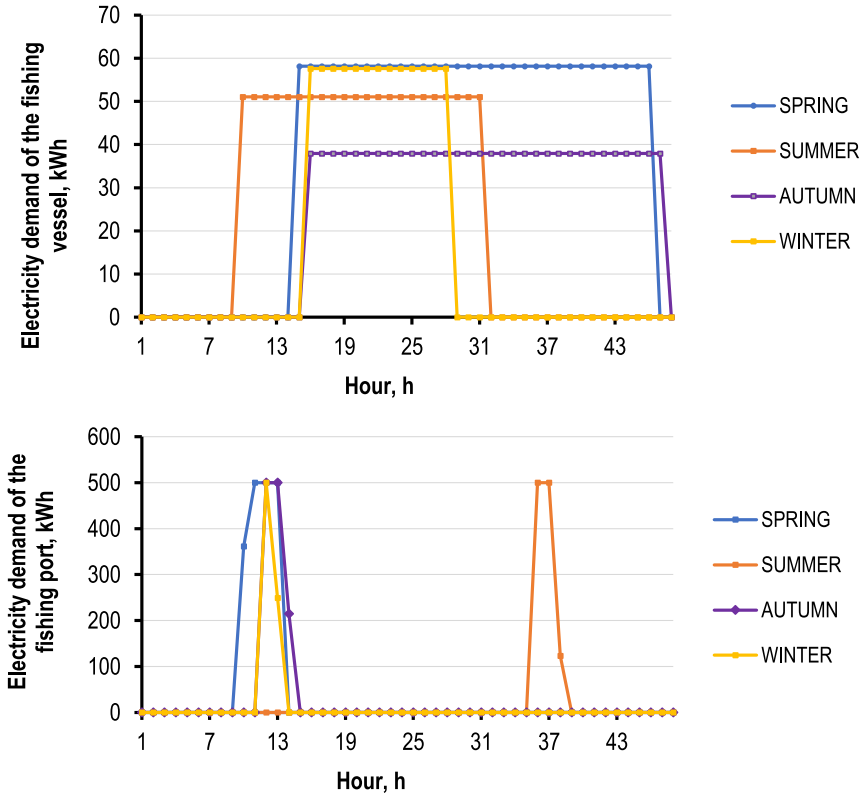


Fig. 10. Electricity consumption of the fishing vessel and electricity demand of the fishing port for each operation profile.

batteries and consume electricity only. The annual electricity costs of the fishing port were €128,964.03, €257,928.06, and €386,892.09 in scenarios S2, S4, and S6. The annual investment costs, electricity costs, and maintenance costs are listed in Table 7.

From an analysis of the individual cost, it can be found that 89%, 61%, and 44% of the total IES costs refer to the CDEP costs, while 6%, 20%, and 28% of the total IES costs refer to the investment costs in the scenarios S2, S4, and S6. The share of individual annual costs for the electrification 2030 scenarios are shown in Fig. 15.

The results demonstrate the potential of the nexus between an all-electric fishing industry and the power system of an IES with a high share of RES. The decarbonization potential of a fishing port with a charging infrastructure for all-electric fishing vessels is quantified by comparing the electrification and BAU scenarios. The results of the BAU

Table 3
Characteristics of the IES scenarios for 2030.

Scenario no.	Scenario name	Electricity demand of the island, GWh/year	Fuel demand of the fishing vessels, GWh/year	Electricity demand of the electric fishing vessels, GWh/year	Installed capacity of the PV unit, MW
S1	Business as usual (10 ships)	17.01	2.90	0	21
S2	Electrification (10 ships)	17.01	0	1.65	21
S3	Business as usual (20 ships)	17.01	5.79	0	21
S4	Electrification (20 ships)	17.01	0	3.31	21
S5	Business as usual (30 ship)	17.01	8.69	0	21
S6	Electrification (30 ships)	17.01	0	4.96	21

scenarios indicate that fishing vessels would release annually 773, 1,542, and 2315 tonnes of CO_2 in scenario 1, scenario 3, and scenario 5, respectively. It is clear that in the case of full electrification of the fishing vessels, these CO_2 emissions are eliminated. The integration of fully electric fishing vessels in the energy system can significantly lower the adverse effects on human health and on the ecosystems, such as arsenic in the groundwater (Koley, 2023). The industry must consider advanced holistic approaches to energy planning to increase the flexibility of renewable-driven energy systems (O'Neill-Carrillo et al., 2018). From a sustainability perspective, the integration of fully electric fishing vessels in the renewable-based energy system of an island can reduce CEEP, operating costs, and CO_2 emissions. This indicates that the sectoral coupling of a fully electric fishing sector and a 100% RES power sector effectively increases the flexibility of the power grid and facilitates the integration of RES.

Several limitations of the study should be indicated. The sizing of the battery storage capacity can be done at different levels of complexity and accuracy. The kind of approach that should be adopted depends on an analysis of the scope and the goals. If we set the analysis boundaries to the ship power system and define the battery size of all-electric (or more complex hybrid) vessels according to the ship energy needs and profile, mathematical programme approaches are certainly needed to obtain optimal solutions, since the approach used here will be rather conservative. However, if we consider the nexus between the fleet of ships and the isolated energy system, this approach seems to be much simpler and more robust. If we adopt a mathematical programme approach to the size of the battery of a single ship, the response of the isolated energy system will be practically marginal (even a 50% difference in the battery size of a single ship will not affect the grid response of the isolated system). While the paper demonstrates battery degradation through increased battery capacity using the adopted approach, the presentation of battery degradation on all-electric fishing vessels is relatively limited. Further research of this topic is important to comprehensively understand the long-term performance and reliability of batteries, as well as to gain a deeper understanding of the battery lifetime, maintenance needs, and strategies to mitigate the degradation effects. The lack of available literature on similar cases of electrification in the shipping fleet is another limitation of the study. The scarcity of comparable studies makes it difficult to benchmark findings and evaluate the study's results in a broader context. This limitation confirms the need for further research into the electrification of fishing vessels. Furthermore, sensitivity assessments of the results with respect to some input data, such as, for instance, the specific fuel consumption of diesel engines, the price of diesel fuel, or carbon allowance rates would also be useful.

5. Conclusion

The electrification of the fishing vessels is an opportunity to reduce emissions and operational costs of the fishing industry. This study demonstrates the nexus between fishing vessels and the power system of an IES with a high share of RES. The results indicate that integrating battery-powered electric fishing vessels in the power system with 100% RES can lead to economic and environmental benefits. This paper considers different scenarios of the energy needs of fishing vessels, ranging from 10, 20, and 30 fishing ships in a fishing port in 2030. The scenarios simulate the operation of the IES, which includes the integration of battery-powered electric fishing vessels in the IES powered by 100% PV

Table 4
Annual values of the BUA 2030 scenarios.

Scenario	BUA 2030 (10 fishing vessels)	BUA 2030 (20 fishing vessels)	BUA 2030 (30 fishing vessels)
Electricity demand, GWh/year	16.99	16.99	16.99
Electricity supply, GWh/year	30.63	30.63	30.63
CEEP, GWh/year	22.76	22.76	22.76
CDEP, GWh/year	9.11	9.11	9.11
Fuel demand of the fishing port, GWh/year	2.89	5.79	8.69

Table 5
Annual investment, diesel fuel, and maintenance costs of the BUA 2030 scenarios.

Scenario	BUA 2030 (10 fishing vessels)	BUA 2030 (20 fishing vessels)	BUA 2030 (30 fishing vessels)
Investment costs of new diesel engine, €	2,125,000	4,250,000	6,375,000
Diesel fuel cost, €	485,763	971,527	1,457,290
Maintenance cost, €	40,552	81,105	121,658
Total, €	**2,651,315**	**5,302,632**	**7,953,948**

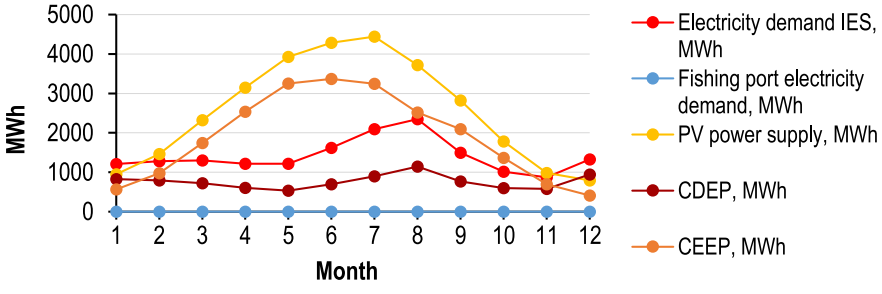


Fig. 11. Average monthly values of the electricity demand, electricity supply, CEEP, CDEP, and electricity demand of the fishing port for the BUA 2030 scenarios.

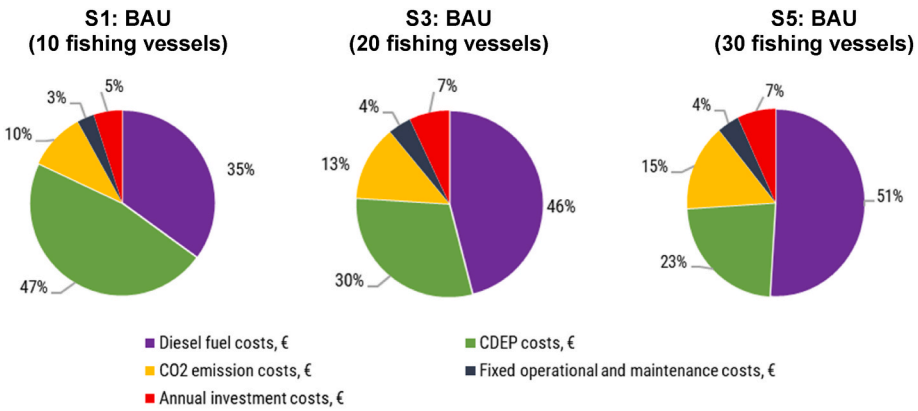


Fig. 12. Share of annual investment costs for the BAU 2030 scenarios (S1, S3, S5).

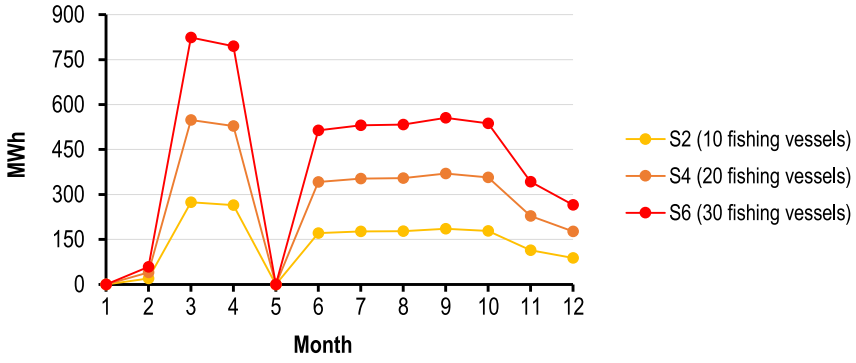


Fig. 13. Monthly values of the electricity demand of the fishing port for S2, S4, S6.

power systems. The paper demonstrates that as the number of battery-powered electric fishing vessels in the fishing port increases, the CEEP of the IES decreases, and vice versa. The results show the following:

Business as usual (BAU) 2030 scenario:

- The total energy consumption of the diesel fuel required for 10 fishing vessels is 2.89 GWh/year, whereas for 20 and 30 fishing vessels the consumption is 5.79 GWh/year and 8.69 GWh/year, respectively.
- The peak electricity demand of the IES occurs during the summer months when there is an increased number of tourists on the island. There is no electricity demand of the fishing port because fishing vessels consume only diesel fuel.
- From the total IES costs, 47%, 30%, and 23% relate to the CDEP costs.
- In S1, S3, and S5, 35%, 46%, and 51% of the total IES costs relate to diesel fuel costs.

Electrification 2030 scenario:

- There is no diesel fuel demand of the fishing port because the fishing vessels are powered by lithium-ion batteries and consume electricity.
- The electricity production from the local PV power systems equals 30.63 GWh/year, while the electricity demand of the island is 16.99 GWh/year.
- A lithium-ion battery with a capacity of 2791.49 kWh is required to ensure navigation of the fishing vessel throughout the year.
- The total electricity demand of the fishing port is 1.65 GWh/year, 3.31 GWh/year, and 4.96 GWh/year in scenarios S2, S4 and S6, respectively. The peak electricity demand of the fishing port for scenarios S2, S4 and S6 occurs in March.
- The electricity demand of the fishing port correlates with the electricity supply of the PV power systems in the IES and reduces the CEEP.
- The annual electricity costs connected to the fishing port are €128,964, €257,928, and €386,892 in scenarios S2, S4 and S6. It can be found that 44%, 30%, and 24% of the total IES costs relate to the CDEP costs, while 28%, 35%, and 38% of the total IES costs relate to the investment costs in scenarios S2, S4 and S6.

The results highlight the need for further research and development in the electrification of fishing vessels, including assessing the technical feasibility, performance, and efficiency of electric propulsion systems in different types and sizes of fishing vessels. The nexus between fully electric fishing vessels and RES in the IES can create benefits such as reducing CEEP, operating system costs, and emissions of CO_2. The establishment of an adequate onshore charging infrastructure with ship-to-grid (S2G) technology is essential to achieve the sustainable decarbonization of the fishing sector and the power sector of an IES. With the development of technology, there is no limitation to coupling a fully electric fishing sector with the 100% RES power sector of an IES.

CRediT authorship contribution statement

Marija Koričan: Conceptualization, Funding acquisition, Data curation, Formal analysis, Writing – original draft, Conception and design of study, acquisition of data, analysis and/or interpretation of data, Drafting the manuscript, revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published. **Lovro Frković:** Conceptualization, Funding acquisition, Data curation, Formal analysis, Writing – original draft, Conception and design of study, acquisition of data, analysis and/or

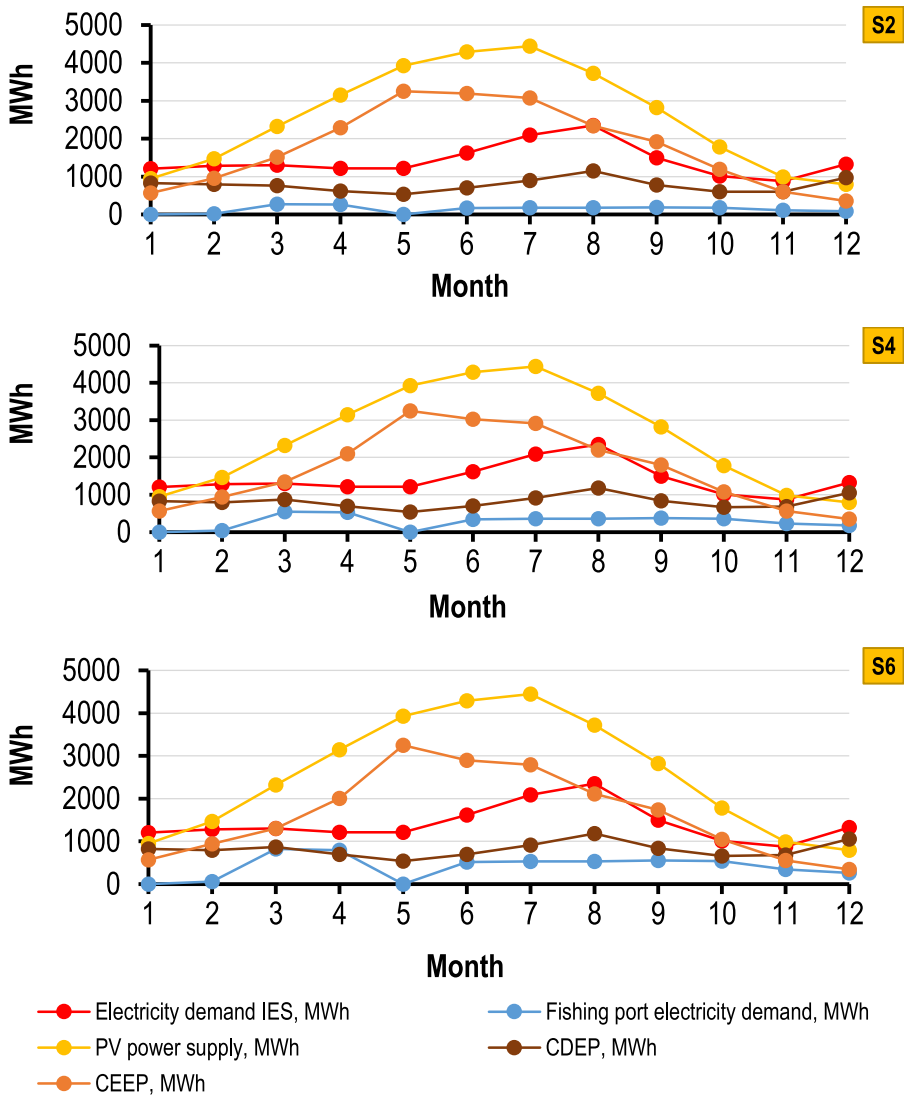


Fig. 14. Average monthly values of the electricity demand, electricity supply, CEEP, CDEP, and electricity demand of the fishing port for the electrification 2030 scenarios.

Table 6
Annual values of the electrification 2030 scenarios.

Scenario	Electrification 2030 (10 fishing vessels)	Electrification 2030 (20 fishing vessels)	Electrification 2030 (30 fishing vessels)
Electricity demand, GWh/year	16.99	16.99	16.99
Electricity supply, GWh/year	30.63	30.63	30.63
CEEP, GWh/year	21.24	20.10	19.53
CDEP, GWh/year	9.24	9.75	10.84
Electricity demand of the fishing port, GWh/year	1.65	3.30	4.95

Table 7
Annual investment, electricity, and maintenance costs of the electrification 2030 scenarios.

Scenario	Electrification 2030 (10 fishing vessels)	Electrification 2030 (20 fishing vessels)	Electrification 2030 (30 fishing vessels)
Investment costs, €	414,000	827,000	1,241,000
CDEP cost, €	650,000	696,000	794,000
Fixed operational and maintenance cost, €	413,000	826,000	1,239,000
Total, €	**1,477,000**	**2,349,000**	**3,274,000**

interpretation of data, Drafting the manuscript, revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published. **Nikola Vladimir:** Conceptualization, Funding acquisition, Data curation, Formal analysis, Writing – original draft, Conception and design of study, acquisition of data, analysis and/or interpretation of data, Drafting the manuscript, revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published.

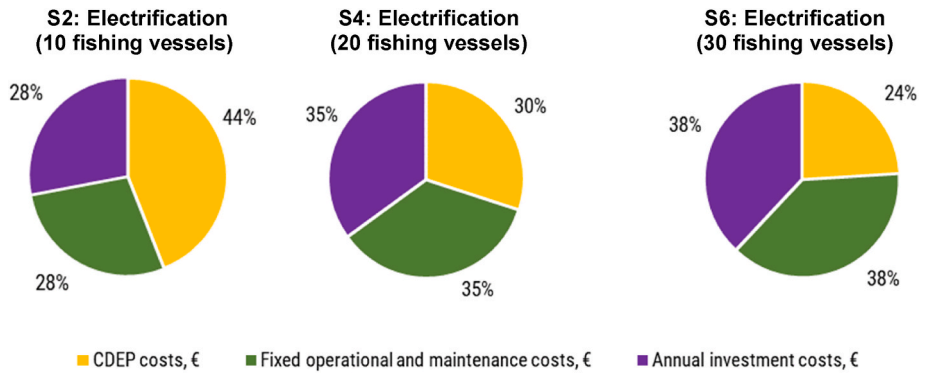


Fig. 15. Share of annual investment costs for the electrification 2030 scenarios (S2, S4, S6).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Life-cycle cost assessment of hull protection technologies considering their effect on the environmental friendliness of fishing vessels

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ABSTRACT

Biofouling represents a global challenge for the maritime industry, affecting vessel performance and environmental footprint. This paper analyses various antifouling technologies to reduce the vessel's environmental impact and its operating costs by reduced fuel consumption and less frequent dry-docking. It evaluates both passive and active technologies – passive referring to antifouling coatings and active involving systems that continuously prevent biofouling using energy. The methodology employs mathematical models to quantify the additional resistance and emissions caused by biofouling. Using the case of a fishing vessel operating in the Adriatic Sea, operational features and potential economic and environmental benefits resulting implementing an innovative biofouling protection system are analysed. Economic analysis includes a comprehensive cost structure, investment details, maintenance and operating costs, and possible future carbon taxation scenarios. The research indicates that active antifouling protection is more efficient than passive protection, including a potential reduction of the required power of up to 120 kW, leading to decreased fuel consumption and lower environmental impact, particularly at higher speeds. Despite higher initial investments, life-cycle cost analysis favours active protection systems.

Nomenclature

Variables	
A	quality of antifouling protection
AF	total cost of antifouling coating (EUR)
AHR	average hull roughness
AP	acidification potential (kg $SO_{2\text{-eq}}$)
B	lifespan of antifouling protection
CA	carbon scenario
C_{ef}	Efficiency coefficient
CS	roughness allowance
EF	emission factor (g emission/kg)
E_i	emission (kg emission/kg fuel)
EI	environmental footprint
EP	eutrophication potential (kg $NO_{2\text{-eq}}$)
FC	fuel consumption (kg/kg fish)
GWP	global warming potential (kg $CO_{2\text{-eq}}$)
h_i	increase in roughness
k	form factor
$LCCE$	life-cycle emission costs (EUR)
$LCFC$	life-cycle fuel cost (EUR)
L_{WL}	length at the waterline
N	Total number of elementary surfaces
n	number of coating layers
P	main engine power (kW)
p_i	attachment probability
PR	price (EUR)
r_i	growth rate of certain species
S	wetted surface area
SFC	specific fuel consumption (kg/kWh)
t	time
v	speed (kn)
V	quantity of coating (l)
X	uniform random variable between 0 and 1
α, β, γ	weighting factors
ΔP	increase in engine power (kW)
ΔP	increase in main engine power
η	propulsion efficiency
ρ	density (kg/m^3)

Abbreviations	
APS	Announced Pledges Scenario
CF	Carbon Footprint
ETS	Emissions Trading Scheme
GFCM	General Fisheries Commission for the Mediterranean
GHG	Greenhouse Gas

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GPS	Global Position System
IMO	International Maritime Organization
LCCA	Life-Cycle Cost Assessment
MGPS	Marine Growth Protection System
MRV	EU's Monitoring, Reporting and Verification system
NZES	Net Zero Emissions Scenario
SPS	Stated Policies Scenario
Subscripts	
A	annual
D	docking
d	diesel fuel
ef	efficiency
FO	biofouling
NB	initial roughness of vessel hull
S	service
wet	wetted surface area
WL	waterline

1. Introduction

1.1. General on biofouling in the shipping sector

Biofouling represents the attachment of undesirable molecules, microorganisms, algae, and marine organisms to submerged structures such as vessels and offshore structures (Knobloch et al., 2021). Its negative effects include increased resistance of vessels, failure of vessels' internal seawater systems, mass gains of offshore structures, and acceleration of corrosion processes on submerged metal and concrete structures in general (Juraga et al., 2012). On the biological side, it also represents a threat to the environment since invasive species are transferred from one location to another and can cause changes in flora and fauna (Costello et al., 2022). High fouling variability is especially emphasized in busy, touristic harbours, making them susceptible areas for further spread at a local level (Tempesti et al., 2022).

Upon initial contact between surfaces and the marine environment, bioufouling rapidly commences regardless of the material type. The available research results prove that the biofouling process begins within the first few hours after vessel launching, as seen in Fig. 1 (International Maritime Organization, 2023). The process is usually divided into two primary stages including microfouling and macrofouling. Microfouling includes rapid colonization by marine bacteria, leading to the formation of a bacterial biofilm on the surface while macrofouling stands for the attachment of organisms such as barnacles, mussels, soft corals, and seaweed (Hayek et al., 2021). Microfouling alone can increase fuel consumption by up to 18 % and decrease sailing speed by a minimum of 20 % (Trepos, 2016). The biofouling process is highly dynamic and is affected by various factors including sea currents, salinity, temperature, insolation, pollution levels, concentration of nutrients, mechanical damages, and others (Trepos, 2016).

1.2. Impact of biofouling in the shipping sector with a focus on fishing vessels

Biofouling of the vessel's wetted surface is thus reflected directly in its performance, mainly in the increase of hydrodynamic resistance and decrease of propeller efficiency. Juraga et al. (2012) estimated that slime on the wetted surface results in a resistance increase of 1–2 %, while (International Maritime Organization, 2022a) showed that a thin layer of slime of approximately 0.5 mm covering up to 50 % of a hull can increase Greenhouse Gas (GHG) emissions by 20 % to 25 %, depending on the specific characteristics of the vessel, its speed, and other prevailing conditions. In the case when seaweed is present, the increase of resistance is estimated to be about 10 %, while benthic organisms situated at the bottom and alongside the wetted surface of a vessel can cause an increase in resistance of up to 40 % (Juraga et al., 2012) boosting growth in GHG emissions up to 55 % (International Maritime Organization, 2023). In the case of hard fouling, Farkas et al. (2020) investigated the increase of frictional resistance coefficient for merchant ships. In case of a container ship, their results showed an increase from 77.5 % to 144.5 % depending on the severity of the fouling, while in the case of a crude carrier, the increase ranged from 66.7 % to 126.2 %. The research by Uzun et al. (2020) also showed an increase in frictional resistance due to barnacle fouling, however, it also showed the impact of settlement patterns and coverage ratios. For example, for 10 % surface coverage of mixed barnacles, frictional resistance increases by approximately 52 %, while natural (chaotic) settlement patterns cause a 63 % increase. The highest percentage increase is noticed in the case of mixed configuration with 50 % coverage area when frictional resistance increases by 194 % (Uzun et al., 2020). Biofouling assessment reveals that it reduces a vessel's speed by about 10 %. Alternatively, it will induce an increase in fuel consumption by up to 40 % when maintaining operational speed (Ahmadzadehtalatapeh and Mousavi, 2015). In the case of relatively slow vessels, like the majority of cargo and fishing vessels, the proportion of frictional resistance in total resistance can reach up to 90

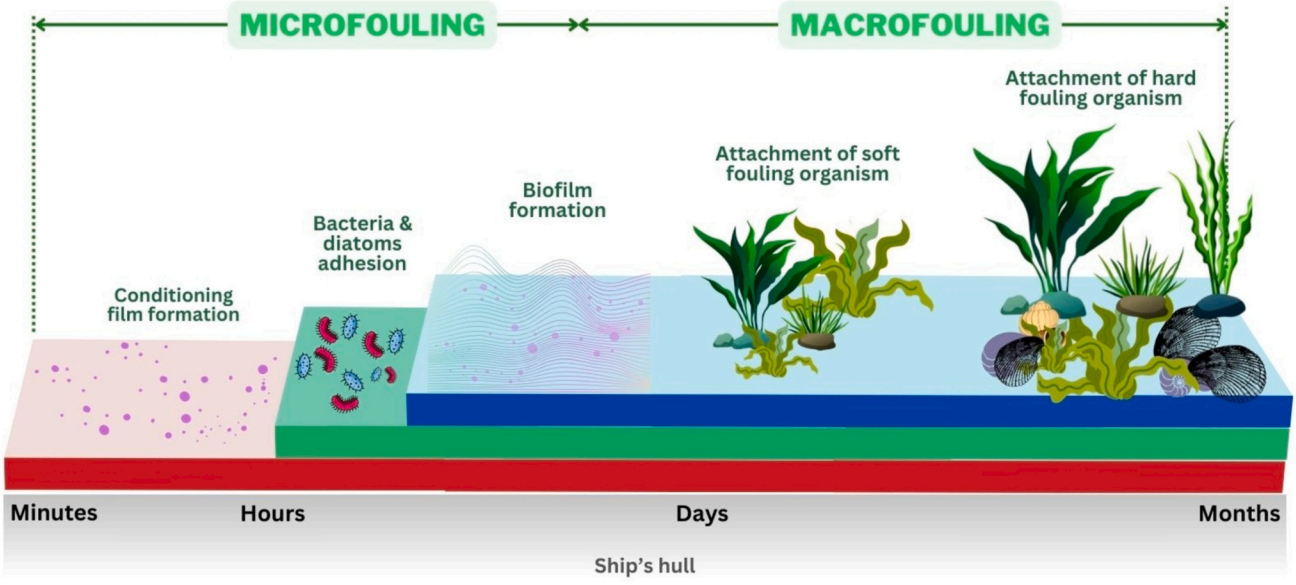


Fig. 1. Biofouling formation (Romeu and Mergulhão, 2023).

% (Juraga et al., 2012), mostly due to biofouling and surface wear, thus increasing the vessel's hydrodynamic drag. The research on energy-intensive vessels like trawlers indicates that even a very thin, invisible layer of slime on the hull surface can cause an increase in fuel consumption by 8 % or more, while more significant accumulations of marine life lead to fuel consumption spikes exceeding 18 % (Notti et al., 2019). In addition, the life-cycle assessment of fishing vessels concerning economic aspects and the associated environmental impacts pointed out a strong relationship between engine power requirements and different antifouling and maintenance scenarios. Namely, the research results showed an increase in the required power of the main engine by 53 % in the case without hull cleaning, between 19 and 53 % with hull cleaning intervals of 1, 2, 3, and 5 years, and by 0.3 % in the case of regular maintenance of the fouled surface employing an underwater robot (Song et al., 2021).

1.3. *Antifouling technologies*

Antifouling protection based on various technologies is one of the key factors leading to energy-efficient sailing and vessel operation. Conventional protection systems include hull coating using antifouling paints to deter the attachment and growth of marine organisms. These coatings often contain biocides or other substances that prevent biofouling and can be, in most cases, associated with a highly negative environmental impact. For instance, Soon et al. (2021) investigated the release of antifouling paint residues containing toxic substances during hull cleaning and showed that copper and zinc concentrations in the effluents were 209 μg/L and 1510 μg/L. Concentrations vary but pose a clear risk to the marine environment unless wastewater is collected or treated before discharge. Therefore, an alternative technology for biofouling prevention based on electric power devices and ultrasonic vibrations was developed recently following the concept of impressed current cathodic protection normally used for vessel hulls. A visual comparison of passive and active antifouling technologies is presented in Fig. 2.

Protective coatings are a common passive method to ensure long-term protection of structures exposed to harsh conditions such as marine environment and aggressive chemicals. There are different categories of coatings, such as biocidal and non-biocidal, hydrophobic or nano-coatings (Jiang et al., 2011). In this paper, antifouling coatings are divided on traditional, organotin compounds (tributyltin compounds, TBT), and novel (biocide, non-biocide or foul-release, hydrophobic).The primary purpose of a coating is to form a barrier (solid film) between the metal material and the environment, which requires high coating stability and durability conditioned to the operating conditions of the structure. A typical coating protection system includes a primer layer, one or more intermediate layers, and a topcoat, each performing its specific function (Juraga et al., 2012). In such a context, passive antifouling technology represents a special type of coating containing organic substances like organotin compounds or biocide elements like copper and zinc or their compounds with other elements that, when applied to the wetted surface of vessels, prevent or reduce the attachment of various marine organisms to the hull.

Tributyltin (TBT) compounds were essential in antifouling coatings, significantly reducing fuel consumption and maintaining smooth hydrodynamic profiles. However, their release into seawater has caused environmental harm, leading to a ban on TBT and a shift toward copper and zinc-based biocidal coatings (Ali et al., 2020; International Maritime Organization, 2023). Current biocidal coatings are based on copper or zinc. The coatings release biocides into marine environment, potentially affecting marine organisms (Pistone et al., 2021). However, the release of copper from a coating can harm the marine biosystem, and can accumulate in marine organisms by penetrating the food chain. Due to the potential harm, many countries have strict regulations and restrictions on the use of copper coatings and some are even banned or subject to special guidelines to reduce their environmental impact (Srinivasan and Swain, 2007; Lagerström et al., 2020). For example, a number of USA states enacted a phased-in ban on coatings containing >0.5 % copper since 2011, and the EU Biocide Regulation (528/2012/EC) regulates the use of biocides to ensure safe use, protect human health and the environment while facilitating the approval and monitoring of biocidal products within the European market (McNeil, 2018). Although their use is limited, the sampling conducted by Vanavermaete et al. (2023) showed a specific contamination pattern of booster biocides in each investigated port and harbour, such as Irgarol, Diuron, and Dichlofluanid in fishing fleets. Due to the variability and differences in biological impact depending on the concentration and size of the biocide particles, knowledge is still limited and further research and monitoring are needed to determine their impact on the marine environment (Turner, 2010; Soon et al., 2021; Vanavermaete et al., 2023).

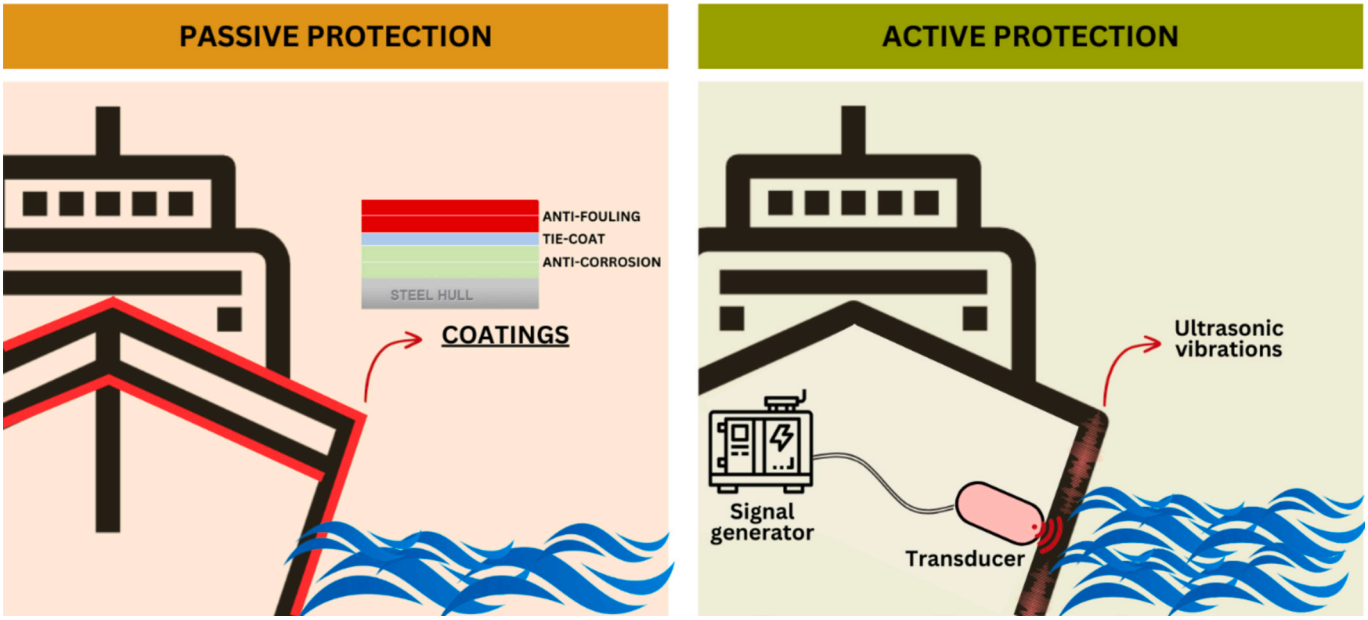


Fig. 2. Comparison of passive and active antifouling technologies.

Growing awareness of the harmful environmental effects of toxic biocides has stimulated the development of non-toxic, eco-friendly alternatives, including fouling-release coatings that use polymers (such as silicones and fluoropolymers), waxes, oils, etc. (Maan et al., 2020). Unlike biocidal coating, foul-release coatings utilize special surface characteristics to prevent or facilitate the detachment of marine organisms from the surface of the vessel and have a lesser impact on the marine environment and do not cause environmental harm associated with biocide release (Juraga et al., 2012; Ahmadzadehtalatapeh and Mousavi, 2015). Lin et al. (2024) investigated the relation between cleaning processes and the ageing of foul-release coatings to improve marine fouling management practices. Their research showed that early-stage cleaning of newly applied foul-release coatings is crucial for preventing biofouling, specifically barnacle adhesion. Since foul-release coatings degrade over time due to environmental exposure, resulting in decreased performance and increased biofouling attachment, optimizing underwater cleaning methods helps mitigate degradation and enhance the lifespan (Lin et al., 2024). There are ongoing research focusing on improving the performance and durability of foul-release coatings, from using nanoparticles (Selim et al., 2017) to silicon-based coatings (Ba et al., 2018; Lagerström et al., 2022). However, foul-release coatings tend to be priced higher than traditional antifouling coatings, due to their advanced technology and eco-friendly nature (Kim, 2021; Lagerström et al., 2022).

Recent advancements in fouling technologies have focused on sol-gel techniques to create hydrophobic coatings. These coatings, comprised of fluorinated and alkyl-alkoxysilanes of varying chain lengths, form a smooth layer that hinders organism adhesion to surfaces (Cardiano et al., 2010; Rosace et al., 2018; Hu et al., 2020). Due to the weak bond between the surface and coating, biofouling can be easily removed underwater through cleaning or hydrodynamic forces during navigation (Nendza, 2007). These coatings offer a non-toxic alternative to traditional biofouling coatings that rely on biocides, making them increasingly popular for marine applications.

Marine Growth Protection System (MGPS) refers to a protection system against the development and growth of biofouling on the wetted surface area of a vessel. It includes various technologies that prevent or minimize the colonization of the vessel's wetted surface by marine organisms, including algae, shellfish, and benthic organisms, to preserve the hydrodynamic properties of the vessel and reduce fuel consumption. MGPS systems are also suitable for protecting seawater systems (used for supplying the vessel with fire extinguishing water, ballast, cooling, and heat exchange), which are susceptible to heavy biofouling as they are inaccessible for coating and continuous maintenance (Arndt et al., 2021). Depending on the design, an MGPS system can act as either biofouling prevention or a system for mitigation and removal of attached organisms (Grandison et al., 2012). Amongst different MGPS systems, the focus here is on Impressed Current Cathodic Protection (ICCP) and ultrasonic protection systems only.

ICCP actively creates a protective electrochemical potential on the metal hull of the vessel and represents an efficient system for protecting vessels from corrosion in seawater (Mrdović and Ivošević, 2023). The material is protected by directing electrons toward the metal (cathode) via a direct current's negative pole until its potential drops below the anode's equilibrium potential in the corrosive medium, preventing corrosion and ensuring metal immunity. While typical metal structures have a negative potential of around −800 mV, practical cases reveal potential oversaturation below −1.05 V, leading to excessive currents, accelerated anode consumption, and coating damage (Tezdogan and Demirel, 2014; Xu et al., 2021). The ICCP system enables efficient control of the electrical potential, preventing corrosion and reducing biofouling by marine organisms. Cathodic protection, together with coatings, represents the most common method of vessel hull corrosion prevention. Its effectiveness depends on the protective layer of coating that separates the material from the environment, and cathodic protection that reduces the influence of external factors through electrical potential regulation. As for drawbacks, the ICCP system requires the presence of experts to monitor and maintain the current flow within optimal limits, as well as a continuous power supply. Next to this, there is a need for a high amount of anode material, which replacement in case of malfunction under marine conditions is difficult (Kirchgeorg et al., 2018).

Acoustic energy, such as ultrasound, is also considered a non-toxic method for antifouling protection. These techniques use transducers that emit mechanical waves with operating frequencies ranging from audible (20 Hz - 20 kHz) to ultrasonic (above 20 kHz) frequencies (Legg et al., 2015). Multiple transducers can be used simultaneously to create a series of signals and optimize effectiveness (Habibi and Gan, 2016). Pulsed acoustic energy generated by electrical discharge causing electro-hydraulic shock and transmitted through the vessel's structure, has the potential to reduce biofouling in marine water systems (Brizzolara et al., 2003). The effectiveness of acoustic protection systems is demonstrated in several studies (Grandison et al., 2012; Knobloch et al., 2021; Legg et al., 2015), and the best results were achieved for frequencies between 20 and 50 kHz. Despite its non-toxicity and other advantages, ultrasound can be observed as anthropogenic noise that could negatively impact the marine environment by affecting the behaviour of marine organisms (Knobloch et al., 2021).

1.4. Hull maintenance and protection

Vessel maintenance and corrosion prevention play a key role in the safe and efficient use of vessels but are also an important factor in the overall cost structure. The occurrence of biofouling directly increases maintenance costs as its removal and control require more frequent dry-docking, including hull water jetting, surface conditioning, coating application, and others. However, the available research shows that the application of coatings to an industrial fishing vessel can yield savings from 3.11 % to 10.26 % in total fuel consumption over a fishing season in the General Fisheries Commission for the Mediterranean (GFCM) area, depending on the coating type (Ozyurt et al., 2023). Although the coatings may not have high prices, their required quantity depends on the type of coating and the wetted surface area that needs to be covered. In addition, coating protection entails additional costs such as labour, equipment for surface preparation, solvents, electricity, fuel, waste disposal, etc. (Venettacci et al., 2023). In the case of more frequent inspections and maintenance of coatings, additional costs need to be taken into account because dry-docking outside of regular service schedules is often not economically feasible or logistically possible for owners and operators of larger vessels (Sonak et al., 2010; Arndt et al., 2021). At the same time, there is a risk of profit loss due to idle costs. Despite the costs, Wu et al. (2022) showed that underwater cleaning reduces fuel consumption by 10.1 %, while vessel dry-docking reduces it by 16.1 %, which is not negligible. Active protection methods have several advantages as compared to coatings. Besides being environmentally friendlier (no harmful chemicals, reduced fuel consumption), they provide continuous protection of the vessel's hull without the need for frequent dry-dockings (Lais et al., 2017). An additional advantage is that they can be used on various surfaces, including vessel hulls, floating platforms, and parts of facilities that are difficult to maintain with coatings. Consequently, maintenance costs are reduced because there is no need for regular renewal of antifouling coatings. Of course, according to the Rules for the classification of ships (Croatian Register of Shipping, 2022), ships over 100 GT need to maintain the validity of the certificate of class every 5 years. Renewal of classification licenses implies that the ships meet the minimum requirements, such as properly maintained equipment and no damage or excessive waste of the ship's structures. In addition to this, ships also have to renew the Certificate of Seaworthiness, which requires dry-docking of vessels from 12 to 24 m length at least once in five years (Official Gazette of Republic of Croatia, 2012).

Each biofouling prevention system must be properly supervised and maintained for efficient operation. Usually, supervision includes regular

visual inspections that enable early detection of corrosion or coating damages and prompt interventions, while maintenance includes water jetting, mechanical or ultrasonic hull cleaning, and coating application in line with the requirements of classification societies (Wang et al., 2018a, 2018b; Maduka et al., 2023). When considering technologies for biofouling prevention, it is crucial to acknowledge that there is no universal approach suitable for all conditions. Therefore, it is necessary to weigh the associated investment and operational costs, technology applicability depending on the vessel type, the vessel's operational modes including idle time, navigation area, and speed, the expected lifespan of the protective system, regulations, and other factors. In this context, an increasing number of emerging technologies intend to reduce biofouling and improve the overall performance of the vessel. This fact enables us to establish comprehensive hull protection strategies, ensuring the endurance and efficiency of the vessel while simultaneously reducing its environmental impact.

When discussing the impact of different antifouling technologies on fuel consumption and accompanying emissions of harmful gases, Life-cycle Assessment (LCA) is used a common tool to make informed decisions about which antifouling technologies provide the best balance between operational cost savings and environmental benefits. Such research is provided by Uzun et al. (2019) who investigated the effects of ship operating profile and route on the fuel penalty due to biofouling accumulation, in three case studies. Depending on the number of idling days, the increase in effective power ranges 20–86 %, resulting in extra fuel costs from 5.3 mil. USD to 21.2 mil. USD and total CO_2 emission from 539 mil. kg to 566 mil. kg emissions. Similar research was conducted by Wang et al. (2018b), who carried out a LCA analysis using GaBi software to investigate the environmental impact of hull maintenance for a short-route ferry. While considering the hull degradation, the re-coating interval and costs of CO_2 emissions which incurred during hull maintenance, the case study showed that the optimal interval for steel renewal is 10 years. It was found that more frequent re-coating intervals result in lower life cycle costs and showed the correlation between cost and environmental impacts related to ship hull maintenance strategies. When comparing different antifouling coating, one with copper and other with zinc biocides, it is revealed that the production phase has the highest environmental impact ranging from 70 % to 90 % of total impact (Rossini et al., 2019). On the biotoxicity level, both coatings showed a high release of biocides to the water, accompanied with other heavy metals. Authors Demirel et al. (2018) investigated a silicone-based fouling-release coating and a tin free self-polishing antifouling paint, applied on a tanker over a 30-year life-cycle. The silicone-based coating lead to fuel saving due to mitigation of fouling, resulting in lower overall emissions of 3 % and cost reduction in approximately 2.5 %, compared to the self-polishing one.

1.5. Aims and novelty of the paper

Given the presented literature review, the following research gaps in the field of biofouling protection technologies for marine vehicles can be identified:

- Even though there is a number of well-known technologies, their long-term efficacy and durability are still under-researched;
- The available literature often omits data on the effectiveness of different antifouling technologies in different types of vessels and operating conditions;
- The lack of data is particularly highlighted in the fishing sector, where the unique operational characteristics and environmental conditions are often left unmarked;
- The International Maritime Organization issued guidelines for the control and management of biofouling on vessels to mitigate the transfer of invasive species and improve energy efficiency and emission reduction (International Maritime Organization, 2022b), applicable to all fleets. However, it does not provide information on the duration of protection and how its selection affects long-term costs.

Hence, further research is needed to develop biofouling management strategies to meet the specific needs and challenges of the fishing sector, considering factors such as vessel design, gear type, operational practices, and regulatory requirements. Assessing the economic viability is essential during the selection of antifouling technology. Besides ensuring optimal vessel performance and productivity, as well as the efficiency of the protection in the long term, it is necessary to assess the total costs of the selected antifouling system to choose the most economically favourable one. The costs include not only investment costs, but lifetime realizable costs that include maintenance costs and fuel costs, all of which biofouling impacts directly and indirectly.

Two fundamental approaches to the prevention of biofouling effects are considered in this study. The first one takes into account passive protection systems like conventional coating applications, while the second one includes an active protection approach. In both cases, the applied mathematical models demonstrate their effectiveness concerning the increase of hull resistance and the direct impact on emissions. A novel methodology is implemented to evaluate the vessel powering demand conditioned to biofouling dynamic development while assuming the biofouling of the wetted surface only. A 54-month-long operative horizon of a purse seiner is considered and the impact of biofouling on its required power is estimated. Given that, two preventive technologies are compared concerning the associated perspective of their environmental impact in terms of atmospheric emissions and the economic aspect through a comprehensive analysis of total costs. The environmental analysis results in the value of the annual emissions depending on the sailing speed as a prevailing factor associated with fishing vessels. Following environmental regulations and guidelines for achieving net-zero emission production, the calculated emissions are further employed to estimate the carbon tax, which can have a significant impact on the total costs in the future, depending on the particular scenario. In addition to the carbon tax, a life-cycle cost assessment is carried out to gain insight into the overall cost structure, taking into account the impact of biofouling on fuel and maintenance costs for both passive and active prevention technologies.

2. Methodology

This paper presents the effect of biofouling on the roughness of the vessel's wetted surface and its accompanying side effects, according to the work diagram shown in Fig. 3. The research starts with data gathering, using experimental and numerical methods, followed by the assessment of wetted surface roughness and added resistance and effective power. After assessing the increase in power, its influence on fuel consumption is analysed. The environmental assessment gives a better understanding of the emissions released during navigation, while the economic assessment compares the overall costs of implementing active or passive protection. Carbon taxation is also calculated for both antifouling technologies and included in overall costs. Based on the obtained results, it will be possible to give recommendations to ship owners or shipbuilders on which antifouling system would suit them better while taking into account total costs and environmental friendliness in the long term.

2.1. Assessment of added resistance and effective power

Added resistance and the effective power of the main engine, highly depend on the roughness of the wetted surface area, which can be mathematically defined by employing the well-known Rt_{50} definition standing for the difference between the highest and lowest point of the observed 50 mm long and 50 mm wide elementary surface profile. From a theoretical perspective, this kind of approach correlates well with the roughness function in the case of moderately rough surfaces with $Rt_{50} <$

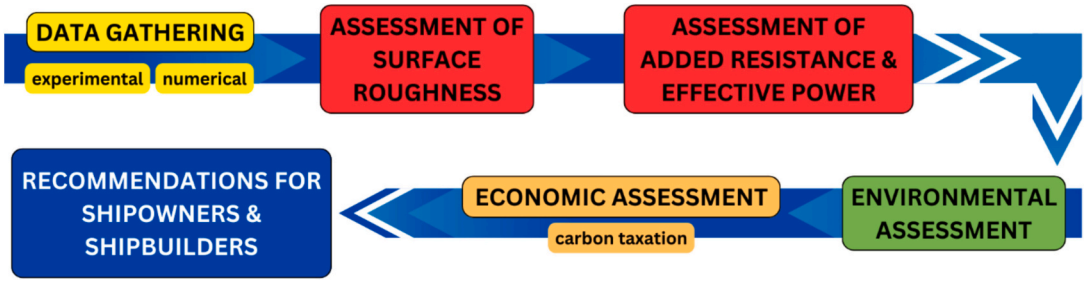


Fig. 3. Workgraph of the presented research.

230 μm (Townsin, 2003; ITTC, 2011). However, such constraint may be significantly below the requirements of realistic biofouling associated with larger peak-to-through heights or even additional implications such as roughness density, frontal solidity, slope, skewness, and others (Chung et al., 2021). On the other hand, the average hull roughness (AHR) approach based on the Rt_{50} concept proved to be sufficiently accurate in the case of practical wetted surface area roughness evaluation yielding sufficiently accurate results both in terms of full-scale measurements and computational fluid dynamics models (Hadžić et al., 2022). Thus, the average hull roughness is defined as a roughness parameter reflecting the surface roughness profile, which differs from the standard average profile height (R_a) defined as the arithmetic average along the line.

The average hull roughness may thus be determined as a ratio $AHR = \sum_{i=1}^{N} Rt_{50,i}/N$, where N marks the total number of elementary surfaces (Schultz, 2007). Although this approach may seem rather simplified it enables efficient evaluation of vessel techno-economic properties conditioned to the dynamic of biofouling development. In that way, the wetted surface roughness may be defined as a superposition of four different roughness sources concerning vessel operation and maintenance as (Hadžić et al., 2022)

$$AHR = AHR_{NB} + AHR_S + AHR_D + AHR_{FO} \tag{1}$$

where AHR_{NB} is the initial roughness of the vessel hull, AHR_S service roughness, AHR_D docking roughness, and AHR_{FO} biofouling roughness. The initial or newbuilding roughness, AHR_{NB}, stands for the surface roughness of structural elements of the wetted surface as built in the shipyard. Thus, depending on the hull material, it may take a value between 70 and 100 μm. The service roughness, AHR_S, represents the roughness induced by deteriroration of the ship's hull due to its service. Hence, it can be empirically estimated to a rate of 2.8 μm per month of vessel's service. Similarly, the docking roughness, AHR_D, represents the deterioration of the hull surface due to its cleaning and other docking operations and can be estimated to about 14 μm per docking (Hadžić et al., 2022). The biofouling roughness, AHR_{FO}, due to its complexity and dominating contribution to the average roughness of the wetted surface requires special attention. First, it should be noted that biofouling roughness depends on the navigation areas and species involved influencing the dynamic of attachment and growth of marine organisms. In addition, the roughness induced by biofouling effects depends on the quality of the antifouling protection prohibiting its increase to a certain extent.

The dynamic of biofouling can be defined by employing the attachment probability, $p_i(x, y, z, t)$, and growth rate of certain species in time, $r_i(x, y, z, t)$, depending on the species i, the observed zone of the wetted surface and the season (e.g. month). Thus, vessels of different hull forms are also expected to have different attachment probabilities and growth rates. The attachment probability and species growth rates must be determined empirically or experimentally. This research takes into account the values for the Adriatic Sea obtained by full-scale measurements including green algae, tube worms, and balanidae as the most frequent marine growth species. The associated attachment probabilities and growth rates are presented in Tables 1 and 2 depending on a particular zone of the wetted surface of a vessel, Fig. 4 (Hadžić et al., 2022).

The efficiency of the antifouling protection plays a vital part in the dynamic of biofouling development, regardless of the antifouling technology type. It can be taken into account using the efficiency coefficient defined similarly to the Prandtl tip loss function as:

$$C_{ef} = \frac{2}{\pi} arccos\left[(Ae)^{-\frac{t}{B}}\right], \tag{2}$$

where A denotes the quality of the antifouling protection concerning coating technology and B the lifespan of the protection. The coefficient A is determined based on in-situ coating surveys and is defined in the range between 1 and 10 where 1 denotes excellent quality and 10 poor quality of the coating technology. By combining eq. (2) and parameters $p_i(x, y, z, t)$ and $r_i(x, y, z, t)$, the increase in roughness, h_i, on the elementary surface associated with species i equals

$$h_i = \begin{cases} C_{ef} r_i, X > p_i, \\ 0, X \le p_i, \end{cases} \tag{3}$$

where X marks the uniform random variable between 0 and 1. Thus, the biofouling roughness AHR_{FO} equals:

$$AHR_{FO} = \frac{1}{N}\sum_{i=1}^{N} C_{ef} r_i \Delta t, \tag{4}$$

where Δt marks the time elapsed from a successful attachment (in months).

Finally, the increase of the main engine power due to roughness induced by biofouling and deterioration effects equals

$$\Delta P = \frac{1}{2}\frac{\rho v^3 S \Delta C_F}{\eta} \tag{5}$$

where ρ denotes the density of seawater, v navigation speed, S wetted surface area, η propulsion efficiency and ΔC_F, the roughness allowance determined as

$$\Delta C_F = 0.044[1 + k]\frac{AHR_{j+1}^{\frac{1}{3}} - AHR_j^{\frac{1}{3}}}{L_{WL}^{\frac{1}{3}}} \tag{6}$$

where k is the form factor and L_{WL} is the length at the waterline (ITTC, 1978).

2.2. Environmental assessment

The environmental footprint represents a measure of GHG emissions and other harmful gases resulting from certain operations or activities, in this case, fishing operations. In the context of maritime transport, it is used to assess the environmental impact, especially emissions of CO_2, CH_4, N_2O, and other gases like SO_X and NO_X, which contribute to climate change (Koričan et al., 2023; Perčić et al., 2023). The

Table 1
The attachment probability in the case of green algae, tube worms, and balanidae in the Adriatic Sea (Hadžić et al., 2022).

	Type	Green algae, p_1		Tube worm, p_2		Balanidae, p_3	
	Zone	1–3, 7–9, 13–15 Bottom	4–6, 10–12, 16–18 Alongside	1–3, 7–9, 13–15 Bottom	4–6, 10–12, 16–18 Alongside	1–3, 7–9, 13–15 Bottom	4–6, 10–12, 16–18 Alongside
Month	January	1	1	0	0.125	0	0.062
	February	1	1	0.375	0.062	0.062	0.187
	March	1	1	0.562	0.125	0.125	0.500
	April	1	1	0.875	0.312	0.062	0.562
	May	1	1	0.750	0.312	0.187	0.625
	June	1	1	0.937	0.437	0.312	1
	July	1	1	1	0.562	0.312	1
	August	1	1	1	0.812	0.375	1
	September	1	1	0.937	1	0.250	1
	October	1	1	0.750	0.312	0.125	0.250
	November	1	1	0.375	0.250	0.187	0.562
	December	1	1	0.062	0	0.125	0.062

Table 2
Growth rates in the case of green algae, tube worms, and balanidae in the Adriatic Sea (Hadžić et al., 2022).

Type		Green algae, r_1, [mm/month]	Tube worm, r_2, [mm/month]	Balanidae, r_3, [mm/month]
Zone	1	0.0375	1.666	0.666
	2	0.0375	1.666	0.500
	3	0.0375	1.666	0.500
	4	0.0375	1.666	0.500
	5	0.0375	1.666	0.166
	6	0.0375	0	0
	7	0.0375	1.250	0.666
	8	0.0375	1.250	0.666
	9	0.0375	2.083	0.666
	10	0.0375	0.833	0.250
	11	0.0375	0	0
	12	0.0375	0	0
	13	0.0375	0.416	0.833
	14	0.0375	0.416	0.250
	15	0.0375	0.416	0.250
	16	0.0375	0.416	0.250
	17	0.0375	0.833	0.333
	18	0.0375	0	0

environmental footprint *EI* can be calculated by the equation:

$$EI = \alpha \bullet GWP + \beta \bullet AP + \gamma \bullet EP \tag{7}$$

where *GWP* (Global Warming Potential) denotes the potential for global warming, i.e., the impact of CO_2, CH_4, and N_2O emissions – the higher the value, the greater the impact on global warming. *GWP* can be calculated using the following equation and expressed as the equivalent emission of CO_2 (kg $CO_{2\text{-eq}}$):

$$GWP = 1 \bullet E_{CO2} + 26 \bullet E_{CH4} + 298 \bullet E_{N2O}. \tag{8}$$

Acidification Potential *AP,* kg $SO_{2\text{-eq}}$, stands for emissions of acidifying gases, SO_X and NO_X, which can negatively affect soil, water, and flora, contributing to a decrease in pH values in the environment. Similarly, Eutrophication Potential *EP*, kg $NO_{2\text{-eq}}$, represents the impact of NO_X emissions, which negatively affect terrestrial and aquatic ecosystems as well as human health through reduction of oxygen levels in water and respiratory diseases (Koričan et al., 2023; Vladimir and Koričan, 2023). These potentials can be determined as

$$AP = 1 \bullet E_{SOx} + 0.7 \bullet E_{NOx} \tag{9}$$

$$EP = 0.13 \bullet E_{NOx}. \tag{10}$$

Weighting factors denoted by α, β, and γ are determined based on the application area, and in this case, they are taken for the shipbuilding sector (Vladimir and Koričan, 2023). The labels E_{CO2}, E_{CH4}, E_{N20}, E_{SOX}, and E_{NOX} denote emissions resulting from fuel combustion and equal

$$E_i = FC \bullet EF_i \tag{11}$$

where EF_i denotes the emission factor for the observed fuel and types of emissions, Table 3, and *FC* denotes fuel consumption in kg. According to eq. (12), fuel consumption incorporates the total engine power *P* efficiency of 56 % (in kW), specific fuel consumption *SFC* at a value of 215 g/kWh (Koričan et al., 2023), and operating time *t* (in h):

$$FC = (P + \Delta P) \bullet SFC \bullet t. \tag{12}$$

The operating time is calculated by multiplying the number of working days (approximately 200 days annually for fishing vessels) by

Table 3
Emission and weighting factors (International Maritime Organization, 2020).

Emission factor, g emission per kg fuel		Weighting factor	
CO_2	3206	α	0.095
CH_4	0.06	β	18.3
N_20	0.15	γ	21.1
SO_X	61.21		
NO_X	2.64		



Fig. 4. Definition of 18 zones on the wetted surface of a vessel (Hadžić et al., 2022).

the average number of working hours per day. In this case, a working cycle of 18 h is determined. Considering the impact of biofouling on the power increase of the main engine, the added power increase ΔP is also taken into account.

2.3. Economic assessment

In addition to the negative impacts of biofouling on vessel operability and potential environmental harms, the resulting increase in fuel consumption also has a significant economic effect. Therefore, it is of great significance to evaluate the structure of the associated costs as well as their particular shares. The total costs of the selected antifouling technology include investment costs, fuel costs, maintenance costs, end-of-life disposal costs, and idle costs. In addition to that, a carbon dioxide (CO_2) tax for vessels that produce exhaust emissions during their operation has to be taken into account as a recently introduced policy related to fuel consumption. Here, idle costs are omitted by assuming that wetted surface maintenance of fishing vessels usually takes place during vessel inactivity (e.g. during a fishing ban).

Investment costs for each antifouling technology differ in expenses related to the system itself – procurement of the passive/active antifouling protection, the cost of labour required for implementation, and docking costs. Docking and labour costs at shipyards vary, but for illustrative purposes, the price lists of the "Filipi" shipyard in Sukošan and the "Punat" shipyard on the island of Krk will be used in this research (Shipyard "FIlipi,", 2023; Shipyard "Punat,", 2023). The cost of handling a vessel depends on its length. Outside accommodation costs depend on the number of days required to implement the protective system and the daily accommodation rate set by the shipyard, while labour costs include the hourly rate of qualified workers multiplied by the number of working hours.

Regarding active protection, total costs include docking and accommodation costs, but installation is quick and simple, thus lower costs may be expected. Prices for the active system vary depending on the dimensions of the vessel and its purpose. In the case of passive systems, the investment costs are involved directly in the maintenance cost. For that reason, maintenance costs increase significantly. Active protection systems require less frequent maintenance, and if necessary, it can be done on the vessel itself outside the dock (no docking costs). Simultaneously, passive protection systems (coatings) entail much higher maintenance costs as compared to active protection. If there is a need to renew the coating outside the regular service interval, additional docking and accommodation costs arise. In addition to the cost of applying and purchasing the paint, the cost of water jetting and surface conditioning for a new coating should also be considered. The cost of the required quantity of material, i.e., antifouling coating (AF) in EUR, can be calculated as

$$AF = AF_L \bullet V \bullet n \bullet A_{wet} \tag{13}$$

where AF_L denotes the coating price per liter, V is the total required quantity of coating in liters, n is the number of coating layers, and A_{wet} is the wetted surface area in m^2on which the coating is applied. Since passive and active protection methods result in a certain increase in engine power, which further affects the increase in fuel consumption and thus harmful emissions, a good indicator of the economic impact of passive and active protection is the calculation of fuel costs and the associated carbon tax. The total costs are calculated for a period of 54 months as

$$LCFC = 54 \bullet FC \bullet PR_D. \tag{14}$$

where PR_D denotes the price of diesel fuel (EUR/l).

According to (Lloyd's Register, 2023), in 2024, CO_2 emissions from vessels with a 5000 GT and over, reported under the EU's Monitoring, Reporting and Verification (MRV) system will be included in the regional Emissions Trading Scheme (ETS). Thus, the vessels operating in the EU and EEA area will have to purchase permits (EU Allowances) to cover half or more of their GHG emissions. However, after a literature review, the possibility of expanding the application of the carbon tax to other types of vessels should be considered. Additionally, by 2026 the MRV will also require reporting CH_4 and N_2O emissions from vessels, with EUAs to be paid on 100 % of the CO_2 equivalent of those emissions, in addition to CO_2, within the ETS from 2027.

The current price of the carbon tax, valid from September 2023, is about 85 EUR/t CO_2, but according to estimates by the International Energy Agency, this value could reach 238 EUR/t CO_2 by 2050. Following the *International Energy Agency - Annex a, 2023* (2023) report, there are three scenarios for determining the carbon tax for 2030, 2040, and 2050:

- Stated Policies Scenario (SPS) – emission reduction according to current regulations,
- Announced Pledges Scenario (APS) – scenario to achieve net zero emissions by 2050 based on current reduction estimations,
- Net Zero Emissions Scenario (NZES) – scenario with guidelines for the global energy sector to achieve net-zero emissions by 2050, with advanced economies achieving net-zero emissions before others.

These values of carbon tax are presented in Fig. 5 for each possible scenario including annual values obtained by interpolation. The cost of CO_2 emissions, $LCCE$, applies only to vessels powered by fossil fuels, and it can be calculated as

$$LCCE = \sum_{i=1}^{M} E_{CO2} \bullet CA_{sc}. \tag{15}$$

where M is the elapsed time in months, E_{CO2} is the quantity of CO_2 emissions (kg $CO_{2\text{-eq}}$) and CA_{sc} is the value of the carbon tax depending on the scenario.

3. Case study

Fishing vessels can be classified according to the type of fishing gear, which affects its characteristics in terms of speed, route, and other specifications, resulting in significant differences in fuel consumption (Koričan et al., 2022). A detailed overview of the differences between fishing vessels and their specificities is given by Koričan et al. (2023). Purse seiners are fishing vessels that use a net to encircle a school of fish, usually targeting small pelagic species or tuna and catching large quantities. It can be seen that the purse seiner starts in the afternoon and unloads in the dock early in the morning, resulting in a daily operating time of 15 to 20 h. Most of the time and energy is devoted to cruising, while during the night the vessel is stopped so that the noise does not disturb the fish.

The analysis of the operational profile is a crucial step for further calculations, so it is necessary to gather as much data as possible. Hence, the operational profile, working hours, and speed of the fishing vessel were collected through a direct monitoring system, as shown in Fig. 6. The observed vessel is equipped with fuel monitoring systems, a Global Position System (GPS), and accessory switches providing information on the activation/deactivation of specific engines. The "MAPON" software provides real-time data on the route, working hours, specific locations, and many other outputs. Technical data is collected directly from fishers (e.g., number and power of auxiliary engines), while some statistical data concerning catch values is obtained from the Ministry of Agriculture of the Republic of Croatia, Directorate of Fisheries (Ministry of Agriculture of Republic of Croatia, 2023).

4. Results and discussion

The impact of biofouling on the roughness of the vessel's wetted surface, and thus on the increase in resistance, was analysed by means of

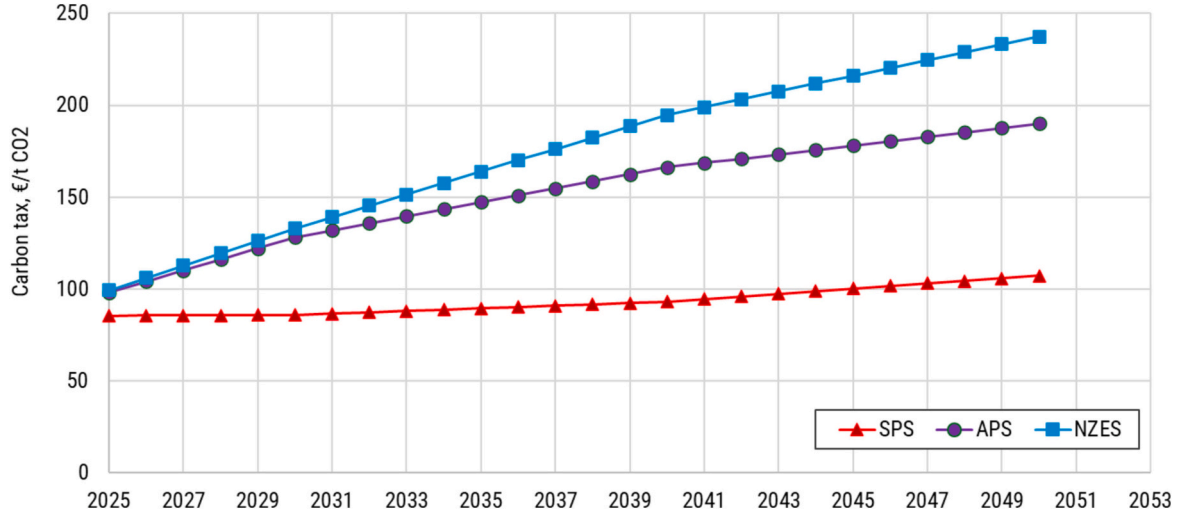


Fig. 5. Carbon tax scenarios.

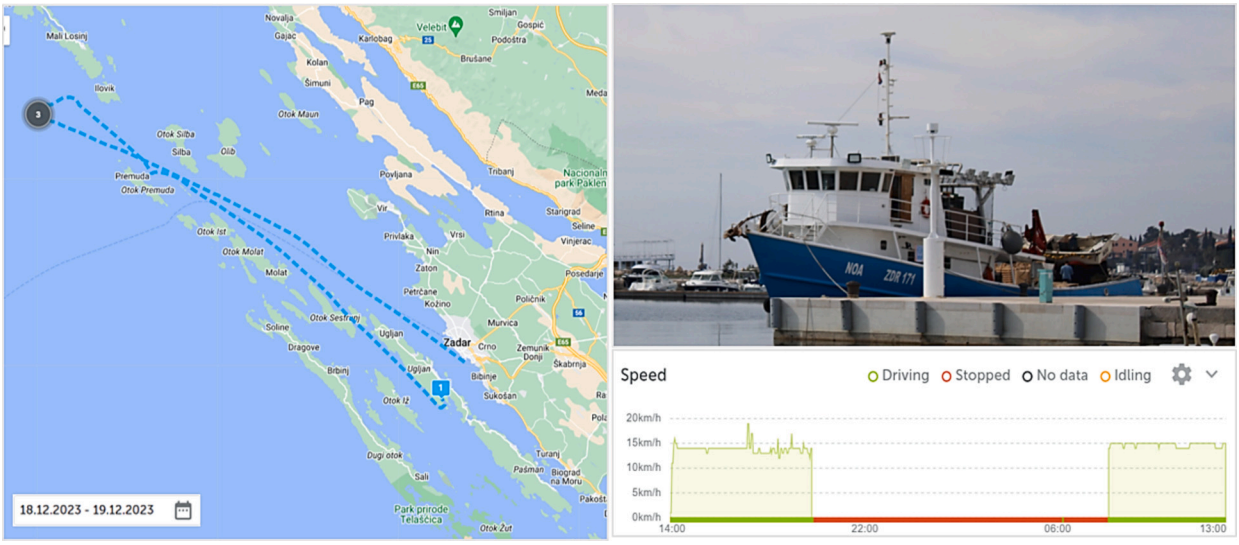


Fig. 6. Example of the fishing route with vessel speed profile.

an in-house software developed at the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb (Hadžić et al., 2022). Biofouling is considered in two separate cases, namely for the case of passive protection using conventional antifouling coatings, and for the case of active protection based on ultrasonic signal prohibiting colonization of the hull surface. In both cases, the same navigation area of the central Adriatic was considered. The development of biofouling was analysed for a period of 54 months representing a theoretical period of approximately three separate drydockings. Input data for the fishing vessel are summarized in Table 4. The results of the assessment are presented in Fig. 7 in the case of passive and active protection. It can be seen that the active biofouling protection system is significantly more effective in terms of engine power increase, with the differences reaching up to 112 kW. It is also worth noting that due to the dynamics of biofouling development on the vessel's hull surface, the selection of the protection system is negligible in the first quarter after drydocking, however, its impact becomes evident in the second and each subsequent quarter.

The environmental impact of active and passive protection was determined by employing eqs. (7–12). The analysis for different speeds and periods provides insight into the efficiency of the active and passive

Table 4
Input data – fishing vessel.

Type of vessel:	Purse seiner
Hull material:	Steel
Operating months:	288
Number of docks:	18
Operating area:	Central Adriatic
Fenders:	0.25, 0.5 and 0.75 l
Length Overall:	27.40 m
Breath:	7.01 m
Draught:	2.84 m
Main engine power:	370 kW
Gross Tonnage:	142
Block coefficient:	0.55
Wetted surface:	320 m^2
Propulsive efficiency coefficient:	0.25
Navigation speed:	2–8 kn
Density of seawater:	1025 kg/m^3
Quality of passive protection:	Excellent quality, $A = 1$
Lasting period of passive protection:	54 months
Quality of active protection:	Excellent quality, $A = 1$
Lasting period of active protection:	Unlimited

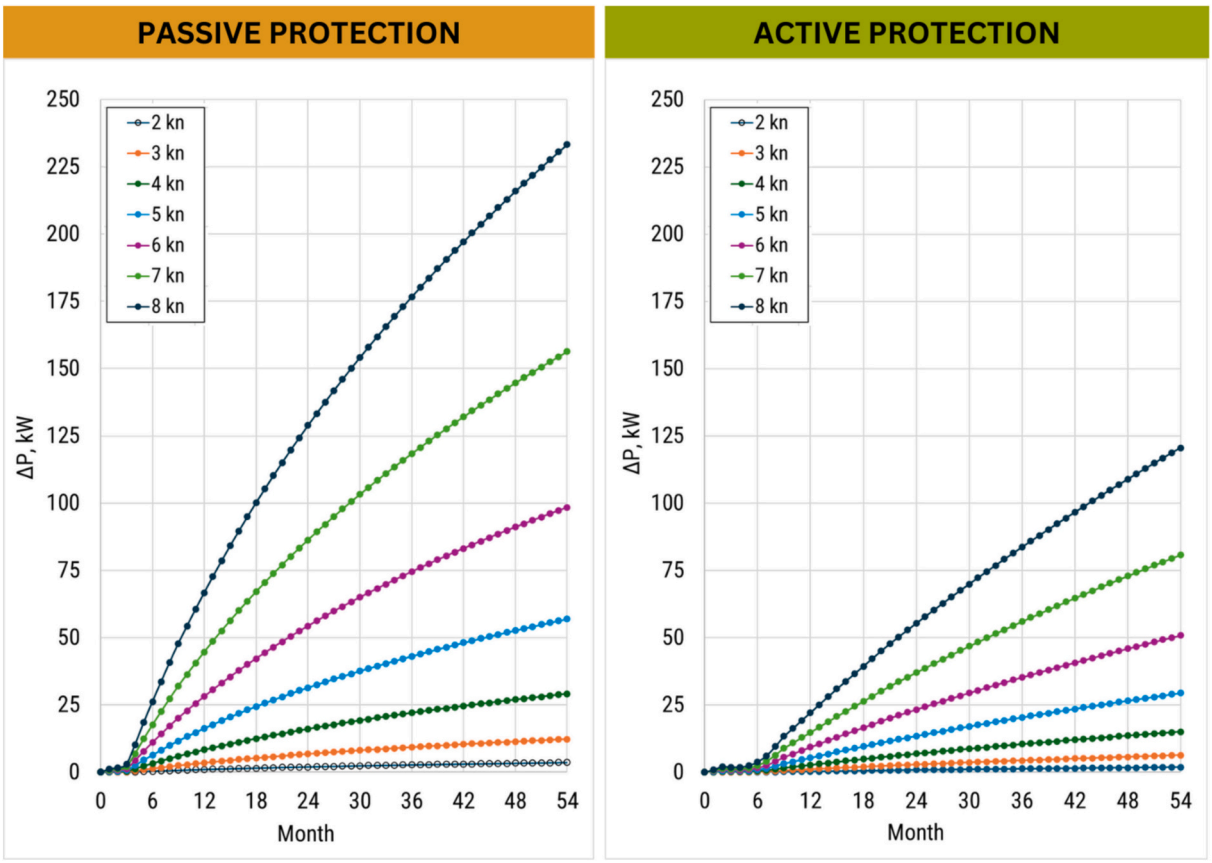


Fig. 7. Comparison of passive and active antifouling protection through the power increase in regards to the navigation speed and time period.

protection systems under the same operative conditions of the observed vessel. Fig. 8 presents the comparison of the environmental footprint in the case of passive and active protection, considering the increase in power after 54 months. It can be observed that the navigation speed has a significant effect on total power, increasing fuel consumption and directly impacting emission levels. At lower speeds, the difference between the active and passive protection methods is not significant. However, at higher speeds of 6–8 kn, the differences become more obvious, and the emission levels increase exponentially. At a speed of 8 kn, the vessel with implemented passive protection shows approximately 23 % higher environmental footprint after 54 months, compared to the active protection. When comparing the results of the environmental assessment in the case of different speeds, in Fig. 9, it can be seen that the emissions increase with higher speed. However, the differences are noticeable only after a certain number of months have passed, more precisely after 18–24 months depending on the observed speed. In the case of a speed of 4 kn, the difference in the environmental footprint of active and passive protection after 18 months is 2.03 %, while in the case of a speed of 8 kn, this difference equals 14.85 %.

The total costs of antifouling protection include dry-docking and accommodation costs, labour costs, and the cost of acquiring the protection system itself. The costs of active and passive protection, used in

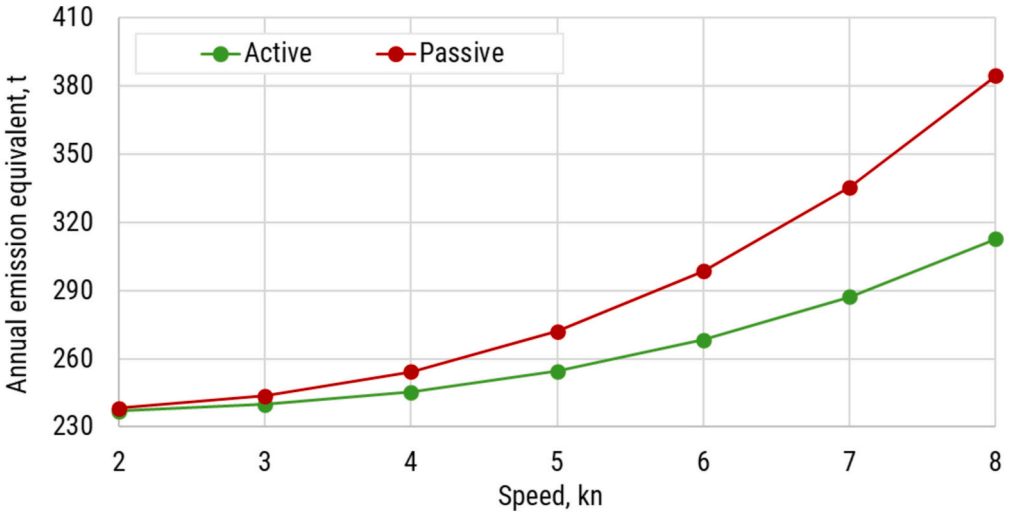


Fig. 8. Emission equivalent in case of passive and active protection after 54 months.

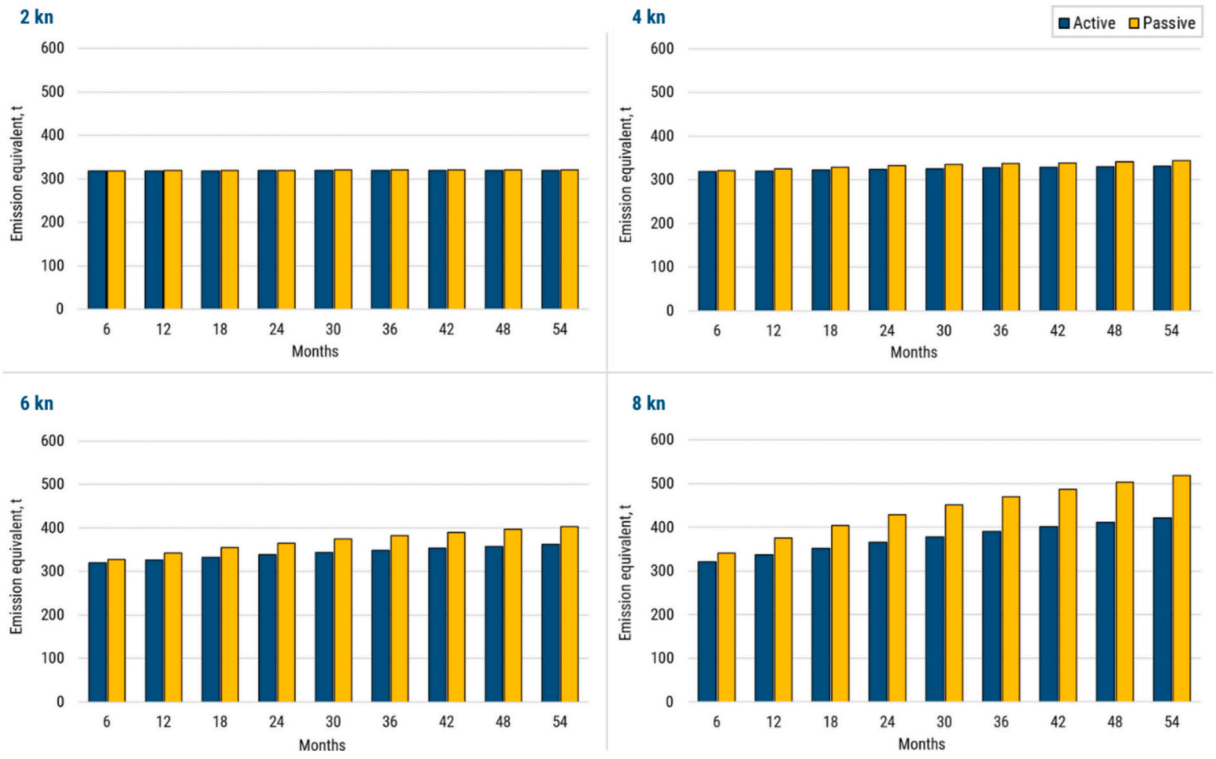


Fig. 9. Emission equivalent for active and passive protection through 54 months in case of different speed values.

this paper, are presented in Table 5. The cost of lifting/lowering a vessel between 25 and 30 m in length is determined according to shipyard price lists, as well as the daily cost of accommodation. In the case of active protection, it is estimated that the vessel spends about 4 days in dry-dock. For the application of coating systems, including vessel positioning, surface preparation, application of primer and coating layers, drying time between layers, and vessel launching, it is estimated that the vessel spends approximately 5 days in dry-dock. As for labour costs, the installation time of the active system is approximately 30 h, but experts are required, with a higher hourly rate than the one in the case of passive protection. The labour cost required for coating has a cheaper unit price, but lasts longer, about 40 h. The price of the protection system itself varies depending on the dimensions of the vessel and the type, brand, and quality of the active system. Considering that the research is related to a larger fishing vessel that sails daily, the maximum investment cost of 8100 EUR has been taken into account including the advantage of the long period between maintenance. Additionally, if there is a need to replace the system and generate electronic waste, the shipyard disposes of such waste for a charge. The cost of material for coating is calculated for a wetted surface area of 320 m^2. It is assumed that the coating is applied using airless spraying technology in two layers, including a thin layer of primer, according to the manufacturer's recommendations (Hempel, 2022). Primer and antifouling paint, as well as their exact quantity, are selected according to the product catalogue - a primer was selected in a total quantity of 30 l, and an antifouling paint in a total quantity of 70 l. As for waste disposal costs, they are negligible in the case of passive protection. A comparison of the cost structure and total costs related to active and passive antifouling technology is presented in Fig. 10.

Table 5
List of costs for passive and active protection.

Costs	Passive protection	Active protection
Lifting/lowering vessel (25–30 m) - drydocking	1300 EUR*	1300 EUR*
Vessel accommodation	146 EUR/day*	146 EUR/day*
Labour - installation	39 EUR/h*	50 EUR/h*
Waste disposal	260 EUR/5 m^3*	260 EUR/5 m^3*
Active system	–	1300–8100 EUR**
Primer	18.40 EUR/l***	–
Antifouling paint	42 EUR/l***	–
Maintenance costs	15 EUR/m^2***	–

* (Shipyard "FIlipi,", 2023; Shipyard "Punat,", 2023)
** (UltraSonic Antifouling LTD, 2023)
*** (Hempel, 2022)

From the results, it is evident that passive protection yields slightly higher costs associated with the time spent in dry-dock. However, active protection with ultrasound systems can be associated with higher investment costs. Therefore, before selecting the appropriate protection technology, the maintenance cost of the protection system over a certain period should also be taken into account, in this case, within 54 months. Although active protection requires more significant investment as compared to passive protection, it is not associated with maintenance costs over a longer period. At the same time, the coating system must be renewed regularly and preferably annually according to the recommendation of the coating provider (Hempel, 2022). Based on that, it is estimated that within 54 months, after the initial coating, it would be necessary to renew the coating system at least twice. In that case, the maintenance costs of the passive system include the cost of removing old paint and biofouling as well, in addition to the costs of dry-docking and material procurement as previously described. Consequently, the total costs for a vessel with a passive system become noticeably higher as compared to the case of an active one.

According to data taken from the official website of the Government of the Republic of Croatia, the price of blue diesel in December 2023 was 0.99 EUR per liter excluding the regulation on determining the maximum retail prices of oil derivatives (Government of the Republic of Croatia, 2023). Based on that, the fuel cost calculation was made for a maximum speed of 8 kn when the power demands and the associated fuel consumption are at the most significant level. The total power achieved in the period after 18, 36, and 54 months was taken into

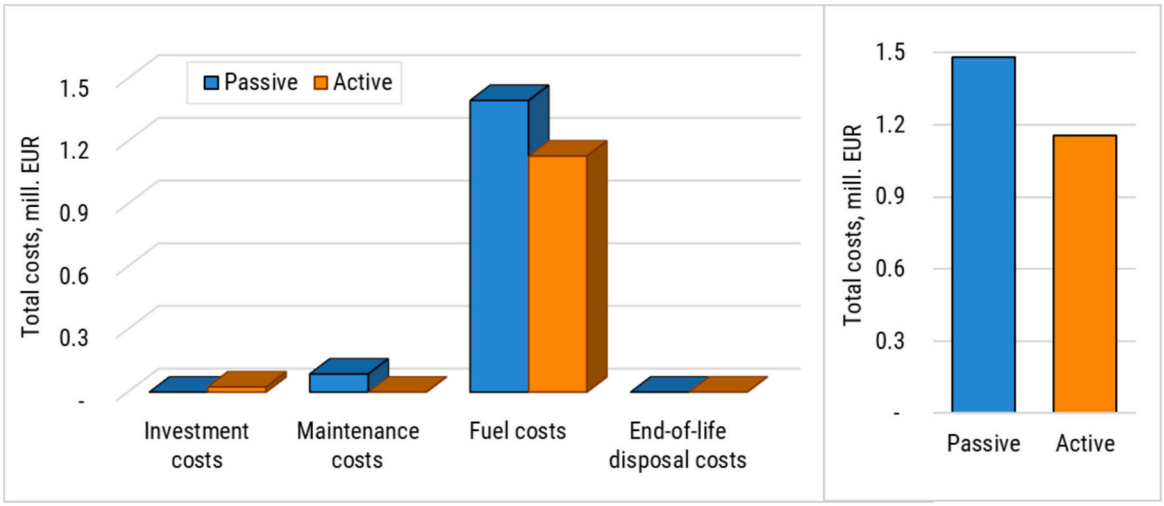


Fig. 10. Total costs in case of passive and active protection.

account, and based on this value, fuel costs were calculated in the case of active and passive protection. The obtained results show that fuel costs associated with passive protection are noticeably higher as compared to those of active protection, which is expected given the more significant power increase. For 18 months, this difference amounts to 15 %, while after 54 months, the difference increases to 24 %. When carbon taxes are added, the total costs related to fuel consumption become even more significant. As expected, the costs of active protection yield lower values, but this difference becomes increasingly significant as the months pass. In the SPS scenario, the difference between the taxes of active and passive protection, after 54 months, is approximately 76.6 thousand EUR. In the NZES scenario for the same period, this difference increases to 104.5 thousand EUR. Finally, it can be concluded that passive protection results in increased operational costs significantly earlier, especially when considering the carbon tax, Fig. 11.

As a limitation of this paper, it should be taken into account in price variations of antifouling technologies. Here, as an example, a comparison of a traditional coating of average price, recommended on the manufacturer's website, is taken, and compared with more modern technology at a higher price. Such a coating, although cheap, requires frequent maintenance, which is a common practice in the fishing sector. If the costs of another type of coating are calculated, the results may differ significantly from those shown here. Eco-friendly coatings are being developed today, with an emphasis on their antifouling effectiveness, durability, ecological impact, and ease of application. Although these coatings can have significantly higher prices compared to the ones shown here, the renewal of the coating is much less frequent and thus maintenance costs are reduced. Despite the advantages, new antifouling coatings are still being optimized to reach their maximum potential for marine applications, which is still insufficient compared to the results achieved in the laboratory (Li et al., 2023). Another limitation can be seen in the environmental analysis. Since the paper focuses on the power increase, which is directly related to fuel consumption, calculations were made only for emissions of harmful gases created during fuel combustion. In order to get a complete insight into the environmental picture of different antifouling technologies, further research should include environmental aspects such as the chemical release of biocides contained in coatings or the impact of noise from active technologies.

5. Conclusion

Biofouling represents a significant challenge for the shipping industry and vessel maintenance, especially if its negative impacts on operational characteristics, energy efficiency, and the environment are considered. This research presents an evaluation of two different

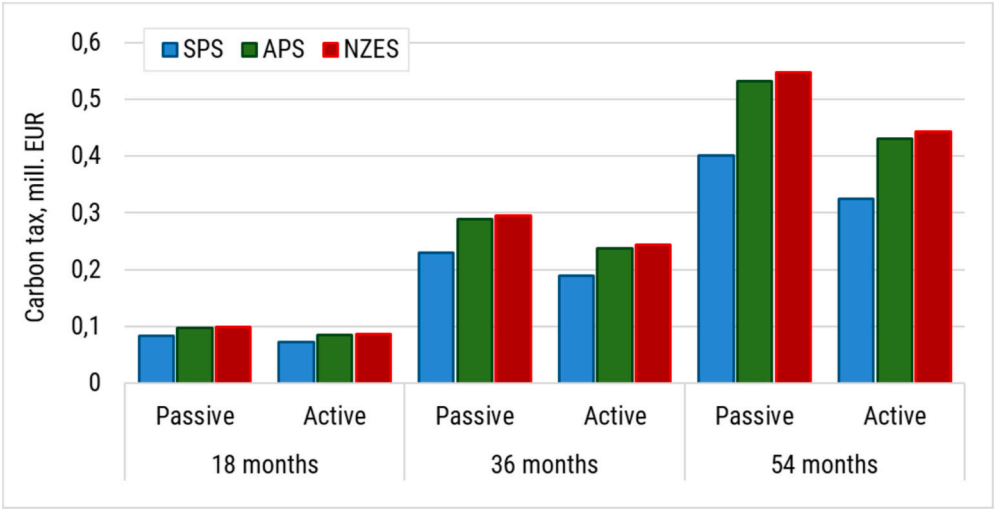


Fig. 11. Carbon tax after 18, 36 and 54 months.

antifouling technologies, coating and ultrasonic protection systems, implemented on purse seiner. The mathematical model of biofouling development and the associated increase in engine power gives insight into the influence of surface roughness on total fuel consumption. By considering both the active and passive antifouling technology, the increase in roughness is modelled as a function of the navigation area and the antifouling protection efficiency. The approach provides data on the increase in engine power caused by an increase in roughness, taking into account relevant parameters such as sea density, sailing speed, propulsion system efficiency, and other vessel resistance factors. The calculations showed that the active technology significantly reduces the power increase of the vessel's engine compared to the passive technology. The difference in the increase in power can reach up to 112 kW, which simultaneously affects fuel consumption, especially over a longer period.

Additionally, a mathematical model for assessing GHG and harmful emissions influenced by biofouling was also developed. The results of the environmental footprint assessment, which takes into account global warming potential, acidification potential and eutrophication potential, showed that the active protection system has a significantly smaller environmental footprint compared to the passive one. At higher speeds, the vessel with passive protection showed a 23 % higher environmental footprint after 54 months of biofouling, compared to active protection. Analysing the biofouling development through a period of 54 months, while taking into account different navigation speeds, showed that active protection results in the reduction of fuel consumption and emissions, thereby contributing to the preservation of the environment. The assessment of total costs also highlighted active protection as economically more favourable, especially if the carbon tax (through various implementation projections) and maintenance costs are taken into account.

Future research should include long-term performance assessment since it could provide valuable insights into the durability and effectiveness of antifouling technologies over extended periods. Mathematical models could be enhanced to simulate better biofouling development and its impact on vessel performance and emissions. Integrating advanced computational fluid dynamics (CFD) simulations could improve the accuracy and predictive capabilities of these models. Deeper insight into life-cycle assessments of antifouling technologies, considering not only their environmental footprint but also their economic effects over the entire lifespan of a vessel, would ensure the development of sustainable biofouling management in the shipping industry, minimize environmental impact and optimize vessel performance.

CRediT authorship contribution statement

Marija Koričan: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Nikola Vladimir:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Neven Hadžić:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis. **Viktor Ložar:** Writing – review & editing, Software, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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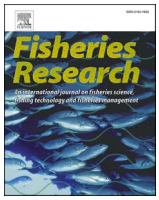
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Analysis of environmental-economic sustainability of fishing vessels and its improvement by alternative powering options in projected decarbonization scenarios

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ABSTRACT

The fishery sector faces various environmental challenges to ensure its sustainability, particularly regarding Greenhouse Gas (GHG) emissions originating from fishing activities. Several measures are aimed at improving the energy efficiency of vessels, from technical measures (alternative fuels, hull modification and maintenance…) to operative ones (journey planning, draft and trim optimization…) and market based measures (incentives, green shipping practices, carbon taxation, etc). This paper develops an environmental-economic sustainability index to address challenges in assessing the sustainability of fishing fleets. The index considers all costs, revenues, as well as potential carbon taxation, ensuring its applicability across various regions, fishing gear, and fuels. The application of the sustainability index is presented in the case of the Croatian large-scale fishing fleet, using real-time data on fuel consumption and exact data on the catch rate according to the type of fishing gear. The results show that while most vessels operate profitably under current regulations, the inclusion of carbon taxation may make them unsustainable. To examine the possibility of using alternative fuels, a life-cycle cost assessment of battery-, methanol- and biodiesel-powered systems was conducted. The results showed that certain solutions can become sustainable but the catch rate must be taken into account when investigating their applicability. Full electrification, although the most environmentally friendly, requires very high investment costs making it unsustainable without incentives.

1. Introduction

Environmental problems in fishing sector have become increasingly significant in recent years, prompting a strong focus on decarbonization efforts. In this sense, this paper contributes to the broader goal of reducing emissions in fishing fleets by developing a unique environmental-economic sustainability index. The index is illustrated taking into account measured fuel consumption and reported catch data from 12 vessels operating in the Adriatic Sea in Croatia. It considers regulatory frameworks, technical, operative and market-based measures aimed at improving fuel efficiency and reducing the sector's carbon footprint.

The structure of this paper is given as follows. In the Introduction, the paper emphasizes the growing need for decarbonization in the fishing sector and introduces the environmental-economic sustainability index developed for Croatian fishing vessels. Also, environmental problems and mitigation solutions in fisheries, highlighting sustainability challenges, global fishery production trends, and strategies for reducing the sector's carbon footprint are discussed. Building on this, the Research gap and aim of the paper section identifies limitations in existing studies, particularly the lack of standardized sustainability indices for fishing fleets, and establishes the study's objectives. The main objectives are to develop an environmental-economic sustainability index that accounts for all costs, revenue, and potential carbon allowances as a market-based decarbonization measure, ensuring its wide applicability across regions, fishing gear, and fuels, while maintaining practicality and simplicity for fishermen. The Methodology section details the development of the environmental-economic sustainability index and the Results section presents key findings on the feasibility of these fuels and illustrates the practical application of the sustainability index to Croatian fishing vessels.

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1.1. Emission mitigation measures in the shipping sector

The International Maritime Organization (IMO) influences the shipping industry by setting technical, operative, and market-based measures aimed at reducing the shipping's environmental impact and promote sustainability. The intention to mitigate GHG emissions intensified in 2011 when IMO adopted the MARPOL Annex VI consisting of technical and operational energy efficiency measures. By 2021, the measures further progressed to the goal of reducing the carbon intensity of international shipping by at least 40 % in 2030 compared to 2008. In 2023, the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) entered into force intending to increase energy efficiency in the short-term and to measure the energy efficiency to initiate the collection of data for the reporting of CII (International Maritime Organization, 2022). In the context of sustainability, the measures support its three pillars of development: environmental, social and economic (International Chamber of Shipping, 2013). Next to environmental, described above, social sustainability focuses on fair labor practices, seafarer welfare, and high safety standards, while economic emphasizes the need for a commercially viable shipping industry. This paper analyses the importance of technical and market-based measures, such as alternative fuels and carbon taxation, respectively, in achiving environmetal-economic sustainability of fishing vessels.

Technical measures include guidelines for vessel design, changes in propulsion, and equipment. Recent research showed a large interest in alternative fuels, and many recognize this technical measure as the optimal one for achieving the required emission reduction (Ampah et al., 2021; Lindstad et al., 2022; Schroer et al., 2022; Perčić et al., 2023). Traditional power systems are being replaced by alternative ones promising to achieve lower emission levels, with a CO_2 reduction by 20–100 % depending on the type of fuel (Islam Rony et al., 2023). Perčić et al. (2023) gave a comprehensive review of alternative marine fuels and conducted a life cycle assessment and cost analysis to compare their environmental and economic performance, taking Croatian fishing vessels as the test fleet. Results indicate that methanol is the most suitable alternative, with a 22.4 % reduction in GHG emissions and 23.3 % lower costs compared to a diesel-powered ship. Additionally, the paper highlights the sensitivity of fuel prices to total costs and identifies methanol and Liquified Petroleum Gas (LPG) as the most appropriate fuels that satisfy both environmental and economic criteria. LPG and bio-LPG are also analysed by Kim et al. (2023), who showed that the fuels result in 30–65 % lower GHG emissions than diesel-powered fishing vessels. Koričan et al. (2022) provided an environmental and economic assessment of different alternative fuels implemented on a trawler and stated that ammonia results in the highest GHG emissions, while methanol presents an optimal solution considering also the life-cycle costs. Even though electrification presents the most environmentally friendly option, confirmed in multiple research, it also results in high investment costs and still is characterized with a lack of charging infrastructure (Koričan et al., 2022, 2023b; Perčić et al., 2023). Market-based measures could accelerate the transition to "greener" shipping, by providing an economic incentive for the maritime industry to reduce its fuel consumption by investing in more fuel-efficient ships and technologies (International Maritime Organization, 2024) or enforcing different carbon taxation scenarios (Chen et al., 2023). It is important to mention that these measures apply to ships of 400 GT and above, and fishing vessels are excluded from these measures, although there are those that meet this condition. Even if the measures are applied to the fishing sector, analysis and adaptation of existing guidelines would be necessary due to the specificity of fishing operations (Díaz-Secades, 2024).

1.2. Environmental problems and mitigation solutions in fisheries

The fishery sector plays a crucial role in the global food industry, supplying protein-rich food but also ensuring livelihoods in coastal communities. According to Food and Agriculture Organization of the United Nations, (2024), in 2022, global capture fisheries production amounted to 90.3 million tonnes, and 78.8 million tonnes represented marine captures. Depending on the population growth, fish consumption is expected to slowly grow in the next decade, reaching 21.2 kg per capita globally, compared to 20.4 kg in the period from 2020 to 2022 (OECD/FAO, 2023). The ratio between sustainable and unsustainable fishery stocks varies depending on the fishing area, fishery development stage, management and fishery stock status, but also the level of implementation of environmental regulations (Food and Agriculture Organization of United Nations, 2022). In addition to the concern related to the restoration of the fish stock, great attention is paid to the Greenhouse Gases (GHGs) emissions. Since the majority of fishing vessels are powered by fossil fuels (Koričan et al., 2023c), the emission level of the global fishing fleet reached 179 million tonnes of GHGs in 2011 (UNCTAD, 2024). According to Mariani et al. (2020), from 1950 to 2014 global fisheries extracted 318.4 million metric tonnes of large fish from the ocean, equivalent to 37.5 ± 7.4 million metric tonnes of carbon released into the atmosphere. Even though the fish processing also contributes to total GHG emissions, the fishing stage represents the greatest share of energy consumption and emissions throughout the value chain of fish products (Høyli and Aarsæther, 2023).

Following international environmental agreements promoting carbon neutrality goals, the Paris Agreement (UNFCCC, 2016) and Glasgow Climate Pact (UNFCCC, 2021), mitigation measures are being adopted in the fisheries sector which resulted in a continuous decline in emissions, since 2015 (Xu et al., 2023). A good example are the Icelandic demersal fisheries which reduced the average emissions per unit of catch by around 40 %, emphasizing the importance of efficient and sustainable utilization of fish resources (Kristofersson et al., 2021). Sandison et al. (2021) highlighted the improvement of fuel efficiency as a major contributor to achieving established principles of sustainability, reducing fuel use and lowering the Carbon Footprint (CF) of the Scottish fishing fleet. However, the data on the sustainability of the fishing fleet is extremely deficient, especially when it comes to reporting emissions. IMO strives to improve the energy efficiency of ships and ensure the reduction of harmful emissions, which is why it is often expressed in CO_2 emissions per ship's capacity mile. On the other hand, IMO measures ignore fishing vessels, so their energy efficiency is still most often expressed as the Fuel Use Intensity (FUI) index, which measures the fuel consumption to catch 1 tonne of target species (Basurko et al., 2022). For this reason, it is very difficult to find data on the sustainability of the fishing fleet, especially those related to carbon scenarios.

Although carbon taxation is expected to be applied to fishing vessels, thereby encouraging the reduction of fossil fuels, fuel subsidies are simultaneously provided to encourage the development of the industry and more employment in the sector (Isaksen et al., 2015; Roll et al., 2022; Wiskich, 2024). Opinions about the effectiveness of these strategies depend on perspective, so it is easy to find the advantages and disadvantages of both. Carbon taxation ensures a reduction in the consumption of fossil fuels and a reduction in emissions, but it can increase operative costs, leading to a larger number of unemployed in the sector (Koričan et al., 2023c; Xu et al., 2023; Wiskich, 2024). On the other hand, subsidies could lead to overcapacity, overfishing, often increase CO_2 emissions (Machado et al., 2021; Our Fish, 2021) and slow down the transit towards more energy-efficient technologies, but they also enable fishers to invest in their own business, by securing funds for the purchase of fuel, improvement of vessels and fishing gear (Harper et al., 2012).

Most of the researches include limitations such as the lack of data on the catch rate (Koričan et al., 2023c), the lack of accuracy related to operative time location-specific (Sandison et al., 2021), introduce error coefficients into their calculations (Kristofersson et al., 2021) or generally state the possibility of a lack of accuracy in the results due to the unavailability/non-existence of data (Ricci Rodrigues et al., 2019; Food and Agriculture Organization of United Nations, 2022; General Fisheries

Commission for the Mediterranean, 2023; Hilborn, 2023; Pascoe et al., 2024). An additional obstacle in research is the numerous types of fishing gear, fishing methods and targeted species (Koričan et al., 2022, 2023c), which is why many assessments are focused on specific vessels and not on fishing fleets in general (Wong and Yong, 2020). Sumaila et al. (2016) emphasize the importance of fisheries management to reduce overfishing and ensure sustainability, which is also mentioned in other papers through catch-related improvement and restrictive regulations that could be widely implemented, independent of the type of fishing vessel (Knoche and Lupi, 2016).

1.3. Research gap and aim of the paper

To address the mentioned challenges, this research aims to develop a comprehensive sustainability index that considers expenses and revenues across various fishing vessels, regions, and fuel types. The paper contributes to the following research gaps:

- There is no standardized index for assessing the sustainability of fishing fleets, and the existing indices such as EEDI, EEXI, CII, etc., applied on larger vessels are based on transport work, making them inapplicable for fishing vessels;
- Although there are three pillars of sustainability, most research focuses only on the environmental factor (CO_2 emissions), while the economic component is most often separate and investigated for the purpose of analyzing the market of marine products or fuel prices;
- Lack of exact data on operative time and fuel consumption reduces the accuracy of the results;
- Due to the lack of data on the catch rate, estimates are based on the annual total catch, which is not appropriate because the prices of different marine organisms significantly scatter.

The third limitation is solved by using a database established through direct measurements on 12 fishing vessels operating in the Adriatic Sea. The Croatian fishing fleet, analysed in this paper, comprises 7808 vessels, primarily consisting of those under 6 m in length (56.4 %). Despite making up 86.5 % of active vessels, small-scale coastal vessels accounted for just 2.9 % of landed weight in 2022, while the large-scale fleet (13.5 %) contributed 97 % of landings and 81.7 % of value. In a larger scale, the fleet contributes 5.74 % to the total catch in the Mediterranean area, and purse seiners ranging from 24 to 40 m stand out with a 90 % contribution to total landings (in 2020). A detailed description of the fishing fleet is given by Koričan et al. (2023b) and exact data can be found on the official website of the Ministry of Agriculture of Republic of Croatia (2023). Due to the significant contribution of large-scale fisheries, the research was conducted on a group of 12 commercial purse seiners and trawlers which are under a strict management regime (Ministry of Agriculture of Republic of Croatia, 2023). The research group is equipped with fuel flowmeters and fuel level sensors, and monitored in real-time by computer software. The database consists of data on fuel consumption, speed, routes and similar data. A more detailed description is given under Section 3.

The last limitation is circumvented by using data on the exact catch rate, according to species and used fishing gear, for the period from 2015 to 2022. By using the available data, the sustainability of fishing vessels is assessed. Thus, the main objectives of the paper are:

- development of an environmental-economic sustainability index that takes into account all costs and revenue as well as potential carbon allowance as an emerging market-based measure for decarbonization of different industry sectors, regardless of the type of fishing vessel;
- ensuring wide applicability of the index (various regions, fishing gear, fuels, etc.);
- ensuring practicality and simplicity for end-users (fishers).

The carbon taxation input in its calculation connects the environmental (amount of emissions) and the economic component (price t $CO_{2\text{-}eq}$), which enables the index to become a completely monetary value. Reducing all inputs to economic indicators enables the applicability of the index to the entire fleet, given that vessel-specific inputs are eliminated. Environmental-economic sustainability index developed in this paper represents a step closer to determining the sustainability of the fishing fleet, including future environmental measures such as carbon taxation. Fishers are enabled to analyze the effectiveness of new technologies that are often proposed in environmental protection guidelines, taking into account all their costs and realized income. This way, the end-users can take into account regulations, such as the ban on fishing or reduction of engine power, and assess the profitability of fishing in new conditions.

2. Methodology

The workflow, presented in Fig. 1, for calculating the sustainability index begins with data collection and validation. Data includes technical specifications of the vessels and their power configuration, total fuel consumption, landed catch, and emissions estimation. This is followed by cost calculations, incorporating capital expenditures (CAPEX), operating expenses (OPEX), and carbon tax. Revenue is then calculated using the total catch and the average price per species. The calculated costs and revenue values are used to evaluate the sustainability index of a vessel. Finally, the results undergo evaluation and validation to ensure accuracy and reliability. A more detailed description of each input is given in the following subsections.

2.1. Development of environmental-economic sustainability index

The environmental-economic sustainability index is an indicator of the efficiency of fishing vessels, which takes into account capital and operating expenses in relation to revenue, Fig. 2. The equation according to which the sustainability index *SI* can be determined is equal to

$$SI = \frac{CapEx + OpEx + CA}{Revenue} \tag{1}$$

where *CapEx* denotes capital costs, *OpEx* operative costs and *CA* marks carbon taxation costs.

The revenue is calculated using data on catch rate and average price according to species, by the following equation:

$$Revenue = m_i \bullet PR_i, \tag{2}$$

where m_i marks the total mass of the landed species and PR_i marks the average price of the species. The average price is determined based on the data gathered for Ministry of Agriculture of Republic of Croatia (2023). The prices of several fish are presented in Fig. 3, where it can be noticed that certain species show a continuous increase in value while others show random fluctuations through the years. Depending on the type of marine organisms, the price can vary from as low as 0.42 €/kg to much higher prices of 94.20 €/kg. A complete overview of the marine species used in this research, their FAO code, scientific name, and the average price in Croatia based on data from 2015 to 2022 are shown in Appendix A.

Total capital costs, *CapEx*, refer to the installation of the power system. Considering that the majority of fishing vessels are diesel-powered, the capital costs are calculated by (Koričan et al., 2023a):

$$CapEx = P_{eng} \bullet PR_{eng} \bullet t \tag{3}$$

where P_{eng} refers to the power of the diesel engine, PR_{eng} marks the cost of the engine of 250 €/kW (Koričan et al., 2023a) and t marks the number of years for which the costs are calculated. Capital costs may also include the cost of purchasing fishing equipment, auxiliary equipment and other costs, but these are not taken into account in this paper.

Total annual operating costs, *OpEx*, consist of fuel costs and

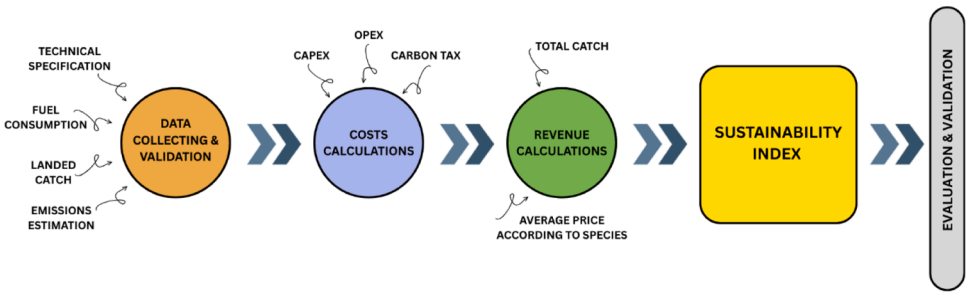


Fig. 1. Workflow of the sustainability index calculation.

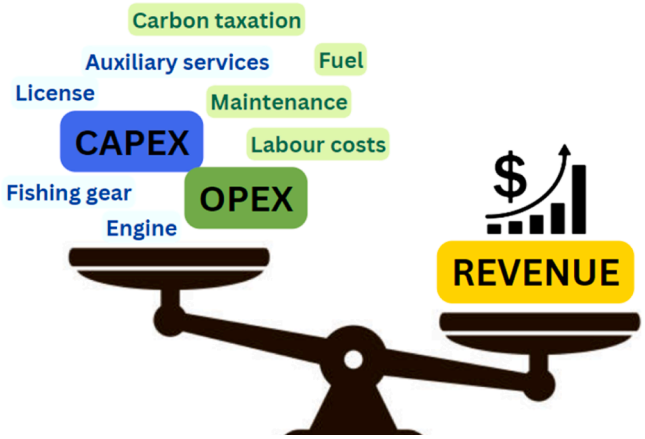


Fig. 2. Cost-to-income ratio in the fishing sector.

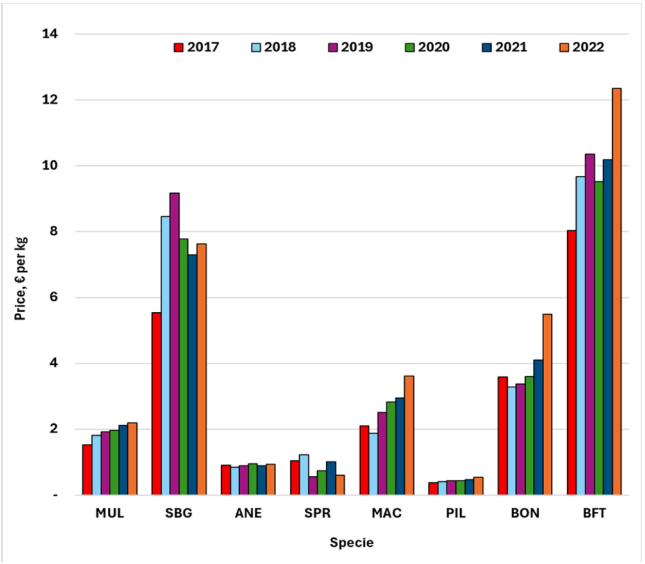


Fig. 3. Example of price fluctuations for different types of marine organisms, 2017–2022 (Ministry of Agriculture of Republic of Croatia, 2023).

maintenance costs:

$$OpEx = FC_D \bullet PR_D \bullet t + EC \bullet PR_{M-D} \quad \bullet t \tag{4}$$

The data on fuel consumption, FC_D (kg), is gathered by a direct measuring system and the price of fuel, PR_{FC} (€/kg), is determined based on the prices of previous years obtained from public databases. For the calculation, fuel density of 0.845 kg/l is considered (Perčić et al., 2021). All analysed vessels from the Croatian fishing fleet are diesel-powered, with an average diesel fuel price of 0.84 €/kg (Government of the Republic of Croatia, 2023). The maintenance cost can include various costs, from the maintenance of the hull of the ship to the repairs of the fishing net, but in this case, only the cost of maintaining the engine is included. The annual maintenance is calculated by multiplying the vessels's annual energy consumption with a conversion factor, $PR_{M\text{-}FC}$, of 0.014 €/kWh (Perčić et al., 2023). The energy consumption, EC (kWh), can be obtained by the following equation:

$$EC = \frac{FC_D}{SFC_D} \tag{5}$$

where SFC_D, in g/kWh, marks the specific fuel consumption of 0.175 g/kWh, in the case of diesel fuel according to the Fourth IMO GHG Study 2020 (International Maritime Organization, 2020).

2.2. Carbon taxation

Carbon taxation is a strategy aimed at reducing carbon dioxide (CO_2) emissions, which are one of the main GHGs and a major contributor to climate change and global warming. By placing a tax on the carbon content of fossil fuels, the reduction of the use of fossil fuels and the transition to green alternatives are encouraged (Andersen et al., 2024). Currently, CO_2 emissions from vessels with 5000 GT and over, operating in the EU and EEA area will have to purchase permits to cover half or more of their GHG emissions (Lloyd's Register, 2023). Given that taxation is expected to be extended to ships with a smaller GT, which includes the fishing fleet, the calculation of total costs includes carbon taxes. The current rate of the carbon tax stands at around 85 EUR/CO_2, but it could increase up to 238 EUR/CO_2 by the year 2050 (International Energy Agency - Annex A, 2023). According to the International Energy Agency, there are different carbon taxation scenarios that gradually tighten measures and accelerate the achievement of net-zero emissions: Stated Policies Scenario (SPS), Announced Pledges Scenario (APS) and Net Zero Emissions Scenario (NZES). In Fig. 4, the values of all three scenarios and the interpolation of these values until 2050 are shown. The strictest scenario, NZES, achieves the highest tax value and for this reason, it was taken for calculation.

The cost of carbon taxation CA (€) is applied only to vessels powered by fossil fuels and is calculated by the following equation:

$$CA = \sum_{i=1}^{year} E_{CO2} \bullet CA_{sc-year} \tag{6}$$

The E_{CO2} marks the CO_2 emissions released due to fuel combustion and are calculated by multiplying the fuel consumption FC (kg) with the emission factor of 3.206 kg gas/kg fuel (International Maritime Organization, 2020).

2.3. Life-cycle cost assessment of different fuels

Life-cycle Cost Assessment (LCCA) considers total costs which occurred during the lifetime of the product, i.e. vessel. The LCCA can also include the cost of externalities associated with directives, in this case cost of carbon taxation (European Commission, 2024). The cost

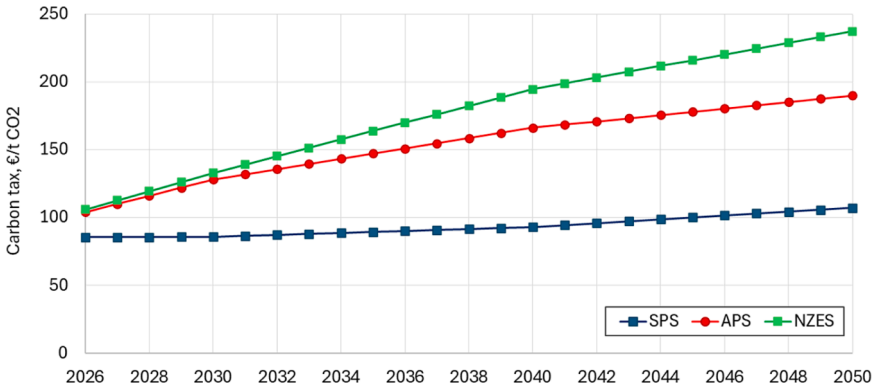


Fig. 4. Carbon tax scenarios.

structure is presented in Fig. 5. This paper considers the overall costs of different power systems over the vessel's lifetime of 20 years. Alternative fuels have been extensively researched and represent a good solution for the transition from traditional power systems to clean systems and reducing emissions. This paper calculates the sustainability index for three alternative options – batteries, methanol and biodiesel, and compares them to the traditional diesel-powered system of large-scale fishing vessels. The calculations are performed by means of in-house procedure incorporated in Phyton routines, and the relevant equations are outlined in the subsections below. To simplify the analysis, the calculations focus on total costs rather than annual variations. For instance, maintenance costs of a diesel system are calculated using a conversion factor regarding maintenance and the assumed total energy consumption over the vessel's 20-year lifespan, as described in subsection 2.1. This method provides a general overview of the economic impact of adopting alternative power systems but does not capture annual fluctuations or more detailed operational variations.

Battery-powered vessels represent one of the cleanest propulsion systems since there are no exhaust gases during operations. This makes them a suitable option in the case of applying carbon taxation because there is no additional cost in this regard. The capital costs of battery-powered vessels take into account the battery capacity *BC* (kWh) and its accompanying price *BP* of 250 €/kWh (Korberg et al., 2021; Koričan et al., 2023a):

$$BC = 1.5 \bullet P_{eng} \bullet t_h \tag{7}$$

$$CapEx_B = \frac{BC \bullet BP}{0.45} \tag{8}$$

The battery capacity is calculated by multiplying the engine power by its operating time in hours, t_h. Considering that fishing vessels do not have a fixed route or operating time, based on the data gathered from the direct measuring system, it is estimated that the average effective operating time of fishing vessels is 18 hours. Since over time battery gradually degrades it can cause battery capacity to decrease, so *BC* is increased by 50 % of its initial capacity. The operative costs of a battery-powered vessel include electricity costs and maintenance:

$$OpEx_B = EC \bullet PR_{el} \bullet t + 0.05 \bullet CapEx_B \bullet t \tag{9}$$

where electricity price PR_{el} equals 0.037 €/kWh and the maintenance cost equals only 5 % of the capital costs (Perčić et al., 2023). An additional cost is the battery replacement, needed once during the vessel's lifetime and calculated according to Eq. (8), while taking into account that the price declines by 25 %. The carbon taxation does not exist in this case because there are no exhaust emissions.

Methanol is the fuel used in dual-fuel engines, in combination with diesel as pilot fuel, and is already widely used in the marine sector (Ammar, 2019; Perčić et al., 2023). Although with the use of methanol, a certain level of emissions is achieved and the costs of carbon taxation arise, lower investment costs are expected compared to the battery and thus there is a possibility that it is an economically more favourable option. The $CapEx_M$ for methanol is calculated the same as for a diesel-powered vessel, according to Eq. (3), with a cost of dual-engine of 750 €/kW (Perčić et al., 2023). Maintenance costs are the same as in the case of a diesel engine. The fuel costs $OpEx_{M\text{-}FC}$ are calculated as follows:

$$OpEx_{M-FC} = FC_M \bullet PR_M + FC_{P-D} \bullet PR_D \tag{10}$$

The fuel consumption of methanol FC_M and pilot fuel $FC_{P\text{-}D}$ are calculated by the following equations:

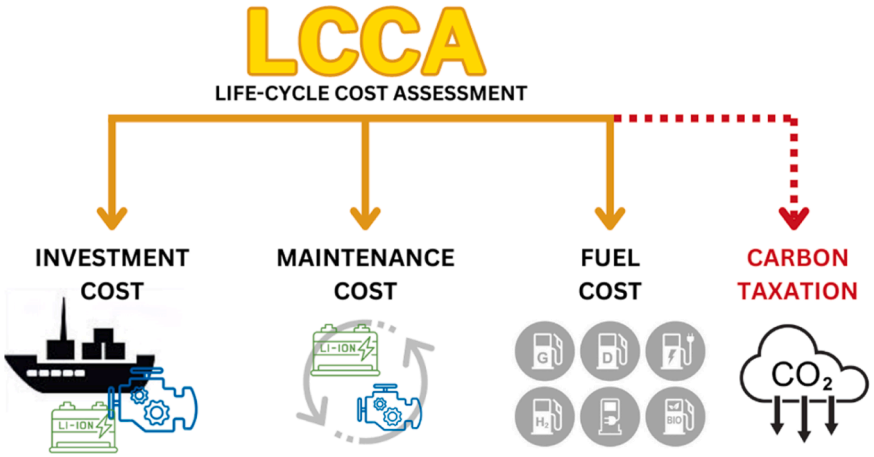


Fig. 5. Life-cycle cost assessment.

$$FC_M = 0.95 \bullet EC \bullet SFC_M \quad (11)$$

$$FC_D = 0.05 \bullet EC \bullet SFC_{P-D} \quad (12)$$

where SFC_M marks the specific fuel consumption of methanol of 327.2 g/kWh and $SFC_{P\text{-}D}$ marks the specific consumption of pilot fuel of 10.1 g/kWh (Perčić et al., 2020). The price of methanol equals 0.47 €/kg (Methanex, 2024).

Biodiesel is a very popular alternative fuel, mainly due to its compatibility with the existing infrastructure and engines powered by traditional, diesel fuel. Similar to methanol, it is usually used in dual engines in a blend with diesel. Even though pure biodiesel can be used, its blends are much more researched (Mahapatra et al., 2021). The capital costs of a biodiesel power system are equal to the ones for a diesel power system. The operative costs, regarding fuel costs, are calculated similarly to the methanol system:

$$OpEx_{BD-FC} = FC_{BD} \bullet PR_{BD} \bullet t + FC_{P-D} \bullet PR_D \bullet t \quad (13)$$

$$FC_{BD} = x_{BD} \bullet EC \bullet SFC_D \quad (14)$$

$$FC_D = x_{P-D} \bullet EC \bullet SFC_{P-D} \quad (15)$$

The fuel consumption of biodiesel FC_{BD} calculates the share of biodiesel in the fuel composition and multiplies it with its energy consumption and specific fuel consumption, the same as for diesel. Fuel consumption of pilot fuel, i.e. diesel, is calculated in the same way. In this paper, a biodiesel blend consisting of 50 % biodiesel and 50 % of diesel is considered. The price of biodiesel equals 1.84 €/kg (International Energy Agency, 2024). The maintenance costs are the same as in the case of a diesel engine.

2.4. Key assumptions, limitations and potential biases

This research was conducted for a research group of only 12 fishing vessels, of which only 2 trawlers. In future research, the entire fleet should be analyzed in order to assess its current state and determine further steps to improve the energy efficiency and sustainability of the fishing fleet. The findings are specific to the sampled vessels and may not be generalizable across all vessel types or fleets without further validation using larger datasets. A multi-criteria approach that balances economic, environmental, and social factors should be incorporated in future research to expand the dataset and improve generalizability. However, implementing such a model in current research presents significant complexity, particularly regarding data availability and the complexity of multi-objective optimization. Another disadvantage of the presented index is that the inputs are based only on the technical features of the vessel (engine power, type of fishing gear, fuel type), while the amount of landed weight is taken as reported data, not considering the sociological indicator. It is important to mention that the weather conditions during fishing, as well as the skill of the fishers, have a significant impact on the landed weight. For this reason, two technically identical vessels can show different results, and the use of specific fuel does not have to be the optimal solution in every case. Future research has the potential to build upon this work by incorporating additional data, such as social factors, weather conditions, and fuel use efficiency for individual vessels.

Several potential biases should also be acknowledged. Selection bias arises from the focus on Croatian fishing vessels, which were used as a case study. While the dataset is region-specific, the methodology and sustainability index are designed to be globally applicable. Although index values may differ across fishing areas, the index itself remains applicable to various types of fishing vessels, allowing for comparative assessments of environmental and economic performance within different fleets. Measurement bias related to fuel flow meter accuracy must also be considered. The installed flow meters in this study achieve a relative accuracy error per chamber of not more than 1 % under typical conditions (Technoton, 2025), and efforts were made to mitigate discrepancies through rigorous data validation techniques.

Lastly, economic assumptions regarding fuel prices and taxation policies introduce uncertainty into the model. Given the inherent unpredictability of future fuel price trends and carbon taxation policies, the robustness of the model may be affected. While this study provides valuable insights into the economic feasibility of alternative fuels in the maritime sector, these limitations and potential biases should be carefully considered when interpreting the results.

3. Case study

To enhance the accuracy of the sustainability index and strengthens its reliability, this study uses exact fuel consumption data measured onboard vessels operating in the Adriatic sea. Thus, the sustainability indices of 12 vessels are analysed – 10 purse seiners (PS) and 2 trawlers (T). The vessels are selected based on their relevance to the research objectives, i.e. operating area (central Adriatic) and the installed monitoring equipment, such as fuel flow meters and GPS for data collection. The sample ensures representative coverage of the fleet while taking account the possibility of data collection. Data on trawlers is more limited due to restrictions on their operations (McConnaughey et al., 2020), making purse seiners more aligned with the study's focus. The main inputs used in the calculations, i.e. average fuel consumption and landed catch on an annual basis, are presented in Table 1. The displayed data are not estimated, but are exact data obtained by the Directorate of Fisheries, Ministry of Agriculture of Republic of Croatia (2023). Data on the duration of sailing, used in the assessment of energy consumption in the previous section, is obtained by analyzing data collected by direct measurements on the vessels from May 2022 till December 2024. The measurement system, in addition to fuel consumption, collects data about the route (time, location) and the speed of the vessel itself. Fuel flow meters are precise measurement devices that detect fuel changes by converting physical variations into electrical signals and provide real-time data influenced by voyage conditions, including draft, trim, weather, and operating procedures. By using these devices, the end user develops a comprehensive database of real-time fuel consumption, vessel speed and other parameters, enabling detailed energy analysis, environmental impact assessment and optimization of vessel energy systems, even during specific operational phases such as fishing (Vladimir et al., 2022). However, their accuracy varies under different conditions. The findings by (Lee et al., 2021) indicate that the uncertainty caused by vibrations and speed changes can be quantified as the variation in the error range of the ultrasonic flow meter. Specifically, under vibrations, the error increases from 0.12 % to 0.5 %, resulting in an uncertainty range of 0.38 %, while under speed changes, the error increases from 0.5 % to 2 %, leading to an uncertainty range of 1.5 %. Manual analysis was conducted, comparing the fuel consumption data with the annual fuel consumption values provided by the Directorate of Fisheries, Ministry of Agriculture of Republic of Croatia (2023). Peaks in

Table 1
Main particulars used in the calculations.

Fishing vessel	Main engine power (kW)	Average fuel consumption (t/year)	Average landed weight (t/year)
PS1	370	74.28	519.46
PS2	477	79.32	637.50
PS3	302	74.05	690.39
PS4	537	47.38	568.91
PS5	526	59.76	481.58
PS6	242	16.84	266.48
PS7	286	41.22	682.17
PS8	480	63.91	708.36
PS9	450	68.44	583.59
PS10	220	25.45	374.92
T1	221	52.63	34.05
T2	223	66.44	42.95

the data caused by connection losses or waves due to bad weather were identified and removed to ensure more reliable results. The analysis of data enables the estimation of the average sailing time of a certain type of vessel. In Fig. 6, the variety of operational profiles of a purse seiner operating in the Adriatic Sea is illustrated, with a display of the route and observed vessel.

Given that a major limitation of the paper is the small sample size, a statistical analysis was performed. Statistical tests evaluate differences between vessel types, and the Mann-Whitney *U* test is applied to account for the small sample size and non-normal data distribution. At a 5 % significance level, the results of the Mann-Whitney *U* test indicate that there is no statistically significant difference between the two groups of vessels based on their engine power. Additional statistical values are presented in Table 2.

The engine power varies between 220 and 537 kW, regardless of the type of vessel. The influence of fishing gear is evident in the annual catch itself – trawlers achieve an average of 15 times less total catch. The difference is in the catch itself, as can be seen in Fig. 7. Purse seiners achieve the largest percentage of income from catching small pelagic fish, while trawlers mainly catch whitefish, but also various types of cephalopods, pelagic fish, crustaceans and others.

Table 2
Statistical analysis of sample groups.

	Group PS	Group T
Sample size	10	2
Sum of ranks	73	5
U statistics	2	18
U minimal	2	
Mean value of U	10	
Standard deviation of U	4.65	
Significant difference	0.05	
z-score	−1.72	
p-value	0.0857	

4. Results

The sustainability index SI is firstly calculated for the traditional power system, i.e. diesel powered vessels. The results are shown in the figures below. Fig. 8 shows the ratio of total costs and revenue for each vessel. The current regulations do not include carbon taxation, so it can be concluded that the majority of vessels are currently operating with realizable income, which can be from 1.4 to 3.4 times bigger than the overall costs of the power system. However, when the carbon taxation scenario NZES is included, only 8 vessels achieve profit, while others cannot even cover the total costs. Sustainability indices are calculated for each vessel from 2015 to 2022 and shown in Fig. 9. According to Eq. (1), if SI value is greater than 1 it can be indicated that the vessel may be inefficient, resulting in higher investment and operating costs than it generates in revenue. Value of SI lesser than 1 suggests operational efficiency and sustainable spending relative to revenue. Most SI values are between 0.8 and 1.2, depending on the year and catch rate. The value of SI under 1 shows that revenue is greater than total costs. The SI of purse seiners PS3, PS6, PS7 and PS10 resulted in values below 1 in every analyzed year. The reason for this may be lower engine power, which requires less fuel consumption, and the landed weight is at the level of vessels with stronger engines. An example of them are the purse seiner PS4, PS5 and PS8, which also make an enviable catch, but in cases of a bad fishing season, the revenue barely covers the total costs. In the diagrams, it can be seen that the trawler T1 is particularly prominent. The trawler has been working less well in recent years, which is why the total costs are not in line with the realized revenue and the value of SI is high. In 2022, the vessel became inactive; therefore, there is no SI result for that year.

After calculating SI values for existing power systems, the calculation for alternative power options followed. The results are presented in Figs. 10 and 11. The LCCA results are calculated for a lifetime of 20 years, using data for 2021 as baseline values.

As expected, the battery-powered systems resulted in much higher capital costs. Despite the fact that the cost of electricity is minimal and the carbon tax has been eliminated, the capital costs make this form of investment unsustainable in the current fishing industry. The results for vessels PS7, PS9 and PS10 showed that even with the application of the battery system, despite the high investment prices, they can generate profit. The reason for this may be the low power of the main engine, as for the vessels PS7 and PS10, but also a high level of efficiency when

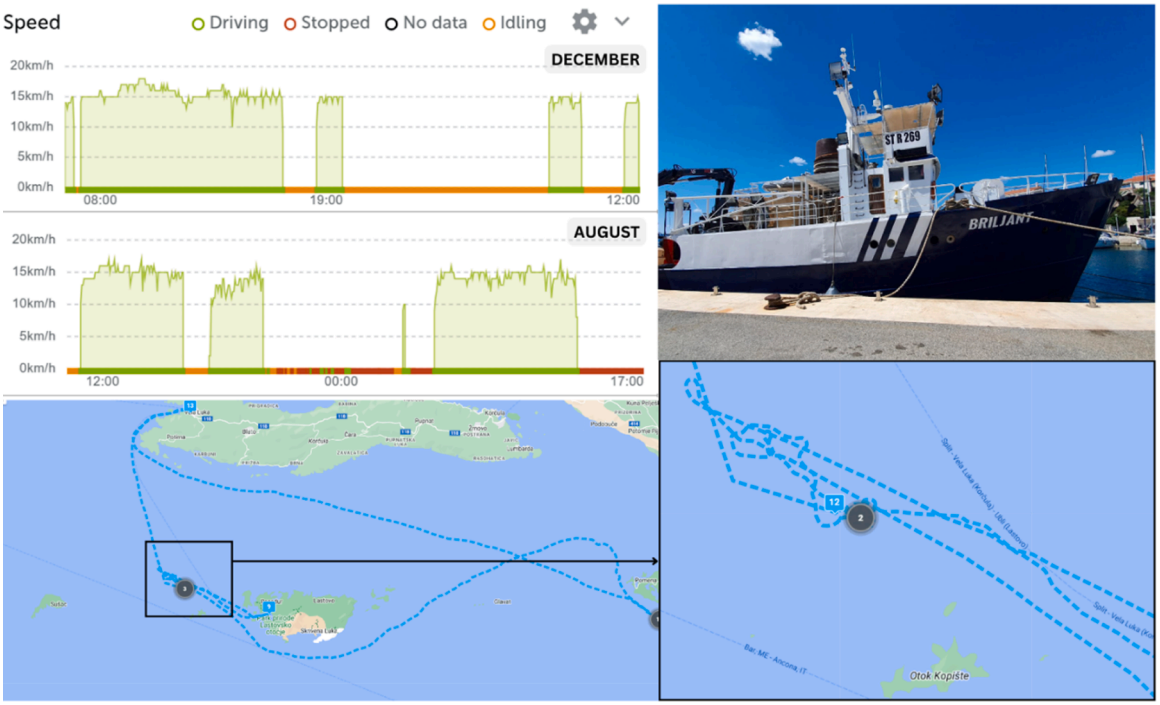


Fig. 6. Examples of operational profiles for the vessel PS8.

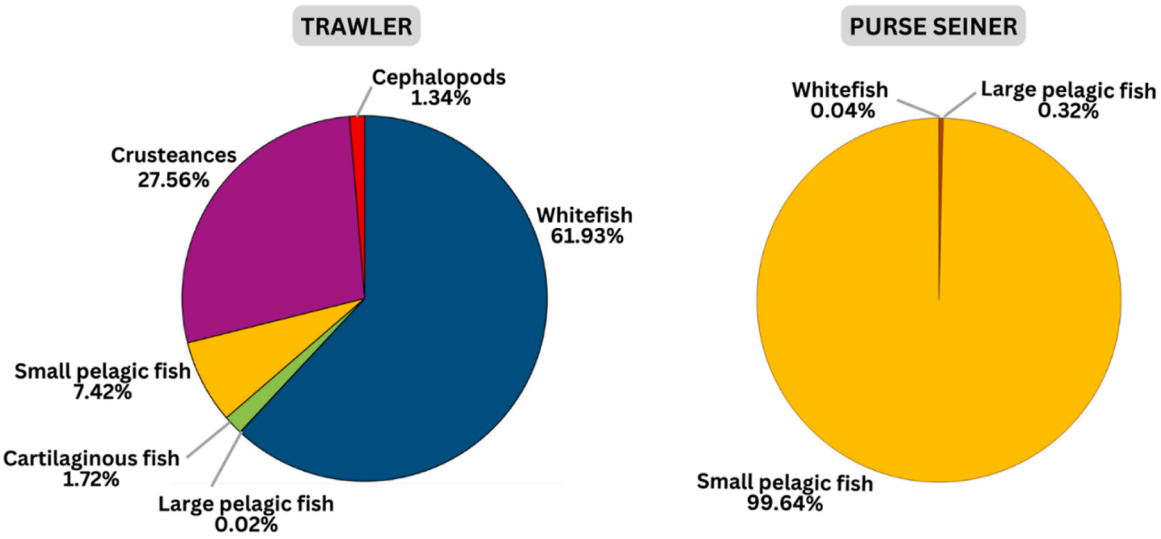


Fig. 7. Differences in catch quality of purse seiners and trawlers.

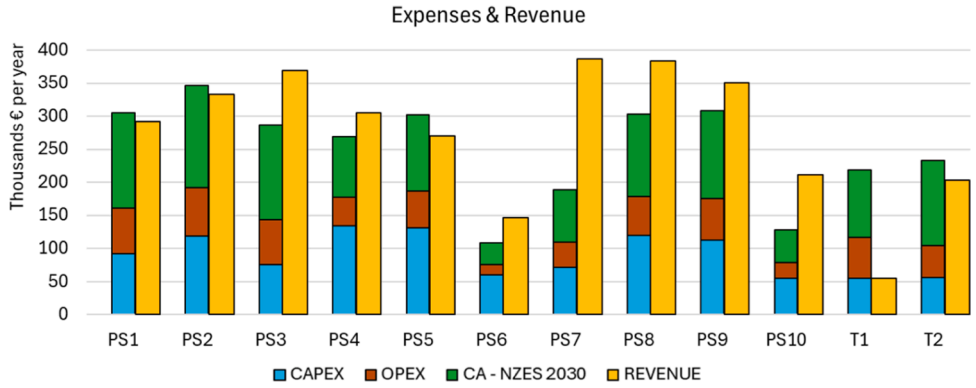


Fig. 8. Comparison of average annual total costs and revenue of diesel-powered vessels.

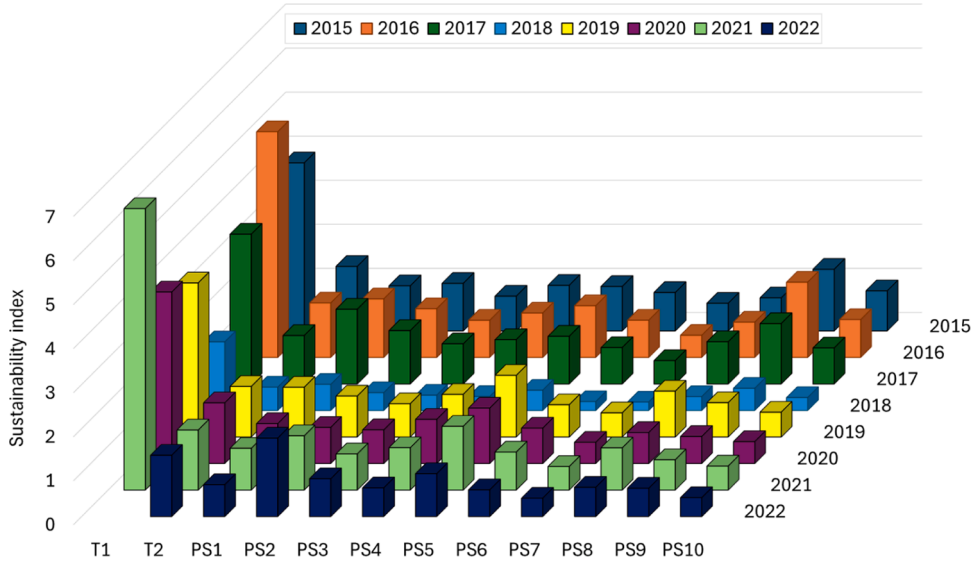


Fig. 9. Sustainability indices per year.

fishing as vessel PS9. If the vessels are further optimized or the landed weight is increased, vessels PS8 and T2 could also become sustainable by using a battery-powered system.

The calculations of the sustainability index for methanol-powered vessels show favourable results. Although the implementation of methanol in the vessel's energy system requires higher investment costs

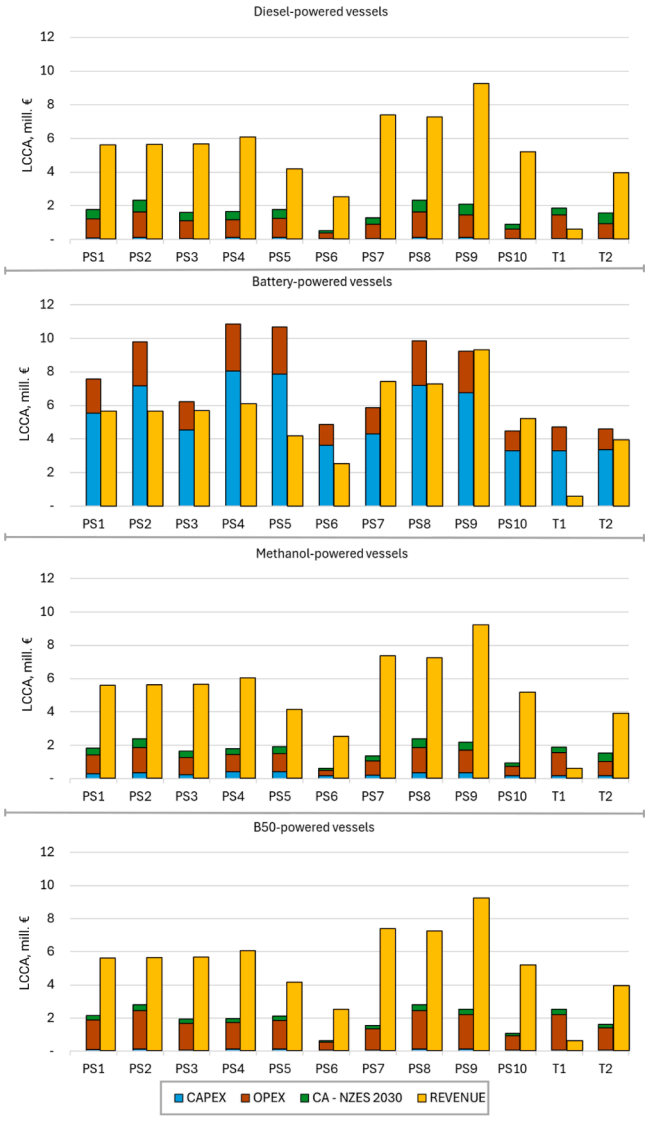


Fig. 10. LCCA of different power configurations.

compared to diesel, these costs are significantly lower than in the case of battery-powered ones. For one case, trawler T1, the use of methanol is not sustainable because the total costs are three times as expensive as the achieved revenue. Therefore, it is evident that the amount of catch plays a significant role in the sustainability of the application of some new technologies. In other cases, the implementation of methanol could cause significant savings, even with the introduction of carbon taxation.

Biodiesel-powered systems show very similar results as diesel-powered ones. Capital costs and maintenance costs are the same as in a diesel system, which shows lower values compared to methanol. Of course, due to the higher price of biodiesel and its large share in the blend, operating costs are slightly higher than those of traditional vessels. A big advantage is the reduction of GHG emissions, which resulted in a twice lower carbon tax than diesel-powered ones. Compared to methanol, the carbon taxes are approximately 52 % lower in the case of biodiesel.

When the alternative power systems are compared to the traditional one, as seen in Fig. 11, it is easy to assess the effectiveness of implementing alternative fuel into the vessels. Although battery-powered systems do not produce harmful emissions and are the most environmentally acceptable option, due to the high investment costs they are not currently suitable for implementation on fishing vessels in general. Their application requires further research and full optimization of the vessel design, which could require additional costs that shipowners may not be able to cover. The SI values for battery-powered are several times higher than those for diesel, methanol and biodiesel. As for methanol, its implementation results in approximately similar SI compared to diesel, the differences are only ± 3 %. If the fisher can realize a subsidy for the implementation of more environmentally acceptable technologies, this form of investment could be acceptable. Unexpectedly, biodiesel showed a higher SI than methanol. The values are approximately 20 % higher than the ones for the case of diesel. The reason for this is the higher price of biodiesel, compared to methanol and diesel. If its share in the mixture is reduced, it would be possible to achieve SI similar to the traditional propulsion system. But at the same time, this would increase the costs of the carbon tax.

5. Discussion

The sustainability index shows the importance of revenue, but also its fluctuations over the years. Supply, demand and market prices all have a significant impact on the final profit. Market prices are influenced by a number of factors, from seasonality, and size of species to fuel prices (Yildiz et al., 2023). Fig. 12 shows a comparison of the total landed weight with the realized revenue for the cases of three purse seiners. The

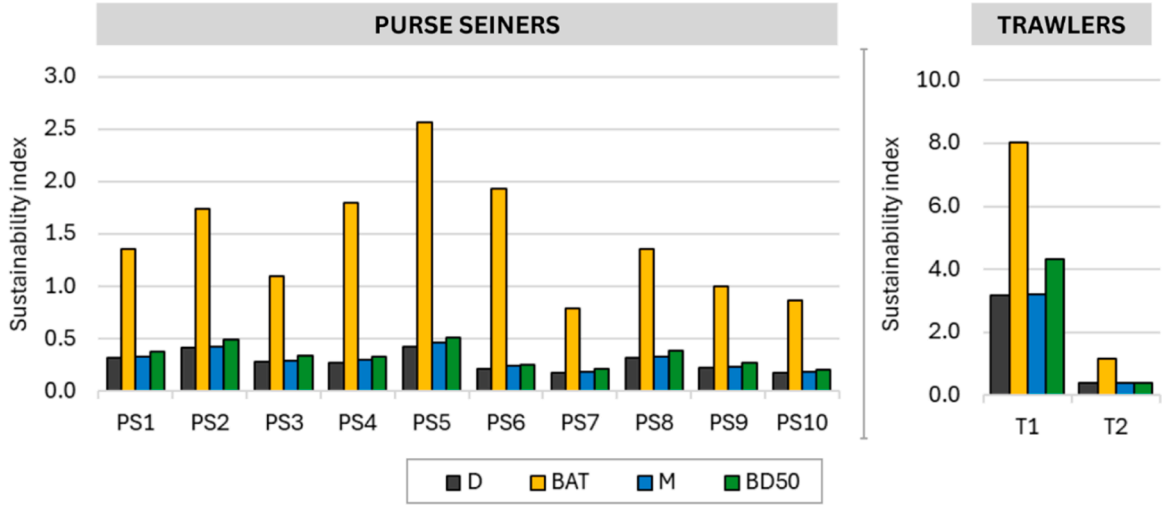


Fig. 11. Sustainability indices of different power configurations after a 20-year lifecycle.

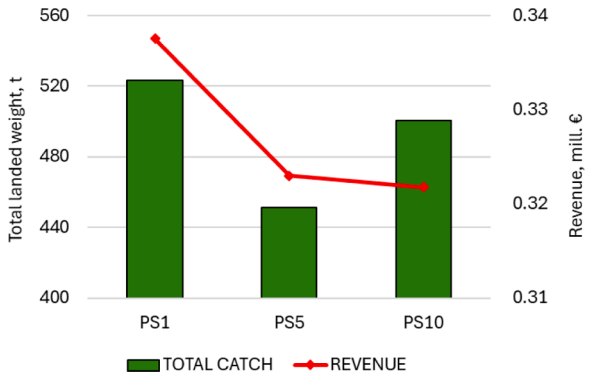


Fig. 12. Market influence on revenue in 2022.

total catch of vessels PS1 and PS10 differs by 22.8 t, while their revenues differ by 15.78 thousand €. On the other hand, vessel PS5 has 49.18 t less catch than PS10, and they achieve a similar revenue (the difference is only 1500 €). The data shows that monitoring market trends and taking into account influential factors is essential for determining the sustainability of fishing vessels. This also shows that the sustainability index can be a practical tool for stakeholders, such as shipowners and poly-makers for fisheires management. For shipowners, the index provides a decision-making tool for fleet optimization, enabling them to select fuel-efficient vessels and alternative fuels while considering long-term economic and regulatory impacts. Policy-makers and regulators can use the index to design targeted policies that balance environmental and economic factors, ensuring compliance with carbon reduction targets and promoting sustainable maritime operations.

Since inflation is not explicitly considered in the initial calculations, a sensitivity analysis provides insight into how such an economic factor could impact the sustainability index under fluctuating cost and revenue conditions. The sensitivity analysis of the sustainability index under varying fuel cost and revenue scenarios reveals distinct trends and differences among the three cases (PS1, PS5, and PS10), Fig. 13. For fuel cost fluctuations (left), the sustainability index increases as fuel costs rise from −30 % to + 30 %. Among the cases, PS5 consistently shows the highest sustainability index. PS1 exhibits moderate sensitivity, with a steady but smaller increase in sustainability, while PS10 demonstrates the lowest sustainability index across all fuel cost scenarios. In contrast, revenue fluctuations (right) from −30 % to + 30 %, reduce the sustainability index in all cases. PS1 shows moderate sensitivity, with a less steep decline compared to PS10. PS10, however, experiences the sharpest drop. The trends in the right graph are less linear and more variable compared to the left graph. In the left graph, representing fuel costs, the lines for all scenarios are smooth and almost straight, indicating a consistent and predictable relationship between rising fuel costs and the sustainability index. However, in the right graph the lines are less straight and display some curvature, reflecting a more complex and nonlinear relationship between revenue changes and sustainability.

Since carbon tax policies influence the sustainability index, an analysis of its effect across these three vessels under varying policy frameworks (SPS, APS, and NZES) provides valuable insights. The trends in Fig. 14 highlight distinct variations among the vessels based on the carbon tax policy applied. Under the SPS policy, the sustainability index remains relatively lower across all vessels, with PS5 achieving the highest index, due to higher fuel consumption and smaller achieved revenue. When shifting to APS, there is a noticeable increase in sustainability values for all vessels, while the NZES policy results in the highest sustainability index across all vessels. The trends suggest that the choice of carbon tax policy significantly influences sustainability outcomes. However, vessel-specific characteristics also play a crucial role, as seen in the varying SI values of PS1, PS5, and PS10 to different policies. This underscores the importance of aligning vessel operational strategies with optimal carbon tax policies to maximize sustainability.

In Table 3, several energy efficiency indices and the modelled sustainability index used for evaluating ships are presented, with a particular focus on CO_2 emissions and fuel consumption. The EEDI and EEXI indices are primarily designed for larger ships, with an emphasis on technical characteristics such as capacity and engine performance. These indexes are beneficial for promoting energy-efficient technologies but are limited in scope as they do not account for operational practices or smaller vessels, like fishing vessels. The CII index, on the other hand, focuses on the operational energy efficiency of vessels and is applicable to ships over 5000 GT. Compared to existing indices (EEDI, EEXI, CII), the sustainability index is specifically tailored for the fishing sector, considering a broader economic perspective. It incorporates both capital

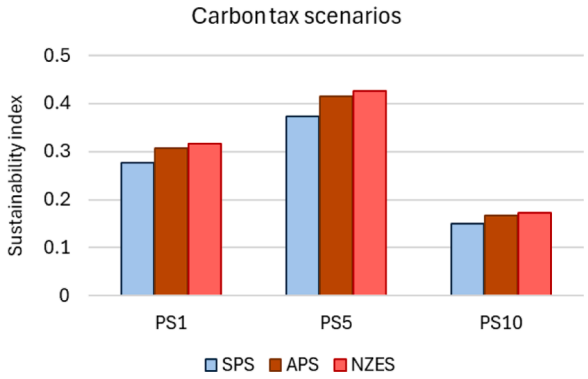


Fig. 14. Comparison of different carbon tax scenarios.

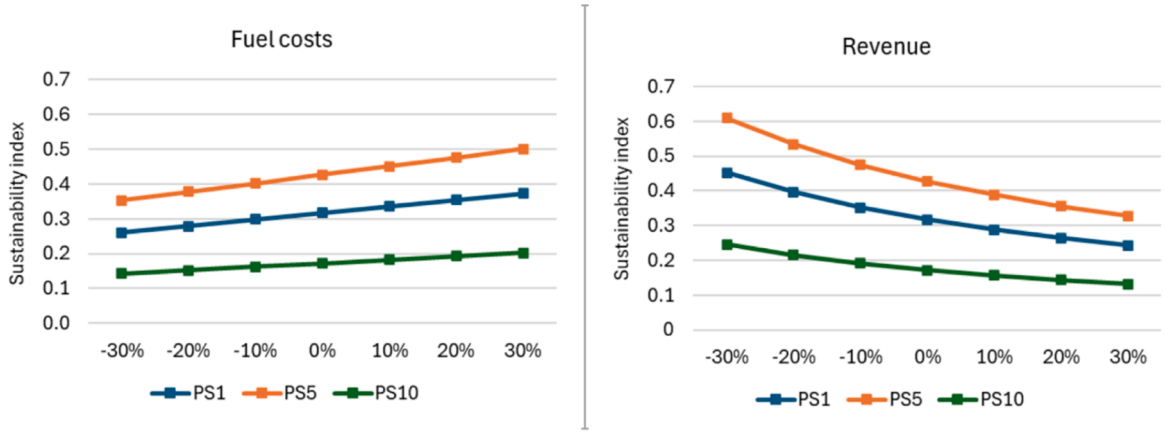


Fig. 13. Sensitivity analysis of sustainability index based on fuel costs and revenue fluctuations.

Table 3
Comparison of available energy efficiency indices and modelled sustainability index.

Index	Simplified Representation	APPLICABILITY	PROS & CONS
EEDI *	$EEDI = \frac{CO_2 emissions}{Capacity - mile}$ • Energy efficiency in accordance to the ship's capacity-mile. • Based on technical characteristics of the ship.	• Applies to new ships of 400 GT or above.	• Promotes the use of more energy-efficient equipment and engines in new ship designs. • Limited to new ships • Does not address the operational efficiency of existing vessels. • Does not include smaller vessels (such as fishing).
EEXI*	$EEXI = \frac{CO_2 emissions}{Transported\ work}$ • Energy efficiency in accordance to the capacity of the ship (deadweight or GT). • Based on technical characteristics of the ship.	• Applies to existing ships of 400 GT or above.	• Encourages improvements in the energy efficiency of existing ships. • May necessitate modifications or operational limitations to achieve compliance. • Does not include smaller vessels (such as fishing).
CII*	$CII = \frac{CO_2 emissions}{Cargo - carrying\ capacity\ and\ nautical\ mile}$ • Reflects the operational energy efficiency of ships.	• Applies to all ships above 5000 GT.	• Provides continuous monitoring of a ship's operational efficiency. • Requires accurate data collection and may impact operational practices to maintain favorable ratings. • Does not include smaller vessels (such as fishing).
SI	$SI = \frac{CapEx + OpEx + CA}{Revenue}$	• Applies to all types of fishing vessels.	• Tailored specifically for fishing vessels. • Enables comparisons of different fishing vessels within the same type. • Accuracy depends on the accuracy of the input data (e.g. fuel consumption or landed catch). • Economic factors, such as fuel price fluctuations, enter a level of uncertainty into the model.

* (International Maritime Organization, 2022)

expenditures (CAPEX), operational expenses (OPEX), carbon taxes (CA) and revenue related to catch, providing a more comprehensive evaluation that captures the economic and operational nuances of fishing vessels. The SI is applicable to all fishing vessels, regardless of size, and offers an important tool for comparing different vessels within the sector. It also faces challenges regarding the accuracy of input data, particularly with fluctuating fuel prices and varying catch quantities, which can introduce some uncertainty in the results. The developed sustainability index can be integrated with AI in fisheries to enhance data processing, predictive analytics, and decision-making. This could eliminate limitations concerning data analysis. For instance, AI-powered algorithms can process real-time data from fuel flow meters, GPS, and onboard sensors to continuously update sustainability index calculations, while machine learning models can clean and filter raw data, removing anomalies caused by connection losses, sensor errors, or extreme weather conditions (European Parlament - Policy Department for Structural and Cohesion Policies, 2022; Welch et al., 2024).

6. Conclusions

The fishing sector faces challenges of sustainability and environmental impact, especially considering the expected increase in global fish consumption. Declining fish stock and rising greenhouse gas emissions from fishing vessels present a global environmental problem. To address these concerns, research efforts have focused on developing sustainable practices and implementation of technical and operational measures. This study contributes to this effort by developing a comprehensive sustainability index that considers costs and revenues across various fishing vessels and fuel types. There are no restrictions on applying the index to other fishing fleets if the relevant input data is available, and by addressing data limitations while focusing on economic indicators, it serves as a practical tool for stakeholders to assess the sustainability of fishing operations.

The applicability of the developed sustainability index is demonstrated on several purse seiners and trawlers with different power configurations. Results from the analysis of traditional diesel-powered vessels show the impact of carbon taxation on profitability and the following statements are concluded:

- Without considering carbon taxation, most vessels appear to operate with a positive income, indicating revenue that exceeds total costs;
- In the case of carbon taxation according to the NZES scenario, the potential financial pressure caused by environmental regulations is highlighted as only a small fraction of vessels remained profitable;
- Majority of SI values from 2015 to 2022 fall between 0.8 and 1.2, indicating that revenue typically exceeds total costs;
- Vessels with stronger engines and consequently greater fuel consumption could periodically struggle to cover total costs due to the fluctuating catch quality.

Transitioning to alternative power systems, such as battery-, biodiesel- and methanol-powered vessels, presents both opportunities and challenges:

- Battery-powered vessels offer emissions-free operation but face challenges due to high capital costs, representing a barrier to widespread adoption in the fishing industry;
- Methanol-powered vessels exhibit lower capital costs compared to battery-powered, potentially making them a more economically viable option;
- Biodiesel-powered vessels are suitable due to their great similarity with existing diesel-powered, facilitating an easier transition, though their effectiveness depends on the blend utilized;
- Methanol results in a similar SI to diesel, while unexpectedly biodiesel shows higher SI values due to its higher fuel cost, which can potentially be mitigated by reducing its proportion in the blend, but risking an increase in the carbon tax.

In the event that subsidies and regulations encourage the adoption of alternative fuels, alternative fuels can become applicable and promote sustainability while ensuring the fishers economic viability.

Further research should include other types of fuel and possible combinations with renewable energy sources. Lifecycle assessments could provide additional insight into the total emissions, including SO_X and NO_X. In addition, the analysis of fluctuations in the prices of marine organisms and fuel, and their impact on the sustainability index, would present interesting results.

CRediT authorship contribution statement

Vladimir Nikola: Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation,

Conceptualization. **Fan Ailong:** Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis. **Koričan Marija:** Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. FAO code, type and average price of marine organisms landed by the Croatian fishing fleet

Group	FAO code*	Type	Scientific name	Average price – Croatia**, €/kg
Whitefish	PAC	Red pandora	Pagellus erythrinus	2.35
	BOG	Bogue	Boops boops	1.01
	MUL	Flathead grey mullet	Mugilidae	1.84
	CTB	Two-banded seabream	Diplodus vulgaris	6.16
	SPC	Picarel	Spicara smaris	1.47
	MNZ	Angler	Lophius spp	6.46
	GUX	Sea robins	Triglidae	6.21
	SBG	Gilt-head bream	Sparus aurata	7.14
	JOD	John dory	Zeus faber	19.74
	SOL	Common sole	Solea solea	8.29
	BSS	European seabass	Dicentrarchus labrax	11.16
	HKE	European hake	Merluccius merluccius	3.85
	RPG	Seabream	Pagrus pagrus	18.78
	LEZ	Megrim	Lepidorhombus spp	3.11
	WEX	Weevers	Trachinus spp	1.89
	SHR	Sharpsnout seabream	Diplodus puntazzo	7.19
	WHG	Whiting	Merlangius merlangus	1.45
	TUR	Turbot	Psetta maxima	13.74
	SLM	Salema porgy	Sarpa salpa	2.82
	RSE	Red scorpiofish	Scorpaena scrofa	17.36
	BBS	Black scorpiofish	Scorpaena porcus	3.21
	MUT	Red mullet	Mullus barbatus	1.77
	MUR	Striped red mullet	Mullus surmuletus	5.54
	COE	European conger	Conger conger	2.40
	SBS	Saddled seabream	Oblada melanura	2.45
	DEC	Common dentex	Dentex dentex	19.02
Cephalopods	OCC	Common octopus	Octopus vulgaris	7.39
	SQR	European squid	Loligo vulgaris	9.43
	SQU	Various squids nei	Loliginidae, Ommastrephidae	1.77
	OCM	Horned and musky octopuses	Eledone spp	3.16
	CTC	Common cuttlefish	Sepia officinalis	5.65
Cartilaginous fishes	MYL	Common eagle ray	Myliobatis aquila	1.25
	SMD	Smooth-hound	Mustelus mustelus	4.64
	SKA	Raja rays nei	Raja spp	2.72
Small pelagic fishes	ANE	European anchovy	Engraulis encrasicolus	0.90
	SPR	European sprat	Sprattus sprattus	1.02
	VMA	Atlantic chub mackerel	Scomber colias	0.42
	MAC	Atlantic mackerel	Scomber scombrus	2.34
	PIL	European pilchard	Sardina pilchardus	0.43
	JAX	Jack and horse mackerels nei	Trachurus spp	0.42
Other	COL	Sardinia coral	Corallium rubrum	66.96
	SPO	Sponges	Spongiidae	94.20
Crustanceas	LBE	European lobster	Homarus gammarus	34.73
	DPS	Deep-water rose shrimp	Parapenaeus longirostris	2.94
	NEP	Norway lobster	Nephrops norvegicus	13.60
Mussels	MSM	Mediterranean mussel	Mytilus galloprovincialis	1.54
	SJA	Great Mediterranean scallop	Pecten jacobaeus	7.45
	OYF	European flat oyster	Ostrea edulis	3.29
	RKQ	Noah's ark	Arca noae	6.20
	VEV	Warty venus	Venus verrucosa	10.54
Large pelagic fishes	AMB	Greater amberjack	Seriola dumerili	8.40
	SWO	Swordfish	Xiphias gladius	9.04
	LTA	Atlantic black skipj	Euthynnus alletteratus	1.78
	BON	Atlantic bonito	Sarda sarda	3.86
	FRZ	Frigate and bullet tunas	Auxis thazard, A, rochei	1.09
	BFT	Atlantic bluefin tuna	Thunnus thynnus	9.87

* (Food and Agriculturle Organization of the United Nations, 2024)
** (Croatian bureau of statistics, 2021)

Data availability

Data will be made available on request.

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Environmental-economic assessment of hybrid power systems for fishing vessels

Marija Koričan[1], Nikola Vladimir[1] and Ailong Fan[2]

Abstract

Decarbonization of the fishing sector is an important step toward achieving global climate goals while ensuring the long-term sustainability of marine ecosystems. This sector, heavily reliant on fossil fuels, particularly for vessel operations, contributes significantly to greenhouse gas (GHG) emissions. Hybrid and multi-source energy systems, including microgrids that integrate renewables and energy storage, offer a sustainable solution for optimizing energy use, enhancing efficiency, and stabilizing power. This paper involves microgrid configurations for trawlers and purse seiners, two types of fishing vessels with distinct operating profiles. Through load scheduling based on fuel consumption measurement results, the study provides a cost-benefit analysis that reflects each vessel's unique energy requirements, offering insights into optimal power solutions for the fishing industry. Three distinct configurations have been analyzed: diesel engine-powered, hybrid (diesel generator with battery storage), and plug-in hybrid. The simulations offer financial variables such as Net Present Cost (NPC) and Operation and Maintenance (O&M) costs to determine the most cost-effective solution. Results show that for purse seiners, diesel engine-powered configurations incurred the highest NPC, primarily due to high diesel fuel costs. Plug-in and model demonstrated lower NPCs, benefiting from greater energy efficiency despite higher initial investments. For trawlers, the plug-in model achieved the lowest NPC, while the hybrid configuration yielded costs higher than diesel engine. Across both vessel types, fuel remained the dominant cost driver, highlighting the critical importance of energy-efficient operation.

Keywords

fishing vessels, gas emissions, decarbonization, hybrid energy systems, microgrid, electrification

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Introduction

Environmental problems in marine sector

Global warming, driven largely by human-induced greenhouse gases (GHGs) from fossil fuels, is a critical environmental issue that is being addressed through number of measures and regulations. The Paris Agreement, effective since 2016, aims to limit global temperature rise below 2°C, ideally to 1.5°C.[1] The 2021 COP26 Glasgow Climate Pact,[2] which calls for swifter action to combat climate change, reinforces the objectives of the Paris Agreement. By 2030, it aims to reduce GHG emissions worldwide by 45% in order to limit warming to 1.5°C. Shipping accounts for 90% of international trade logistics and roughly 3%–5% of world emissions, and increased fuel use in growing global trade raises GHG emissions.[3] Since shipping is heavily fossilized compared to other industries, there is a possible increase of 17% by 2050, if no measures were undertaken.[4] Therefore, the measures set by national, regional and local authorities must also be applied in the shipping sector. Due to the depletion of fossil fuels worldwide and growing environmental concerns, energy-saving and emission-reduction technology have become essential for the shipping sector. To reduce fuel consumption and emissions, the International Maritime Organization (IMO) has implemented international regulations such as the Ship Energy Efficiency Management Plan (SEEMP) and the Energy Efficiency

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Design Index (EEDI), focused on assessing and regulating energy efficiency at the ship design stage and effective since 2013. Further efforts include the introduction of the Energy Efficiency Existing Ship Index (EEXI) in 2023, aimed at significantly reducing CO_2 emissions from ships.[5] There are also other regulations focused on lowering the sulfur level of fuel used for international ships from 3.5% to 0.5%.[6] Together, these measures are driving the maritime industry toward lower emissions and greener practices.

More than 95% of merchant ships are powered by diesel engines,[7] while efforts to reduce fossil fuel dependence are driving interest in alternative fuels and renewable energy. Additionally, integrating energy storage systems improves safety and dependability by stabilizing ship power systems.[8] Development of alternative fuels, such as Liquefied Natural Gas (LNG), biofuels, methanol, and hybrid or fully electric systems, is also being accelerated by the shift to reduced CO_2, NO_x, SO_x, and particulate emissions.[9] Perčić et al.[10] conducted a life-cycle analysis (LCA) and life-cycle cost analysis (LCCA) of various alternative fuels, evaluating both their environmental and economic impacts compared to traditional diesel engine-powered purse seiner. The results highlighted methanol as the most promising alternative, showing 22.4% lower GHG emissions and 23.3% reduction in life-cycle costs compared to diesel. While LNG showed environmental benefits, economic savings are limited due to methane slip and high initial costs. High costs, storage challenges and infrastructure requirements are major problems for hydrogen as a zero-carbon fuel and full electrification. These types of power systems offer the potential for short-sea shipping, which has lower energy requirements and frequent port stops,[11] while LNG, methanol, and similar options are more practical options for deep-sea shipping.[6]

Hybrid energy systems for ships

Due to the specific structure and operational demands of different types of vessels, implementing a single energy source is often insufficient to meet the varying power needs for propulsion, auxiliary systems, and other functions, effectively.[7] This has led to growing interest in hybrid or multi-source energy systems in maritime applications. Hybrid energy systems (HES) offer a sustainable and resilient approach, improving energy efficiency, reducing GHG emissions, and ensuring reliable power through smart energy management. Even though HES promise increased environmental friendliness, studies have to be conducted to analyze the optimal design and financial feasibility of the proposed HES topology.[12] A good example is the research on a ferry with hybrid propulsion system, which showed that effective control strategies can cut fuel consumption and emissions by 15%–35%.[13] Kolodziejski and Michalska-Pozoga[14] investigated the electrification of short-sea vessels (ferries, dredgers, tugs, etc.) using battery storage systems, reporting potential reductions in fuel use by 25% and GHG emissions by up to 50%. While challenges remain, such as high initial costs and system complexity, hybrid systems are increasingly seen as essential for a more sustainable maritime industry. Current research is also advancing toward microgrid configurations for improved integration and flexibility. As shown in Figure 1, shipping, HES, electrification, renewable energy, optimization, and microgrids are all interconnected topics. Using data from the Web of Science Core Collection,[15] from 2020 to 2024, an analysis of 3000 publications is conducted, based on keywords found in the publications (shipping, HES, microgrids, vessels, electrification). The prominent research issues are shown by the visualization, with significant clusters emphasizing electrification, renewable energy, microgrid technology, and the economic feasibility of sustainable solutions. The dominant cluster (blue) centers on electrification, closely linked to energy transition, electric vehicles, and efficiency improvements, underscores the growing focus on decarbonizing transport and integrating low-emission technologies across sectors. Red cluster focused on shipping reflects increasing research on decarbonizing maritime operations through emission reduction, fuel transition, and regulatory compliance. Orange cluster highlights renewable energy, microgrid, wind energy, and batteries, emphasizing the deployment of clean power technologies and off-grid solutions in maritime and remote contexts. Purple cluster emphasizes the financial viability and system optimization in the adoption of hybrid and renewable energy systems. Economic feasibility, including net present cost (NPC), sensitivity analysis, and techno-economic assessments, strengthen the practical considerations of adopting these technologies.

The visualization underscores the interdisciplinary nature of research in this field, where technological advancements in microgrids and hybrid power systems intersect with maritime industry challenges, investment strategies, and risk management.

Microgrids combine multiple energy sources, from renewables to battery storage and alternative fuels, to develop a self-sufficient energy system, Figure 2. This type of power system can operate both autonomously and non-autonomously (interconnected to the grid), providing benefits for different applications. Thus, research into microgrids can be found both in land applications[16] and maritime transportation.[17] Oulis Rousis et al.[17] presented a study on designing an autonomous microgrid for an island community with a main grid connection. By using an optimization software, HOMER Pro,[18] the study optimized the microgrid for minimum NPC and found a solution in the form of a configuration with a 15.3 kW PV system, a 17 kW diesel generator, and 57 kWh of lead-acid batteries. Similar research is done by Bakar et al.,[19] who designed a hybrid system of a seaport microgrid while considering cost minimization. In this case, the optimal design

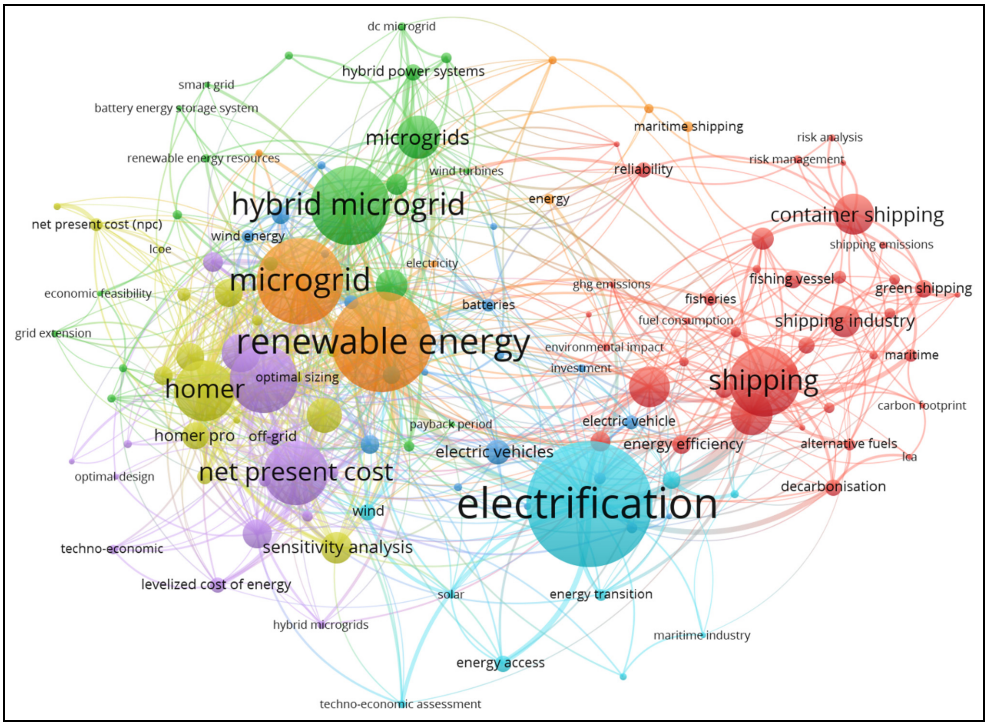


Figure 1. Co-occurrence mapping of keywords in VOSviewer.

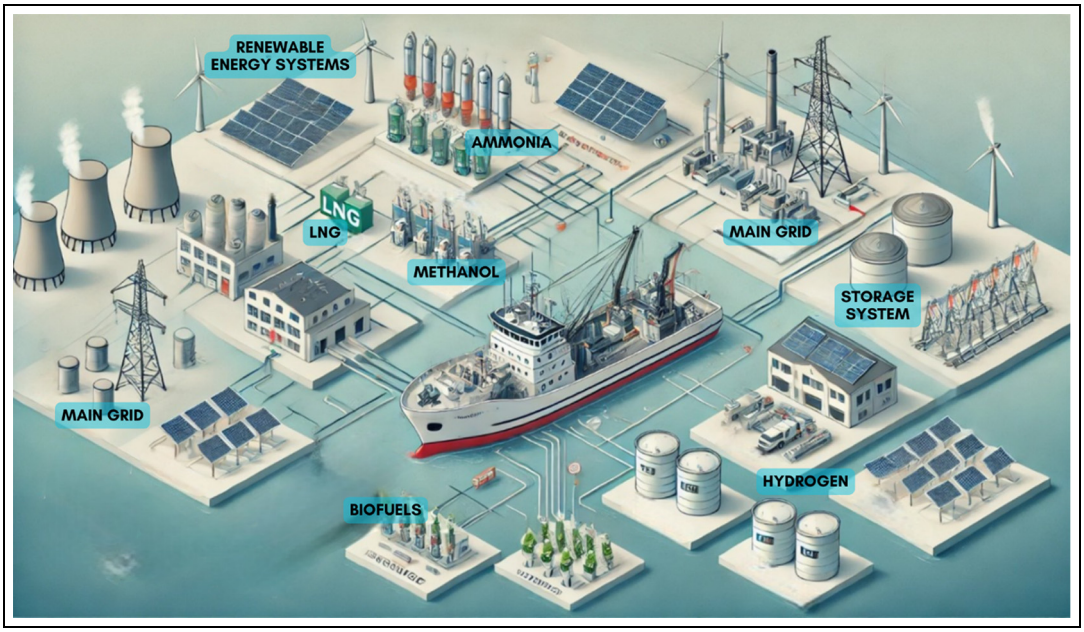


Figure 2. Example of a microgrid in the shipping sector.

resulted in a grid/PV/wind/converter configuration, eliminating the redundant battery and diesel generator components and reducing the costs.

Research gap and aim of the paper

Several limitations in existing studies analyzing the energy efficiency of fishing vessels are identified:

- Many studies evaluate only single-fuel solutions,[20] overlooking the complexity and variability of real-world operations, which affect the efficiency of fishing vessels[21];
- While some works investigate hybrid power systems that can reduce fuel consumption and emissions, they often lack real-time performance analysis under diverse operating conditions[10,22–25];

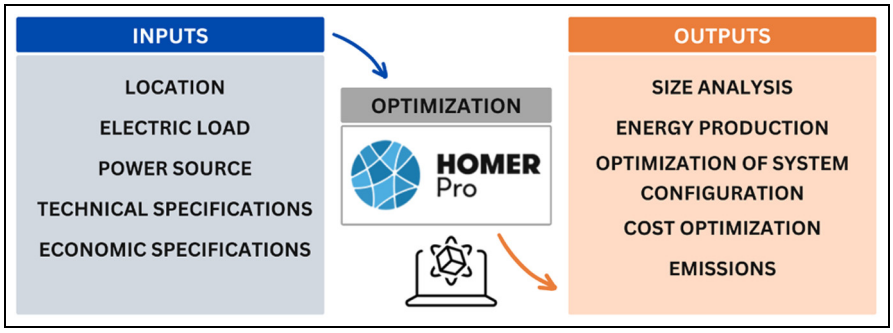


Figure 3. Inputs and outputs in HOMER Pro software.

- The studies often do not account for the significant variation across vessel types with distinct technical and operational characteristics;
- Economic analyses remain limited, with few studies considering life-cycle costs, fluctuating fuel and electricity prices, or the impact of carbon taxation.

Although there are studies promising cost reductions, such as reduced fuel costs compared to diesel-powered vessels, broader economic analyses are needed to assess the long-term financial benefits of transitioning to hybrid power systems for the fishing sector.

To deal with these limitations and research gaps, this paper presents a feasibility study and cost-benefit analysis of fishing vessels using HOMER Pro Software combined with in-house routines developed by the authors. The software is used to model two types of fishing vessels, purse seiner and trawler, and analyze different types of microgrids to find the optimal solution for their powering. Thus, the research provides several key contributions that go beyond previous works:

- Multiple powertrain configurations for two distinct types of fishing vessels (purse seiner and trawler) are compared, using real-world performance data to assess the feasibility of different hybrid microgrid setups;
- It integrates empirical operational profiles, gathered from direct fuel consumption measurements, into a techno-economic modeling framework, ensuring vessel-specific accuracy;
- Inclusion of life-cycle cost analysis (LCCA) with variable pricing for fuel, electricity and carbon tax, enables realistic evaluation of system performance over time.

By combining operational data with advanced modeling techniques and uncertainty analysis, this study offers a more comprehensive and realistic evaluation of hybrid energy systems for fishing vessels.

Methodology

Applications such as distant areas, off-grid systems, and industries requiring reliable power sources benefit greatly from the ability of microgrids. HOMER Pro aids in simulating microgrids, which are crucial for ships that depend on a variety of power sources, to guarantee effective energy utilization and low emissions.[18] The main benefit of the software is to simulate the long-term operation of a proposed microgrid, based on load data and variability in specific costs (such as carbon taxes, electricity prices, etc.), and by using optimization tools and sensitivity analysis to provide knowledge on which model shows optimal specifications. The input data and resulting outputs are presented in Figure 3.

The simulation process includes a combination of components of specific sizes and an operating strategy that defines their mutual interaction in a given environment over an extended period.[16] The system can be connected to the grid or operate autonomously and can serve both DC and AC electrical loads, as well as thermal loads. Based on inputs, the software assesses project feasibility by checking if the system meets user requirements and further calculates lifecycle costs and omptimizes power system configuration. As a result, the configuration with the lowest cost is offered. In this paper, three scenarios have been examined that reflect both current industry practices and emerging technological pathways for small- to mid-sized vessels:

(1) traditional, diesel engine-powered system, representing the conventional baseline in maritime propulsion;
(2) hybrid system (diesel generator combined with battery storage), to improve fuel efficiency and reduce emissions;
(3) plug-in hybrid system where the hybrid configuration is supplemented by the ability to charge from the electrical grid at berth.

These configurations were selected based on their technological maturity, their relevance as demonstrated

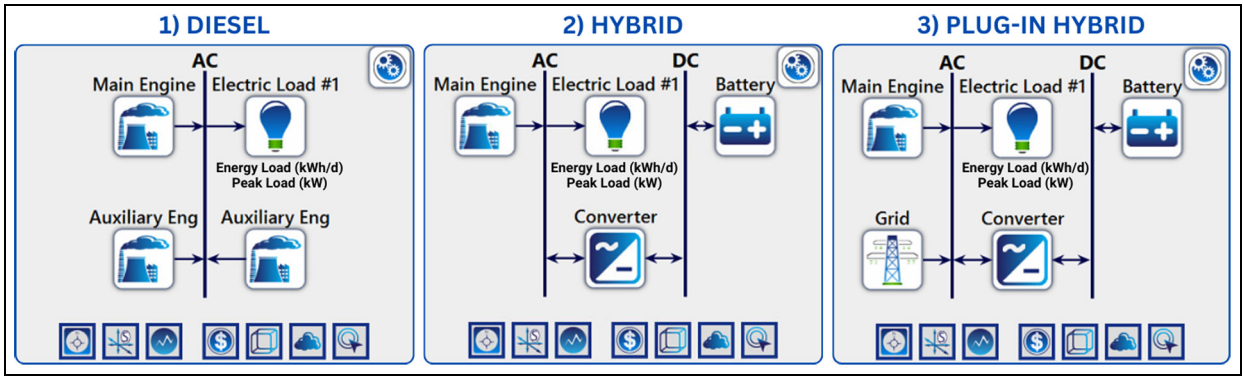


Figure 4. Microgrids designed and analyzed in HOMER Pro software.

in recent academic literature, and their applicability within the context of the ongoing maritime energy transition. The models are schematically presented in Figure 4.

The simulation offers four key financial variables, widely accepted in techno-economic evaluation practices in maritime sector: Net Present Cost (NPC), initial cost, and Operation and Maintenance (O&M) cost.[25] These metrics enable a consistent and comparative assessment of long-term financial viability. The NPC (€) presents the values of all the costs of installing and operating the system over the project lifetime, subtracting the present value of all the revenues that it earns over the project lifetime.[18] O&M (€/year) cost is the cost associated with operating and maintaining of the designed component, calculated as follows[18]:

$$C_{opm,\,other} = C_{opm,\,fixed} + C_{cs} + C_{emissions} \tag{1}$$

$$C_{cs} = c_{cs} \cdot E_{cs}, \tag{2}$$

$$C_{emmisions} = \frac{c_{CO2}M_{CO2} + c_{CO}M_{CO} + c_{UHC}M_{UHC} + c_{PM}M_{PM} + c_{SO2}M_{SO2} + c_{NOX}M_{NOX}}{1000}. \tag{3}$$

In equation (2), O&M costs include system fixed costs $C_{\text{om,fixed}}$ (€/yr), the penalty for capacity shortage C_{cs} (€/yr) and the penalty for emissions $C_{\text{emissions}}$ (€/yr). The capacity shortage penalty C_{cs} is calculated by multiplying the capacity shortage penalty c_{cs} (€/kWh) with the total capacity shortage E_{cs} (kWh/yr). In addition to a detailed economic report, HOMER Pro can also produce environmental-economic input on emissions produced during the operation of the power system and possible penalties, marked as "Emissions costs." Emission factors are required and set by default for four pollutants: carbon monoxide (CO), nitrogen oxides (NO_X), particulate matter (PM), and unburned hydrocarbons (UHCs), while fuel's carbon and sulfur content is used to determine the carbon dioxide (CO_2) and sulfur dioxide (SO_2) emissions factors.[26] The penalty for emissions calculates in the penalty of different emisisons $C_{\text{emissions}}$ (€/yr) with their annual emissions M (kg/yr).

In specific cases, O&M costs also include additional costs such as salvage and replacement. Salvage value calculates the value that remains in the component of a power system at the end of the project lifetime and it is directly correlated with its remaining lifetime[18]:

$$S = C_{rep} \cdot \frac{R_{comp} - (R_{proj} - R_{rep})}{R_{comp}}. \tag{4}$$

The replacement cost is marked as C_{rep} (€), R_{comp} (yr) marks the component lifetime and R_{proj} (yr) marks the project lifetime. The replacement costs duration R_{rep} (yr) is calculated by using the R_{comp}, R_{proj}, and INT() function, which returns the integer part of a real number[18]:

$$R_{rep} = R_{comp} \cdot INT\left(\frac{R_{proj}}{R_{comp}}\right). \tag{5}$$

Simulation of a diesel engine-powered vessel

By means of the HOMER Pro software, a model for LCCA is developed based on the technical and operational characteristics of the observed purse seiner and trawler. Depending on the vessel, the model consists of a main diesel engine, supported by one or two auxiliary engines that ensure continuous operation of the propulsion system and power auxiliary needs (e.g. cooling, lighting, net manipulation, etc.). Although HES does not include internal combustion engines in the software, to compare HES with a traditional energy system, a diesel generator is taken to simulate traditional power system behavior. The load schedule is determined by collected data on fuel consumption. The fuel consumption is collected using flow meters, installed on

board vessels, and gathered in a database accessed through MAPON software.[27] The characteristic fishing days for each month were determined and with the help of the following formula, the load P_{load} (kW) is determined using the data on fuel consumption FC (kg):

$$P_{load} = \frac{FC}{SFC \cdot t} \tag{6}$$

where SFC (kg/kWh) indicates the specific fuel consumption set at 0.215 kg/kWh for high-speed diesel engines[27] and t stands for the observed operating time in hours.

Simulation of a hybrid vessel

The implementation of batteries is a highly investigated topic, focused on reducing fuel consumption by alleviating the load on the main diesel generator. In a hybrid power configuration, the battery is charged by the main diesel engine. Additionally, a converter is used as a component which changes the electrical energy from AC to DC or vice-versa, depending on the type of equipment.[28] The load schedule is the same as the one used in the first scenario. The HOMER Pro software offers several battery storage options, from lead-acid to Li-ion batteries. Li-ion batteries, which are selected in this paper, represent a recognized, mature, and fast-advancing technology, often used in transportation research, including shipping.[29] An Advanced Storage Module, which enables battery optimization based on load requirements is also applied. The module takes into account series resistance, the impact of temperature fluctuations on battery capacity, the effect of temperature changes on battery degradation rate, and cyclic degradation based on the depth of discharge.

Simulation of a plug-in hybrid vessel

A plug-in hybrid configuration consists of a standard hybrid model, as described in Section 2.2, but the battery is also charged by connecting to the electric grid (i.e. seaport grid). Plug-in hybrid vessels offer an innovative approach in the maritime industry by combining conventional diesel or gas engines with electric propulsion and the ability to recharge through electrical outlets.[30] This allows vessels to utilize electric power for harbor maneuvers, reducing GHG emissions and pollutants such as NO_X, SO_X, and PM.[31,32] Advantages of plug-in hybrid vessels include reduced noise and vibration during electric mode operation, which is particularly beneficial in urban ports where environmental protection and passenger comfort are essential. Additionally, the technology enables the use of conventional propulsion for longer journeys or trips outside ports, ensuring reliability and range without frequent recharging. The implementation of plug-in hybrid vessels supports the maritime industry's shift toward environmental sustainability, adapting to stricter emission regulations.[33]

Case studies

The paper investigates vessels belonging to the Croatian fishing fleet, consisting mainly of trawlers and purse seiners. Trawlers account for 14% of the fishing fleet and contribute approximately 8% of the total catch by weight, which includes a variety of white fish, mollusks, crustaceans, and some bycatch. However, larger purse seiners (24–40 m) represent a smaller portion of the fleet yet dominate in landing value and weight.[27] The main difference between these two types of vessels is in their operational profile and consequently, fuel consumption, as seen in Figure 5. Their technical characteristics are presented in Table 1. Both vessels operate in the central Adriatic Sea, around cities Zadar and Primošten.

In Figure 6, the hourly fuel consumption patterns of a purse seiner and a trawler over the course of a year are presented, highlighting their differing operational profiles. The purse seiner shows highly variable fuel usage throughout the day and across seasons, with notable peaks during early morning and late evening hours, reflecting periods of net deployment and catch handling. This variability is especially pronounced during the summer months, indicating intensive operations with fluctuating power demands. In contrast, the trawler displays a more consistent daily fuel consumption profile, with steady activity concentrated between morning and early evening hours. This suggests a more uniform operational pattern, typical of trawling activities that involve continuous towing. Seasonal trends also differ. Both vessel types remain active into the winter months, with distinct periods of reduced fuel consumption (indicative of seasonal downtime). Overall, the purse seiner's profile reflects high-intensity operations with variable load, while the trawler demonstrates continuous activity with relatively stable power requirements.

Other inputs are presented in Table 2. Exact location is required to calculate emissions when using the grid since the electrical mix depends on the country being observed. The electricity mix is taken from the the software database. Values such as inflation rate, capacity shortage, etc. are all inputs that affect optimization during long-term observation.

Figure 7 illustrates the time-of-use electricity rate schedule over a year, distinguishing between two rates: rate 1 (higher cost, shown in purple) and rate 2 (lower cost, shown in light blue). Rate 1 typically applies from 07:00 or 08:00 h until 21:00 or 22:00 h, depending on the month. The remaining hours fall under rate 2. This daily variation reflects demand-based pricing intended to encourage energy use during lower-demand hours. The charging schedule presented in Figure 8 shows that purse seiners charge consistently between 06:00 and

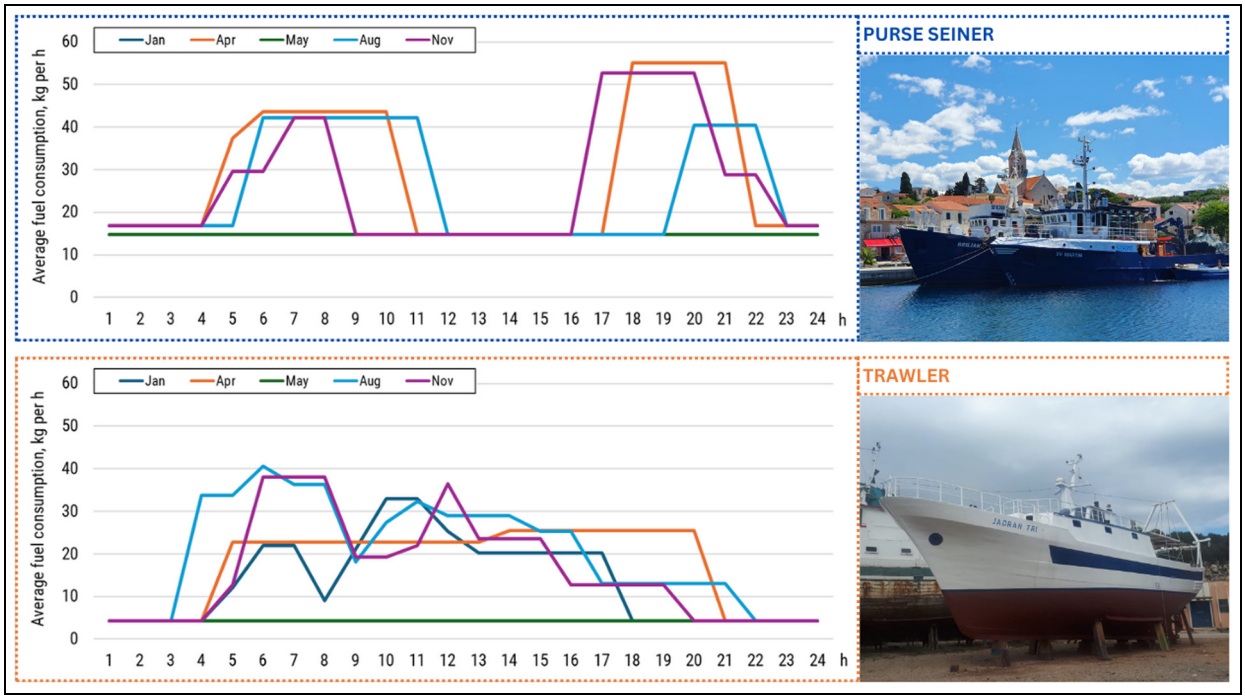


Figure 5. Average fuel consumption comparison of fishing vessels through the year.

Table 1. Main particulars of analyzed fishing vessels.

Item	Trawler	Purse seiner
Lenght overall, m	22.10	32.28
Breadth, m	5.65	7.40
Draught, m	1.99	2.88
GT	65	182
Main engine, kW	223	480
Auxiliary engine (number of engines × power, kW)	1 × 35	2 × 185

18:00, while trawlers indicate an overnight charging. This difference reflects distinct operational profiles, where purse seiners are docked and available for charging during the day, while trawlers are more likely to recharge during nighttime hours.

Results

The results of the Net Present Cost (NPC) analysis for purse seiner and trawler are summarized in Figure 10, which illustrates the breakdown of costs across several categories, including capital, operations and maintenance (O&M), emission costs and energy.

Trawlers displayed a broader range of feasible configurations compared to purse seiners, which heavily relied on fuel-intensive operations. The results emphasize the importance of balancing capital and operating costs to maximize profitability in fishing operations. The results are shown only for the optimal configuration, that is, for the models which resulted in the lowest NPC. The results of the NPC analysis are presented for fixed inputs of CO_2 penalty of 80 €/t, discount rate of 8%, inflation rate of 2% and fuel cost of 0.81 €/l.

As for the hybrid models, the purse seiner power system includes a generator of 470 kW, a Li-ion battery with a nominal capacity of 1197 kWh and a converter of 180 kW. The hybrid trawler model includes a generator of 450 kW, a Li-ion battery of 1237 kWh and a converter of 169 kW. The plug-in models include a grid connection, generators (550 kW for the purse seiner and 320 kW for trawler), Li-ion batteries (with a nominal capacity of 1695 kWh for the purse seiner and 444 kWh for the trawler) and converters (257 kW for the purse seiner and 108 kW for the trawler). Figure 9 presents the annual daily state-of-charge (SOC) patterns of batteries for a purse seiner and trawler under hybrid propulsion configurations. In the hybrid system, the SOC fluctuates continuously throughout each day and across seasons, indicating frequent charging and discharging cycles driven by variable operational loads. In both vessels, the battery operates within a broad SOC range, reflecting the dynamic interaction between the battery and the onboard engine.

In the case of the purse seiner, the highest achieved NPC is found in the diesel engine-powered model yielding 5.72 mill. €, characterized by high fuel costs, Figure 10. The plug-in model shows a NPC of 4.39 mill. €, characterized by higher capital costs and reduced fuel expenses, indicating a more energy-efficient operation. Emission costs are found in all models, between

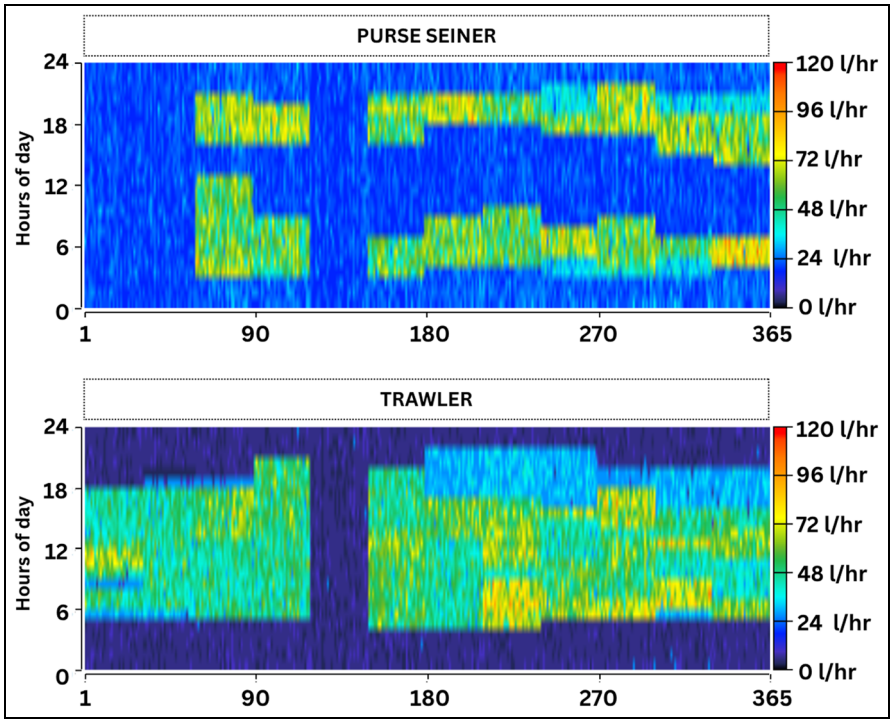


Figure 6. Fuel consumption through the year in case of diesel engine-powered vessels.

Table 2. Input data for HOMER Pro software.

Input type	Input item	Input value	Reference
General	Location	Zadar, Croatia	*selected in HOMER Pro
	Discount rate	5%–10%	*selected in HOMER Pro
	Inflation rate	2%–7%	
	Annual capacity shortage	0%	
	Project lifetime	25 years	*assumed
Load	Variability (day-to-day)	15%	
	Variability (timestep)	20%	
	Year to model	2023	
Generator	Capital cost	500 €/kW	Lao and Chungpaibulpatana[34]
	Replacement cost	500 €/kW	
	O&M cost	0.014 €/kW year	Iannaccone et al.[35]
	Fuel cost	0.81–0.99 €/l	Government of the Republic of Croatia[36]
	Lifetime	15,000 h	*assumed
Battery	Capital cost	300 €/kWh	IRENA[37]
	Replacement cost	250 €/kWh	
	O&M cost	-	*selected in HOMER Pro
	Initial state-of-charge	100%	
	Min. state-of-charge	20%	
	Degradation	30%	
Grid	Electricity cost – rate 1	0.1365 €/kWh	HEP[38]
	Electricity cost – rate 2	0.0803 €/kWh	
Converter	Capital cost	300 €/kW	*selected in HOMER Pro
	Replacement cost	300 €/kW	
	O&M cost	-	
	Lifetime	15 years	
	Efficiency	95%	

0.69 and 0.95 mill. €. The plug-in model consist of an onshore grid, with an electricity mix including a share of fossil sources, which causes costs related to emissions.

In case of the trawler, the highest NPC is indicated in the case of a hybrid model, 4.84 mill. €. Capital, replacement, and O&M costs are similar to purse seiner, suggesting an optimized allocation of resources in

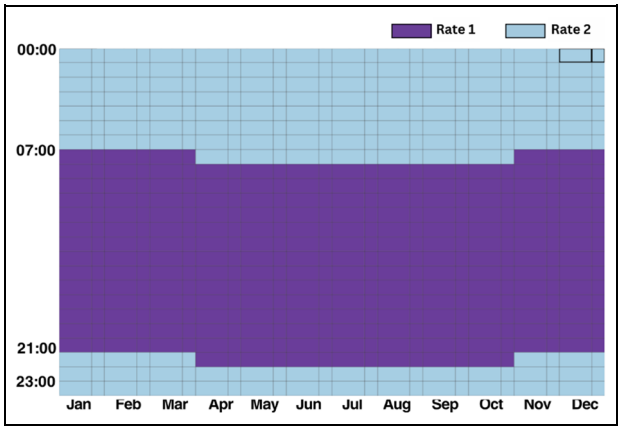


Figure 7. Electricity rates.[38]

high-performing configurations. The lowest NPC is found in the case of a plug-in model, 3.34 mill. €, associated with higher capital costs but reduced fuel consumption. Overall, fuel costs are highlighted as the largest expenses for both vessel types, emphasizing the importance of energy efficiency in improving profitability. As seen in Figure 11, fuel consumption and consequently fuel costs vary significantly across vessel types and propulsion systems, directly influencing overall operating expenses and emissions. For purse seiners, diesel engine-powered systems exhibit the highest average fuel consumption (~40 L/h), leading to elevated fuel costs and associated emissions. Hybrid and plug-in configurations reduce fuel use considerably, which not only lowers operating costs but also translates into notable emissions reductions. For trawler, the fuel consumption is lower overall. However, hybrid systems slightly increase consumption compared to diesel, thus raising both costs and emissions.

A more detailed presentation of the simulation results of harmful emissions is shown in Figure 12, for both types of vessels. In terms of CO_2 emissions, there is a noticeable drop when comparing diesel-engine to hybrid and plug-in purse seiner. Plug-in model shows higher level of CO_2 emissions compared to hybrid, with a maximum difference of 9%. As for the trawler, the highest CO_2 emissions are for hybrid systems, 25%–39% higher compared to diesel and plug-in, respectively. Diesel systems produce the most CO and NO_x emissions, while hybrid configurations reduce these significantly. Of all the possible configurations of purse seiner, diesel-engine systems have the greatest CO and NO_x emissions, with a noticeable peak in SO_2 emissions, as shown in the graph at the bottom-right. Plug-in models mainly show reduced emissions for all pollutants, reflecting their energy-efficient operation, both in the case of the trawler and the purse seiner.

The study on hybrid energy systems and electrification for vessels, conducted using HOMER Pro microgrid software, faces several limitations that should be acknowledged. First, the analysis assumes a consistent

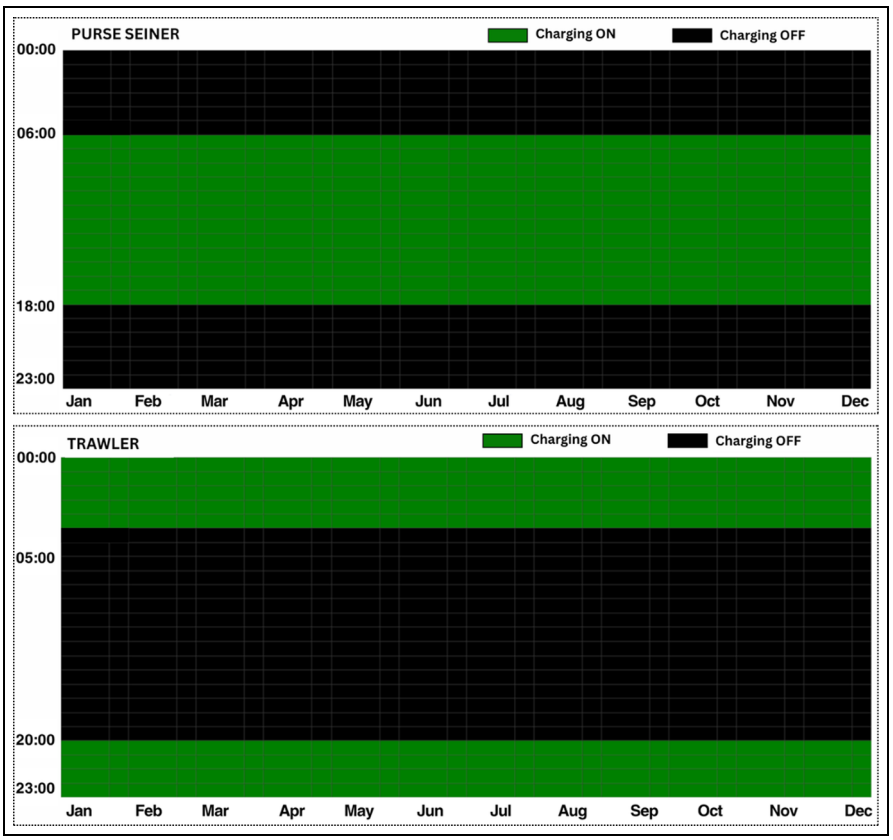


Figure 8. Battery charging schedule for purse seiner and trawler.

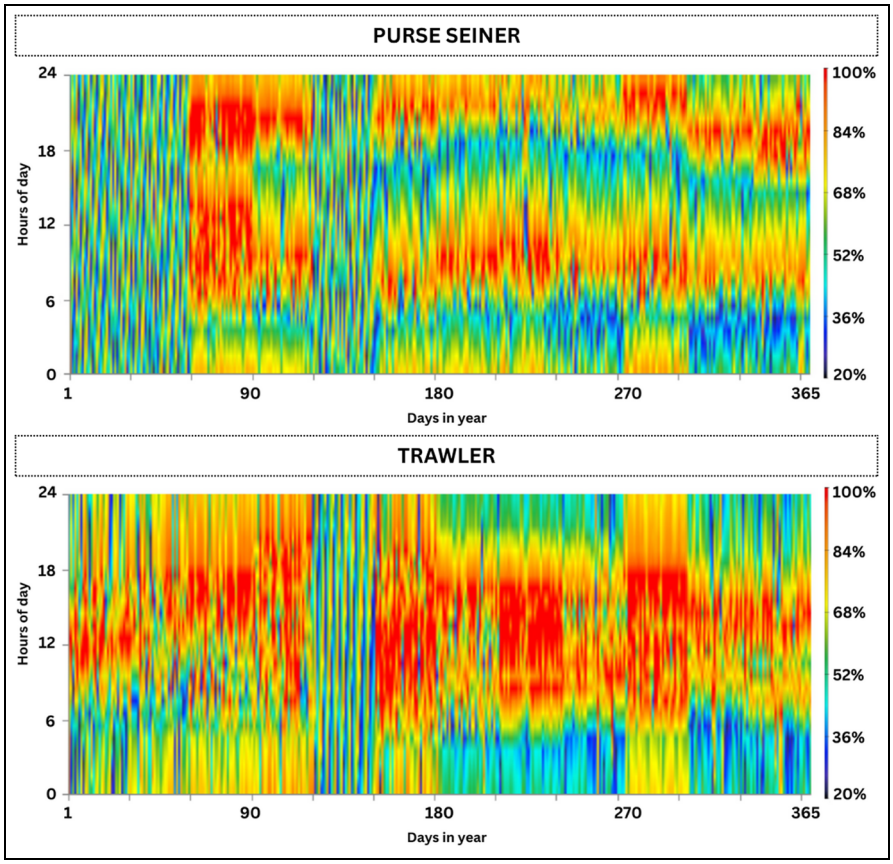


Figure 9. State-of-charge of battery in case of a hybrid power configuration.

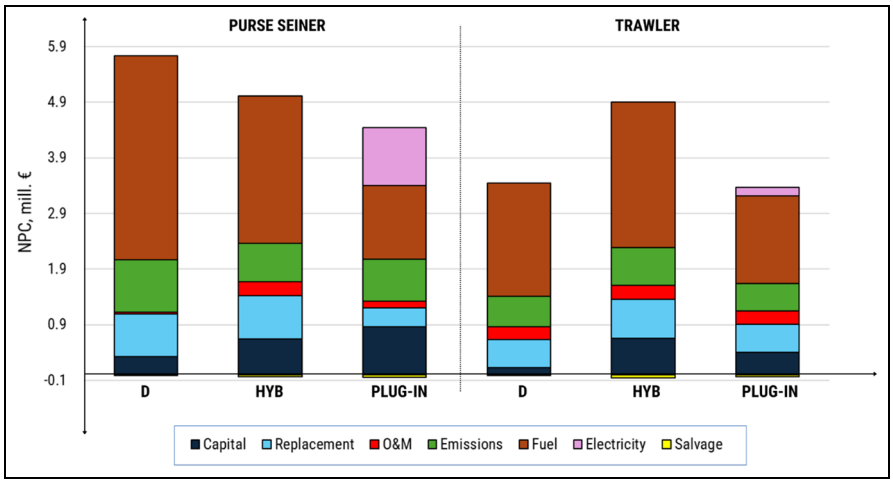


Figure 10. NPC values optimized in HOMER Pro software.

operational schedule throughout the year, focusing solely on the ship's load profile during operation. However, fishing vessels have fluctuating operational regimes, affected by season, weather changes, but also periods when the vessels are longer period in port (such as service or fishing bans). Second, the environmental and economic analysis are highly sensitive to fluctuating market conditions, such as investment and fuel costs, which vary significantly by region. Recognizing the uncertainty in fuel prices and changing rates in electricity prices, the study includes a sensitivity analysis to account for their critical role in life-cycle cost assessments. Similar results are found in previous research focused on the Croatian fishing fleet,[10,22,24,43] where the transition to alternative fuels and electrification has been investigated as part of broader decarbonization strategies. These studies highlight that the feasibility of such transitions is highly dependent on the type and

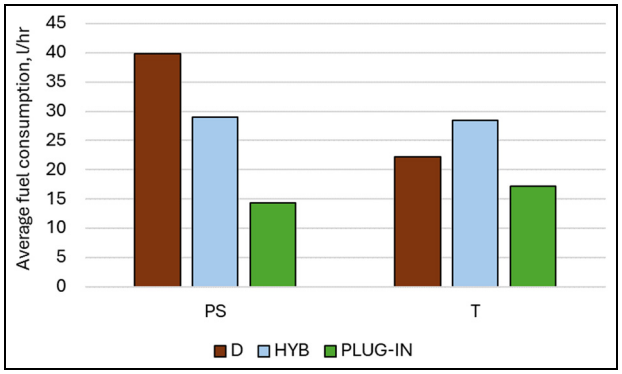


Figure 11. Average fuel consumption for different power configurations in case of purse seiner (PS) and trawler (T).

operational profile of the vessel, while facing greater challenges due to energy demand and storage requirements. Considering new findings, plug-in configurations demonstrate minimal profitability. Thus, full electrification currently appears suboptimal as a decarbonization strategy for most fishing vessels operating in Croatia, given the high investment costs and operational limitations.

An important practical consideration is the availability of shore-side infrastructure to support plug-in hybrid or fully electrified systems. In many regions, port facilities may lack the necessary charging infrastructure, grid capacity, or policy support to accommodate regular electric charging for vessels.[40–42] The successful implementation of electrified maritime systems would therefore require coordinated investment not only in vessel technology but also in onshore energy infrastructure. Additionally, the study does not account for the weight and space requirements of battery systems, which can significantly impact vessel design, stability, and operational performance. Omitting battery weight is an important limitation, as it not only affects the feasibility and efficiency of the vessel, but can also reduce cargo space and thus affect profits.

Sensitivity analyses

Sensitivity analyses are important in assessing the robustness and reliability of simulation results, especially in studies involving complex systems with uncertain or variable input parameters. Using HOMER Pro, sensitivity cases provide a ranked assessment of all feasible systems based on the simulation results. The results of the sensitivity analysis are presented in Figures 13 and 14. Four inputs are analyzed – the discount rate, the inflation rate diesel price and carbon tax level. The effects of their variability on NPC and operating costs are presented for the case of a purse seiner and trawler.

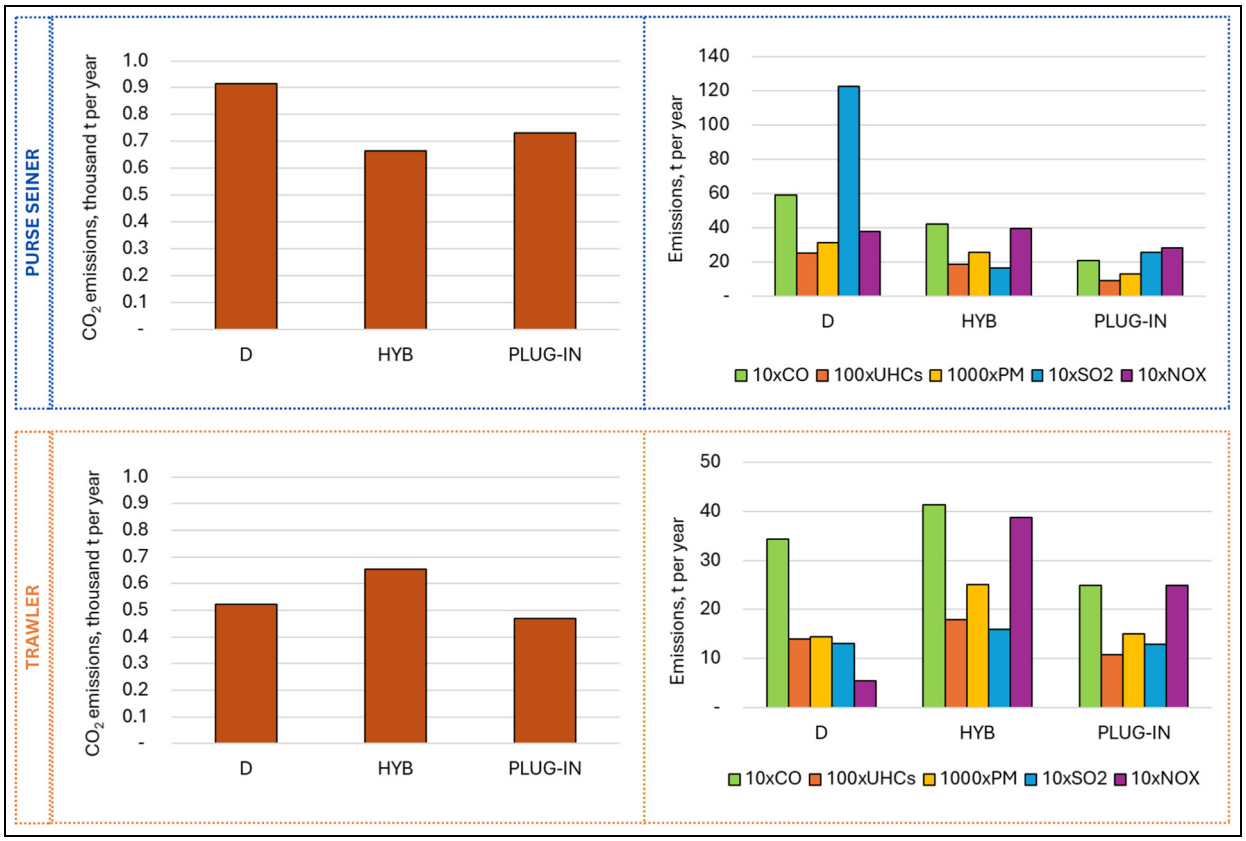


Figure 12. Emission simulation results in HOMER Pro software.

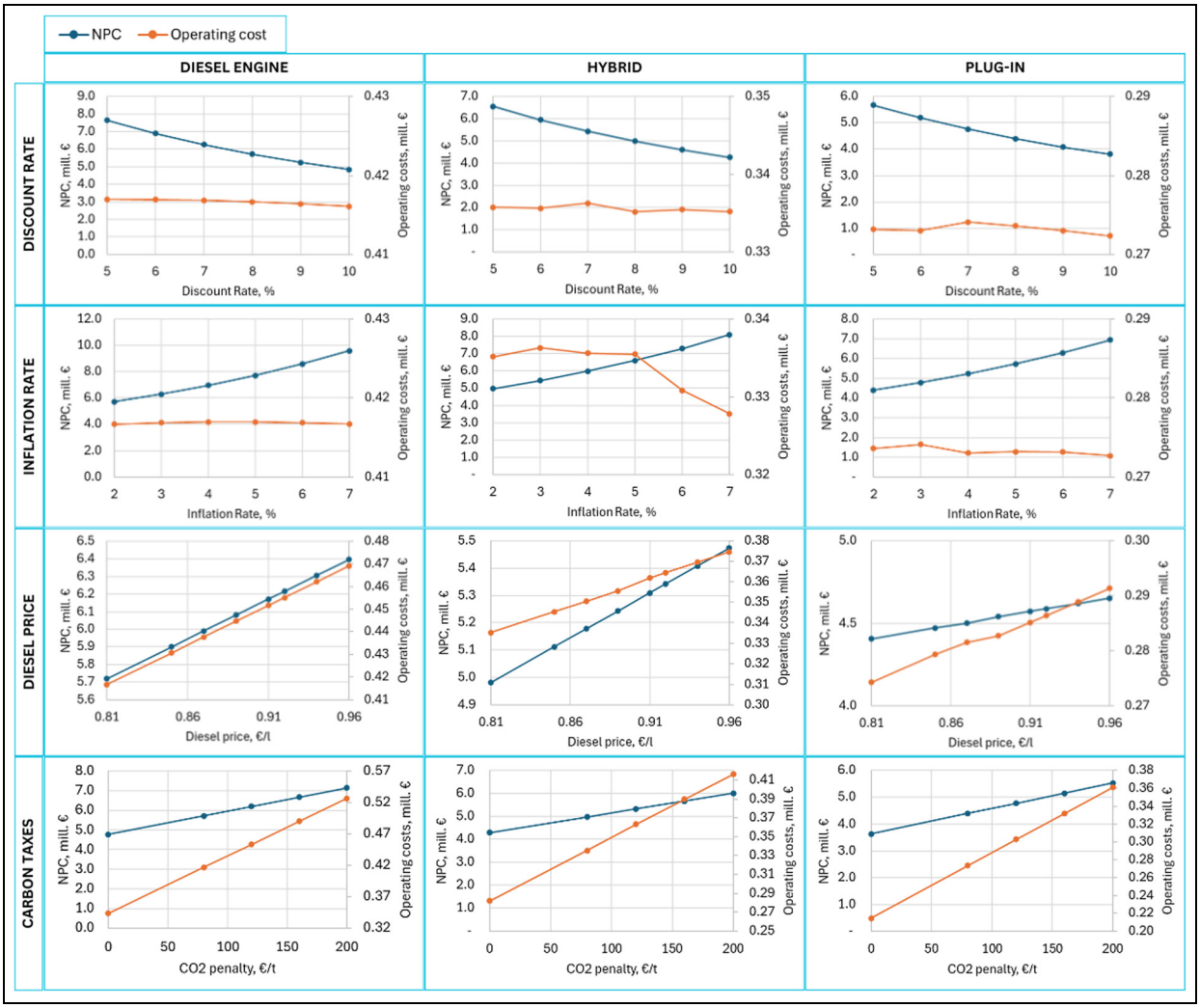


Figure 13. Sensitivity analysis of NPC and operating costs of a purse seiner.

In both cases, it can be noted that across all systems, the NPC decreases as the discount rate increases, while operating costs remain largely unaffected. In contrast, the inflation rate has a moderate influence on NPC – as the inflation rate increases, the NCP also increases. There are noticeable fluctuations in operating costs, specifically for hybrid and plug-in systems. Operating cost includes the annualized value of all costs and revenues other than initial capital costs, that is, the economic impact of the existence of various components (generator, battery, converter) is visible. Diesel price, however, has a significant impact on both NPC and operating costs for all systems, with a steep linear increase observed in configurations where fuel consumption is higher. Plug-in hybrid systems show a more moderate sensitivity to diesel price changes. The impact of increased fuel consumption is also visible in carbon taxes. Currently, the price of the carbon tax is estimated at 80 €/t CO_2, but it is expected to increase to over 200 €/t CO_2 by 2050.[43] With the increase in the price of the carbon tax, the profitability of hybrid and plug-in systems changes significantly.

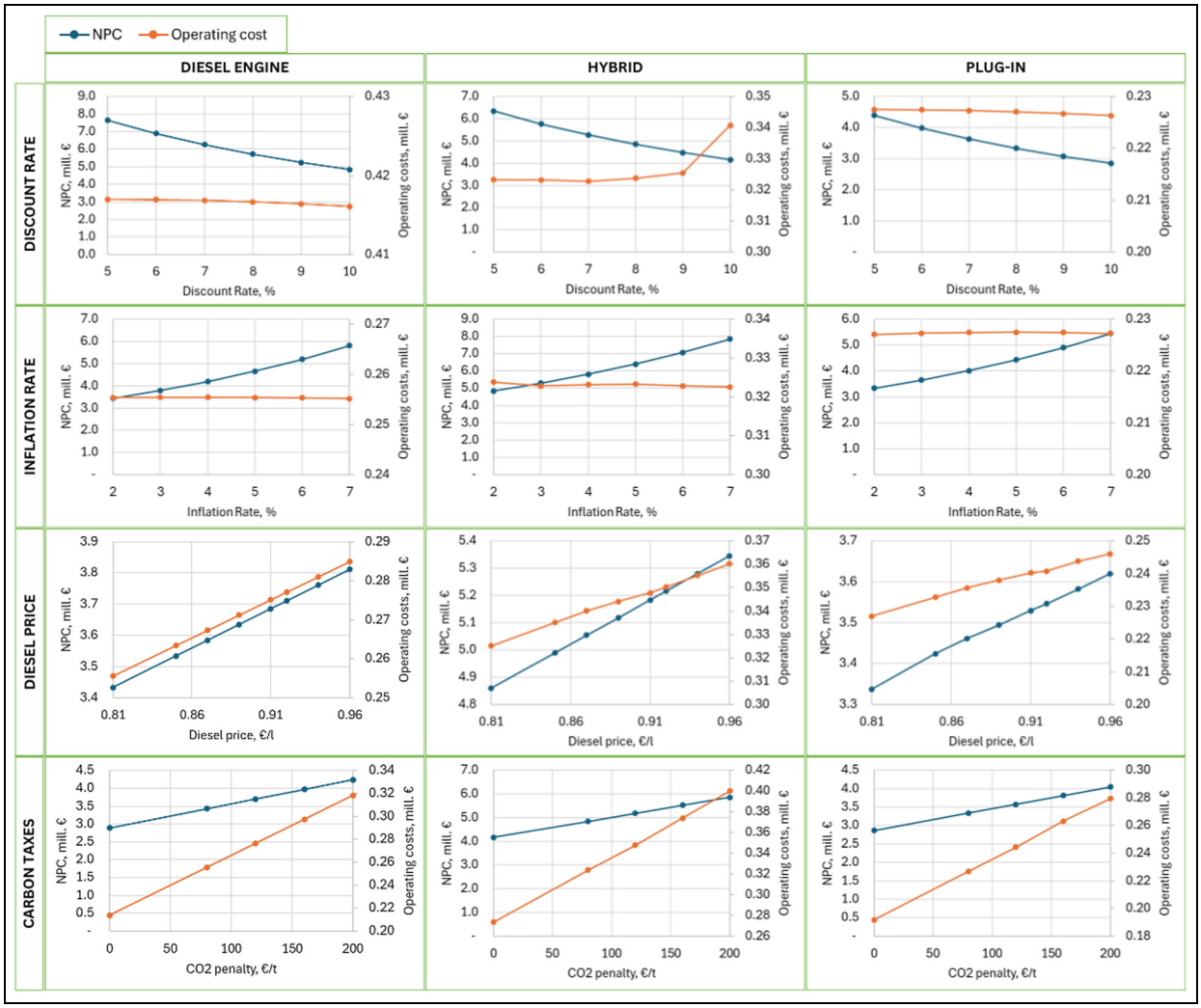


Figure 14. Sensitivity analysis of NPC and operating costs of a trawler.

Conclusions

Comprehensive and creative solutions are needed to address the environmental issues brought on by global warming, especially in the maritime sector. The study offers insights into operational viability, cost-effectiveness, and emissions reduction by analyzing scenarios ranging from conventional diesel systems to hybrid models. The economic analysis for purse seiner and trawler vessels provides crucial insights into the cost dynamics and profitability of various configurations. The findings highlight distinct performance between the vessel types and underline the importance of balancing capital and operating costs for maximum profitability.

For purse seiners, the diesel engine configuration achieved the highest NPC at 5.72 million €, driven largely by fuel expenses. The plug-in configuration, on the other hand, produced lower NPCs of 4.39 mill. €, which were distinguished by greater energy efficiency but higher investment expenditures. The model recognizes that in hybrid configuration diesel generator works near the optimum point, thus fuel costs are reduced compared to diesel engine-powered system. This is particularly emphasized in case of vessels with highly variable operative profile. Fuel cost remained the dominant expense, reflecting the energy-intensive operations of purse seiners. Emission-related costs ranged between 0.69 and 0.95 mill. €, while salvage costs were minimal, with the hybrid model contributing the most.

In case of trawlers, the hybrid model resulted in an NPC of 4.84 mill. €. This is reasonable, since the engine regularly works at high loads, and in case of hybrid solution additional energy transformation with energy loss is introduced. Although the plug-in vessel had resulted in similar fuel costs as the diesel engine model, is still resulted in the lowest NPC of 3.34 mill. €. Fuel costs were the most significant expense, similar to purse seiner, highlighting the importance of energy efficiency for profitability.

While hybrid and plug-in configurations generally reduce harmful pollutants compared to diesel systems, their effectiveness varies by vessel. For purse seiners, both alternatives lower emissions, with plug-in systems

offering the most consistent reductions across all pollutants. In case of trawler, hybrid configurations result in the highest CO_2 emissions, up to 39% higher than diesel, but still contribute to notable reductions in CO and NO_x emissions. Overall, plug-in systems emerge as the most effective option for emission reduction, particularly in energy-intensive operations.

The sensitivity analysis showed that the economic viability of all systems is greatly influenced by fuel price volatility. The diesel system is highly sensitive to fuel price changes but less affected by discount and inflation rates. The hybrid system shows balanced sensitivity to all variables, while the plug-in hybrid system exhibits similar trends but with reduced sensitivity to fuel prices compared to diesel due to reduced fuel consumption. Additionally, as carbon tax rates rise, currently projected to exceed 200 €/t CO_2 by 2050, the economic advantage of low-emission systems like hybrids and plug-ins is expected to grow, further improving their long-term viability.

The study emphasizes the significance fuel prices have on both vessel types' profitability, and it indicates that energy-efficient technology could significantly improve their long-term viability even though they need higher initial investments.

Future research should expand on this study by incorporating variable operational schedules, region-specific port infrastructure availability for electrification, and real-world implementation challenges. Additionally, the development of battery technology, renewable energy integration, and carbon pricing policies will be key factors shaping the feasibility and attractiveness of low-emission maritime technologies. A closer alignment between vessel electrification and port infrastructure development will be critical for scaling up these solutions.

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Research paper

Environmental footprint of hydrogen- and methanol-powered fishing vessel under steady and transient engine operation

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A B S T R A C T

The shipping sector is faced with ever stricter environmental regulations pushing it to reduce its environmental effect by set of technical, operational and market-based measures or their combinations. While these primarily target large merchant vessels, smaller and underregulated fleets, such as fishing vessels, also play a significant role in overall emissions. This study evaluates the environmental feasibility of methanol and hydrogen as alternative fuels for reducing the environmental footprint of fishing trawler traditionally powered by marine diesel oil. A combined 1D/0D engine model is developed using AVL Boost and validated with real-time measurement results onboard a trawler operating in the Adriatic Sea. Simulation model was used under steady-state and transient conditions, across multiple operating cycles. The results indicate that methanol–diesel blends reduce NO_x emissions by up to 82 % and CO_2 emissions by 78.5 %, though specific fuel consumption increases by about 95 % due to methanol's lower energy density. In contrast, hydrogen–diesel blends achieve up to 81.1 % CO_2 reduction and 53 % lower specific fuel consumption but result in a 52 % rise in NO_x emissions, attributed to higher combustion temperatures. The simulation of a split-cycle operation with diesel fuel yielded 8.0 % fuel savings and a 12.78 % reduction in NO_x emissions. Results demonstrate that methanol offers an immediate pathway for NO_x compliance with minimal engine modification, whereas hydrogen provides greater long-term decarbonization potential, highlighting the importance of optimizing fuel strategies for sustainable maritime operations.

Nomenclature

Variables		Abbreviations	
a	Temperature exponent (−)	0D	Zero-dimensional
BSFC	Brake-specific fuel consumption (g/kWh)	1D	One-dimensional
c	Carbon mass fraction (−)	3D	Three-dimensional
C	Multipliers (−)	CII	Carbon intensity indicator
D	User-defined coefficient (Nh^2/km^2)	CFD	Computational fluid dynamics
e	Energy substitution ratio (−)	CO	Intercooler element
E	Activation energy (J/mol)	CO_2	Carbon dioxide
FC	Fuel consumption (kg)	DF	Dual fuel
k	Chemical reaction rate ($mol \cdot m^{-3} \cdot s^{-1}$)	E	Engine element
LHV	Lower heating value (MJ/kg)	ECU	Engine control unit
m	Mass (kg)	EEDI	Energy efficiency design index

(*continued on next column*)

(*continued*)

n_1, n_2, n_3	Soot model constants (−)	EEXI	Energy efficiency existing ship index
p	In-cylinder pressure (Pa)	GHG	Greenhouse gases
R	Individual gas constant (J/kgK)	GT	Gross tonnage
T	In-cylinder temperature (K)	HPDI	High pressure direct injection
T_A	Activation temperature (K)	IMCI	International Marine Certification Institute
v	Speed (kn)	IMO	International Maritime Organization
w	Mass fraction (−)	LNG	Liquefied natural gas
x	Mass substitution ratio (−)	LOA	Length overall
τ	Time (s)	MDO	Marine diesel oil
		NO_x	Nitrogen oxides
		PM	Particulate matter
Subscripts		SEEMP	Ship energy efficiency management plan
act	Actual	SB	System boundary

(*continued on next page*)

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alt	Alternative	SCR	Selective catalytic reduction
char	Characteristic	SFC	Specific fuel consumption
CP	Combustion products	SO_x	Sulfur oxides
diff	Diffusion	TC	Turbocharger
drag	Drag force	V	Vehicle element
equ	Equilibrium		
f	Formation		
fb	Fuel burned		
fv	Fuel vapor		
KM	Kinetic multiplier		
mix	Mixture		
o2	Oxygen		
PPM	Post-processing multiplier		
ref	Reference		

1. Introduction

1.1. Maritime decarbonization framework

Fossil fuel combustion is the primary source of GHGs and other pollutants like nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM) in marine sector. The Paris Agreement, signed in 2016, set a target to limit global temperature rise to below 2 °C, aiming for 1.5 °C above pre-industrial levels (UNFCCC, 2016), with the 2021 COP26 Glasgow Climate Pact reinforcing a 45 % global GHG reduction by 2030 (UNFCCC, 2021). Shipping, responsible for 90 % of international trade, noted emissions rise by 5 % in 2022, recovering to 2017–2018 levels after a decline in 2020 (International Energy Agency, 2025). Since fossil fuels dominate the sector, emissions are projected to rise by 17 % by 2050 without intervention (Deng and Mi, 2023). The International Maritime Organization (IMO) has since introduced regulations to mitigate maritime emissions, including the MARPOL Annex VI. This regulation mandates the reduction of airborne pollutants from ships through measures like the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), targeting vessels over 400 gross tonnage (GT). Recent amendments, such as the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII), became mandatory in 2023, requiring energy efficiency reporting (International Maritime Organization, 2022a, 2022b). In line with climate initiatives, the United Nations Sustainable Development Goals (SDGs) provide a comprehensive framework for advancing environmental sustainability, economic growth, and social well-being. Several SDGs can be directly relevant to maritime decarbonization, particularly SDG 7 (Affordable and Clean Energy), which promotes the adoption of cleaner and more efficient energy systems, and SDG 13 (Climate Action), which urges urgent action to combat climate change and its impacts. The maritime industry also contributes to SDG 9 (Industry, Innovation and Infrastructure) and SDG 14 (Life Below Water) by encouraging technological innovation and reducing marine pollution. Transitioning to low- and zero-carbon fuels aligns with these goals by lowering GHG emissions, improving air quality, and fostering sustainable economic growth through green innovation. Thus, the integration of SDGs into maritime policies and fuel transition strategies ensures that emission reduction efforts not only address climate targets but also contribute to broader global sustainability objectives (United Nations, 2025).

1.2. Alternative fuels in fishing sector

Fishing vessels are the most energy-intensive part of the seafood chain, contributing up to 159 million tons of CO_2 annually – 0.1 %–0.5 % of global emissions (UNCTAD, 2024), Vessel types like purse seiners, trawlers, gillnetters, and longliners vary in fuel efficiency, with trawlers consuming relatively more due to net dragging (Koričan et al., 2022a; 2023). Fuel costs range from 15 % to 70 % of operational expenses (Basurko et al., 2015), driving the shift to alternative fuels amid rising costs and regulatory pressures. The European Economic and Social Committee (Garat Perez, 2023) supports EU fishing fleet decarbonization under the Green Deal's 2050 goals (European Commission, 2025), highlighting high costs, fuel scarcity, and an aging fleet while calling for financial support, modernization, alternative fuel development, delayed fuel taxation, and coordinated action to ensure a just transition. The European Parliamentary Research Service (Ziegler and Hornborg, 2023) outlines two decarbonization pathways: improving energy efficiency and transitioning to alternative fuels. While alternative fuels require major infrastructure investment, hybrid systems and biofuels offer short-term solutions. Energy efficiency measures, such as optimizing fleet structure, adopting low-impact fishing gear, and improving vessel technology, can further reduce fuel consumption. A phased approach combining both strategies is essential to decarbonize the fleet without compromising its viability (Ziegler and Hornborg, 2023).

Technological advances and sustainable practices in fisheries can optimize operations, reduce fuel dependency, and minimize harmful emissions, contributing to global efforts to mitigate climate change. However, 98.8 % of the global fishing fleet still relies on fossil fuels due to high investment costs and complex retrofitting requirements (UNCTAD, 2023). Studies continue to highlight the potential of alternative fuels, driven by the urgent need to reduce CO_2, NO_x, and PM emissions (Hafis et al., 2025). Zamboni et al. (2024) analysed LNG, methanol, and ammonia in cruise ship operations, emphasizing their emission reduction potential and underscoring the need for full environmental assessments to meet IMO and EU targets. Methanol has shown promise, with a life-cycle analysis (LCA) indicating a 22.4 % reduction in GHG emissions and a 23.3 % decrease in life-cycle costs compared to diesel, while LNG reduces emissions but faces challenges such as methane slip and high initial costs (Perčić et al., 2023). According to (Gabrielii and Jafarzadeh, 2020), methanol use eliminates SO_X emissions, significantly reduces PM emissions compared to diesel, lowers NO_X emissions depending on engine technology, and cuts CO_2 emissions by approximately 10 % based on fuel combustion alone. However, emission vary widely depending on the production process. Hydrogen can be used as marine fuel in fuel cells or internal combustion engines, with fuel cells offering higher efficiency and zero emissions during operative phase. However, lifecycle emissions depend on production pathways, with electrolysis from wind power having the lowest environmental impact (Stenersen, 2025). In some cases, the hydrogen production phase can result in 8 times higher emissions, compared to diesel (Koričan et al., 2022). Hydrogen fuel cells, while promising for small passenger ships by 2030, face challenges such as high costs and space requirements (Stenersen, 2025) but also no established procedures for refuelling (Snustad et al., 2024). Economic assessments provide further insight into the viability of alternative fuels. Korberg et al. (2021) analysed fuel costs, showing that methanol has low-cost potential and that fuel cells could compete with traditional propulsion systems if efficiency improvements of 15–20 % were achieved. A review by Yuksel et al. (2024) concluded that no alternative fuel currently achieves significant emission reductions in the supply chain while remaining competitive with marine gas oil. While alternative fuels and technologies show promise, their adoption faces challenges related to cost, installation complexity, and operational feasibility. This is particularly evident in studies on hydrogen power systems, which show strong potential for short-sea shipping due to its lower energy demands and frequent port stops (Melideo and Desideri, 2024). Hydrogen shows specific opportunities, such as use in hybrid systems to power generators or in fuel cells for more efficient electric drivetrains, entirely replacing internal combustion engines. Significant challenges remain, such as high costs and the necessity for specialized storage solutions like cryogenic tanks or pressurized systems. In case of smaller fishing vessel, the issues are even more complex due to existing length regulations, which restrict

their ability to secure adequate bunkering capacity (Stenersen, 2025). While most alternative fuels could be integrated into port operations with minimal adjustments, hydrogen may demand additional infrastructure, such as on-site production facilities powered by the electrical grid or local renewable energy sources (Johnson et al., 2022). Compared to hydrogen, fuels like LNG, methanol, and similar alternatives are more feasible and practical for deep-sea shipping, where longer voyages and higher energy needs dominate (DNV, 2018). Goga et al. (2025) demonstrated that biodiesel–pentanol blends can significantly lower hydrocarbon and CO emissions while maintaining satisfactory brake thermal efficiency, highlighting the potential of higher alcohols for emission control in combustion engines. Similarly, Isa et al. (2025) employed a response surface methodology to optimize a dual-fuel engine running on pentanol–biogas–diesel blends, achieving notable NO_x and smoke reductions with optimal operating conditions at 83 % load, confirming that alcohol–biogas combinations offer emission minimization and performance improvement. The research underlines the significance of multi-fuel blending strategies and statistical optimization methods (such as response surface or Taguchi analysis) in advancing low-emission diesel alternatives (Khan and Goga, 2023; Kumar and Goga, 2023). At last, hybrid propulsion systems are also promising for the fisheries sector's transition towards carbon neutrality. These systems reduce fuel consumption, improve system reliability, and lower maintenance and operating costs, especially when paired with battery energy storage and renewable sources such as solar, wind, and hydrogen (Ma'arif et al., 2025). Although numerous studies explore alternative fuels, a key limitation in current research on fishing vessel decarbonization is the widespread use of fixed specific fuel consumption (SFC) values across varying engine loads (Koričan et al., 2023; Perčić et al., 2023; Simonsen et al., 2018), especially for dual-fuel engines operating under dynamic conditions (Marques et al., 2019). This approach fails to capture the nonlinear relationship between engine load and fuel efficiency, leading to potential inaccuracies in emission assessments and energy efficiency calculations.

In the context of marine engine decarbonization Guo et al. (2025) developed a 0D full-engine simulation model for methanol–diesel mixed combustion to enable efficient design studies. These findings demonstrated methanol's potential to reduce NO_x and particulate emissions in two-stroke dual fuel engines through both experimental and 0D modelling approaches. A recent thermodynamic assessment of medium-speed dual fuel marine engines additionally showed that methanol achieves lower exergy destruction (approximately 70 %) compared to LNG (78.48 %) and ammonia, indicating its favourable efficiency characteristics under varying compression ratios, boost pressures, and air–fuel ratios (Djermouni and Ouadha, 2024). While there is a considerable number of simulation-based studies demonstrating the use of alternative fuels on board ships, this body of research is still limited in scope, since they primarily focus on larger, long-distance vessels such as cargo and container ships. In contrast, simulation research on fishing vessels has largely concentrated on aspects like marine oil leakage and accidental ignition (Li et al., 2023), or general models of fuel consumption under varying operational conditions (Davie et al., 2015; Sun et al., 2011). However, these studies do not specifically address the impact of fishing cycle duration on fuel consumption in trawl fisheries. Understanding this relationship is important for accurately estimating fuel consumption and optimizing vessel exploitation.

1.3. Dual-fuel modelling

There are two different types of dual fuel operation that depend on the mixture preparation and ignition process. In High Pressure Direct Injection (HPDI) dual fuel engine both diesel and additional (alternative) fuel are directly injected into the cylinder during combustion process (Harrington et al., 2002; Königsson et al., 2011) through a single injector. This concept requires design of combustion chamber optimized for HPDI operation and does not allow operation only with diesel fuel. In conventional dual fuel operation, additional (alternative) fuel is port injected and ignited by a small amount of directly injected diesel fuel. The conventional dual fuel operation mode can be obtained by a relatively easy conversion of existing Diesel engines, which has a significant importance in bringing this technology to a market (Königsson et al., 2011).

Upgrades of engine design and conversion to other combustion modes usually includes the application of different complexity simulation models, ranging from 3D-CFD to real time simulations for setting up engine control units. In terms of model complexity and predictivity, so-called cycle simulations are somewhere between 3D-CFD and real time models. Modelling of combustion process in dual fuel operation for cycle simulations becomes very challenging due to neglected spatial effects in the cylinder domain. To overcome this drawback the quasi-dimensional dual fuel combustion model can be applied (Taritas et al., 2017) considering the in-cylinder turbulence and combustion chamber geometry effect on the burning rate. Such combustion models are detailed enough that it can be applied to perform the optimization of injection parameters on the engine performance and emissions (Kozarac et al., 2018). On the other hand, the simulation of transient engine operation (e.g. simulation of driving cycles) requires fast combustion models to simulate engine performance within a reasonable computational time. Single Vibe function can be utilized for the calculation of burned fuel for diesel operating mode, while three different Vibe functions were employed to calculate diffusion and premixed combustion in dual fuel operation of marine engine (Stoumpos et al., 2018). In this study, the single Vibe function was used for the calculation of combustion rate of diesel and conventional dual fuel mode (methanol-diesel and hydrogen-diesel), making the cycle simulation model robust and fast enough under steady and transient engine operation with accurate prediction of fuel consumptions and nitrogen oxides emissions.

1.4. Research gap and aim of the study

Although the potential of alternative fuels in the decarbonization of the marine sector has been widely explored in recent years, several significant research gaps remain, particularly in the context of fishing vessels:

- Most existing studies primarily focus on long-distance maritime transport or short-sea ferry operations, while research into fishing vessels is comparatively limited.
- Available studies on fishing vessels often adopt simplified approaches to modelling specific fuel consumption across varying engine loads, which limits the accuracy of emission assessments, especially for dual fuel engines.
- There is a need for more refined and realistic mathematical models to capture the relationship between load profiles and fuel consumption more accurately.
- Research to date has mostly concentrated on GHG emissions, with relatively few studies addressing NO_x emissions, despite their importance under highly variable engine loads typical for fishing operations.
- Limited measurement data for fishing vessels makes validation of simulation models and desk-based analyses rather difficult.
- To the best of authors knowledge, there are no studies considering effect of fishing cycle duration in trawl fisheries on fuel consumption.

By simulating engine operation, this study aims to address these gaps and to assess the feasibility of methanol and hydrogen onboard fishing vessels. Using the 1D/0D AVL Boost™ model, which involves real-time onboard monitoring data on fuel consumption for the model validation, the study provides a more precise evaluation of fuel consumption and emission production for both fuels. The main objectives of the study are to:

- Quantify the fuel consumption and emission performance of methanol and hydrogen using data-driven engine simulation,
- Investigate the effect of fishing cycle duration on fuel consumption and emissions of fishing trawler by direct simulations, by splitting the operating cycle on two equal 2.5-h net trawling periods,
- Evaluate emission factors for CO_2 and NO_x across various substitution ratios with diesel fuel.

By providing a more dynamic and data-driven evaluation, this study contributes to the ongoing discourse on sustainable fisheries by identifying viable pathways for decarbonization while maintaining operational and economic feasibility.

2. Illustrative example

Trawlers represent 14 % of the Croatian fleet but contribute only 8 % of total catches in terms of weight (Ministry of Agriculture of Republic of Croatia, 2023). They primarily harvest white fish, such as cod, haddock, and pollock, along with molluscs, crustaceans, and some bycatch. Despite capturing a smaller share, their focus on high-value white fish ensures comparable profits to purse seiners, which primarily target small pelagic fish (Koričan et al., 2023). Trawlers, with an average overall length (LOA) of 19 m and engine power between 150 and 250 kW, are smaller and less powerful than purse seiners, with a gross tonnage (GT) nearly half that of their counterparts. In this paper, operation of a Croatian trawler operating in the Zadar region is investigated and its main particulars are presented in Table 1.

The operating cycle of the fishing vessel is monitored using a system that tracks both the main and auxiliary engines. Equipped with fuel monitoring systems, GPS, and switches that indicate when specific engines are activated or deactivated, the vessels provide real-time data visualization through the MAPON software. This data includes information on the vessel's velocity, route, operating time, and location (Koričan et al., 2023). GPS device used in the presented study is Teltonika FMB640. It primarily utilizes the Doppler shift method, where the device determines speed by analyzing the change in frequency of satellite signals caused by the motion of the vessel. This approach provides a high level of accuracy and is largely independent of temporary position fluctuations, resulting in a typical speed error of about 0.1 m/s under normal conditions. As a secondary method, the device may also calculate speed from consecutive position fixes (distance over time), although this approach is more sensitive to positional noise and therefore less accurate. In practice, the FMB640 achieves an accuracy of approximately 0.1–0.2 m/s, which is sufficient for maritime navigation and energy analysis. The specification "<0.1 m/s (within ±15 % error)" reflects both the typical Doppler-based precision (<0.1 m/s) and a worst-case relative deviation (±15 %) observed under degraded signal conditions, such as poor satellite geometry, multipath effects or partial antenna obstruction. The monitoring system also includes fuel flow meters, which measure fuel consumption by tracking the difference between fuel supply to the engine and return flow to the tank, typically between the tank and the low-pressure fuel pump. The fuel flow was measured by DFM Marine 1000CCAN TA flow device with measuring range from 0.02 m^3/h to 1 m^3/h and measuring uncertainty of ±0.5 %. The data collection via fuel flowmeters started in May 2022 and is still in progress. The data is sent to the server every 30 s. Trawling nets are a key factor in both fuel consumption and catch quality. The trawl net directly influences energy use, as the drag of the net typically accounts for about 60 % of a trawler's total gear resistance (Maynou et al., 2021). Trawling speed also has a direct influence on the net mouth, which then affects fishing efficiency. At higher towing speeds, the net mouth tends to open wider, increasing the area and potential catch rate, but excessive speed can deform the net, raise fuel consumption, and cause fish to evade capture. In contrast, at lower speeds, the net opening narrows, reducing water flow and catch efficiency due to diminished net volume and fish entry rate (Xiong et al., 2024). Modifications to the trawl gear, such as altering the mesh size or rigging, can enhance selectivity, reducing bycatch and improving both biological and economic outcomes. These changes, along with improved gear efficiency, contribute to better fuel usage and more sustainable trawling practices (Fakıoğlu et al., 2022).

Table 1
Main particulars of the observed trawler.

Lenght Overall, m	22.1
Breadth, m	5.65
Draught, m	1.99
Gross Tonnage	65
Design speed, kn	6.3

The vessel is propelled by a Cummins NT855-M300 four-stroke diesel engine with main parameters specified in Table 2. The engine is equipped with a turbocharger and intercooler producing the maximum brake power of 224 kW at engine speed of 1800 rpm. According to the engine manufacturer data, the engine satisfies the IMO TIER 2 standard related to maximum NO_x emissions.

In this study the selected two operating cycles during net hauling process are selected. The first operating profile lasts 99 min with average fishing vessel speed equal to 2.73 kn and average fuel consumption of 29.77 L/h. The second operating profile is more dynamic with period of 297.5 min, with average speed of 3.31 kn and average fuel consumption of 25.29 L/h. More details about operating profiles, such as measured velocity profiles and fuel consumptions, can be found under Results section.

3. Methodology

In this study, the cycle simulation model was used to evaluate the influence of alternative fuels in dual fuel combustion on the carbon footprint and NO_x emissions. First, the simulation model was calibrated according to fuel consumption at full load conditions and at several operating points that lay on the typical propeller curve. The NO_x emission sub-model is calibrated at full load condition with nominal engine speed where calculated NO_x emission does not exceed IMO TIER 2 limit.

There are two parts of simulation; the first is based on the engine steady state operating conditions, while the second part includes the simulation of transient engine operation during the period of fishing vessel net towing. In order to define the steady operating point of the engine, measured fuel flow data were used. Assuming the consistency of propeller curve defined by engine manufacturer with the characteristics of propeller used in the selected fishing vessel, it is possible to define the engine speed that corresponds to measured fuel flow, as illustrated in Fig. 1a. After that, the propeller curve of required power was used to define the engine brake power that should be delivered to propeller, Fig. 1b. The engine speed and brake power, specific for each operating cycle of net towing, are then simulated under the different combinations

Table 2
Data and performance of main engine.

Engine	Cummins NT855-M300
Type	4-cycle, water cooled
Aspiration	turbocharged, intercooler
Cylinder arrangement	inline
No. of cylinders	6
Cylinder bore	140 mm
Piston stroke	152 mm
Compression ratio	14.5
No. of valves	2 intake, 2 exhaust
Idling speed	575–650 rpm
High idle speed range	1962–2106 rpm
Maximum brake power	224 kW at 1800 rpm
Maximum brake torque	1306 Nm at 1500 rpm
Emission standard	IMO TIER 2

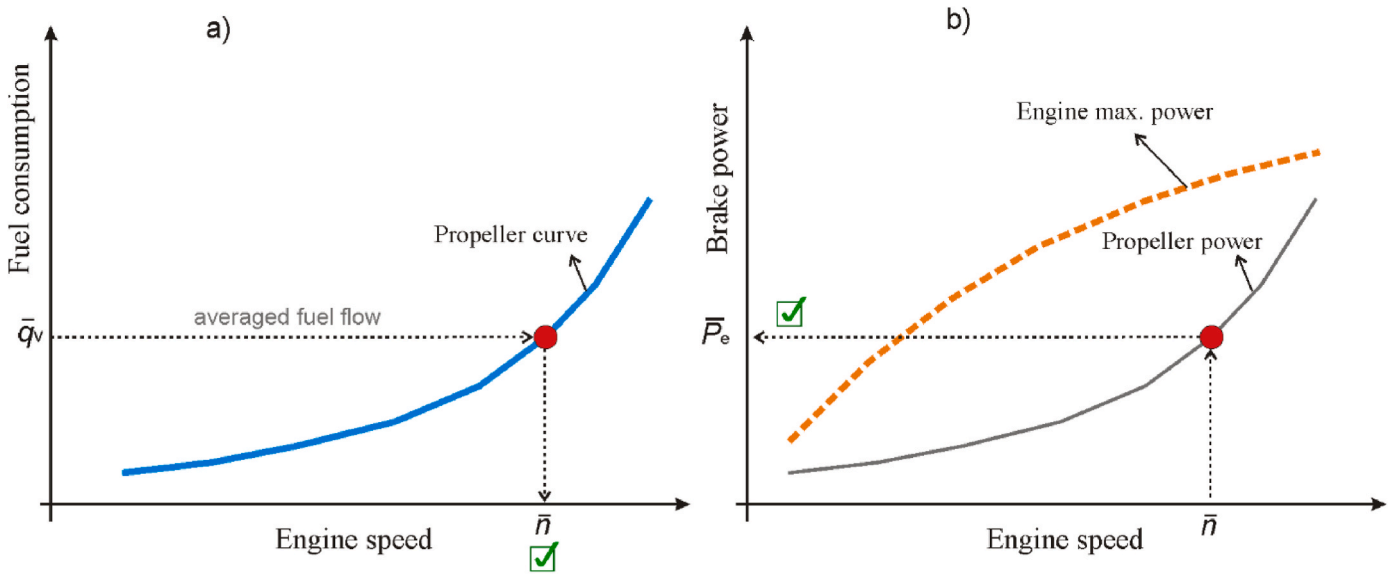


Fig. 1. Definition of steady state operating point, a) engine speed definition using the measured fuel flow and propeller curve, b) definition of required engine brake power using a propeller power curve.

of diesel fuel substitution ratios with alternative fuels.

The transient engine operation was performed simulating the net towing cycles, where the measured vessel speed was imposed as input data into a simulation model. The total drag force of fishing vessel was calibrated to achieve agreement between measured and simulated cumulative fuel consumption, as illustrated in Fig. 2. After that, each operating cycle was analysed under the application of dual fuel combustion with alternative fuels.

Green methanol and hydrogen were considered as alternative fuels for dual fuel combustion with energy substitution ratios equal to 20 %, 40 %, 60 % and 80 %. The results of CO_2 and NO_x emissions and emission factors were compared for different substitution ratios and for the steady and transient engine operating conditions as well.

The full simulation model of Cummins NT855-M300 engine, whose main data are listed in Table 2, was made in AVL Boost™ version 2013.2. The architecture of engine simulation model is shown in Fig. 3.

The engine intake system is described from the system boundary (SB1) element to the intake ports defined by pipe elements 5–10. The engine is equipped with a turbocharger (TC1) and intercooler element (CO1). The exhaust system starts from exhaust ports (pipes 11–17) to system boundary 2 (SB2), where exhaust gases flow out to the environment. Engine element (E1) defines the firing order, engine friction and engine inertia required for transient engine operation. Vehicle element (V1) is connected via mechanical connection to the engine representing the direct connection of the vessel propeller to the engine crankshaft. Vehicle element data include vehicle load characteristic, mass and desired vehicle velocity table that is typical for each vessel operating profile. The ECU1 is applied to control the energy of fuel delivered into cylinders depending on the instantaneous engine load. In the case of diesel engine operation, ECU element controls the mass of diesel fuel directly injected into each cylinder, while in dual fuel operation it controls the total mass of diesel and alternative fuel injected into cylinder. In the conventional dual fuel engine, the intake ports are equipped with low pressure injectors, preparing the premixed mixture of alternative fuel and air, that is ignited with the diesel pilot injection in the cylinder. Since the applied simulation model cannot define the fuel

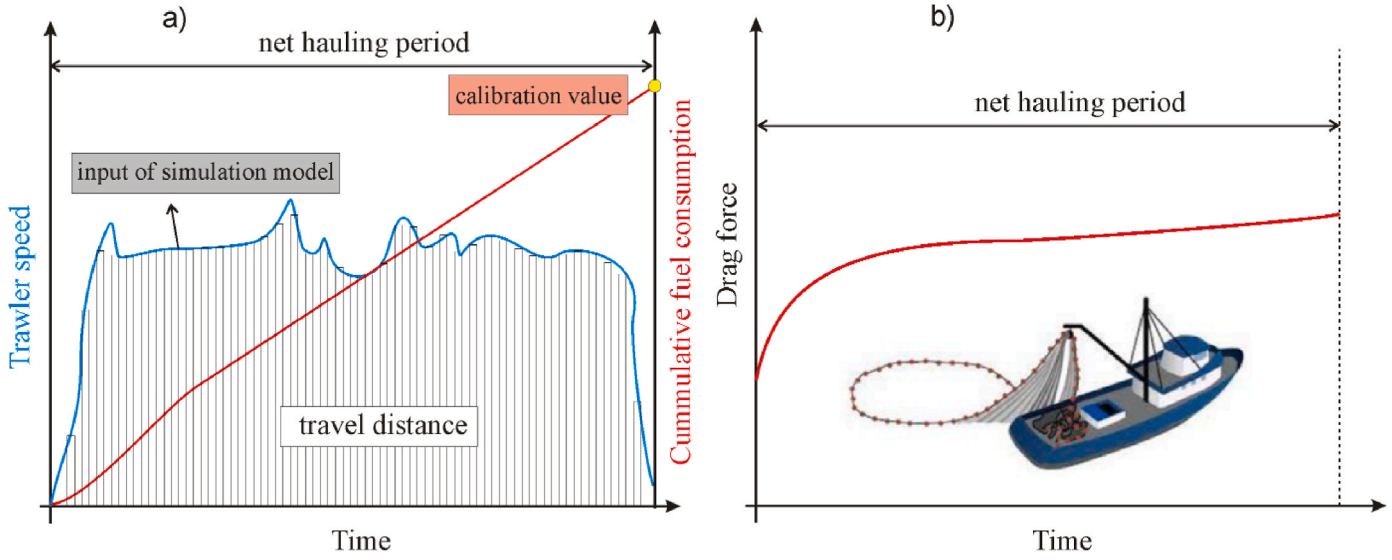


Fig. 2. Definition of transient engine operation; a) illustrative example of fishing vessel speed profile and cumulative fuel consumption, b) adoption of drag force during net hauling.

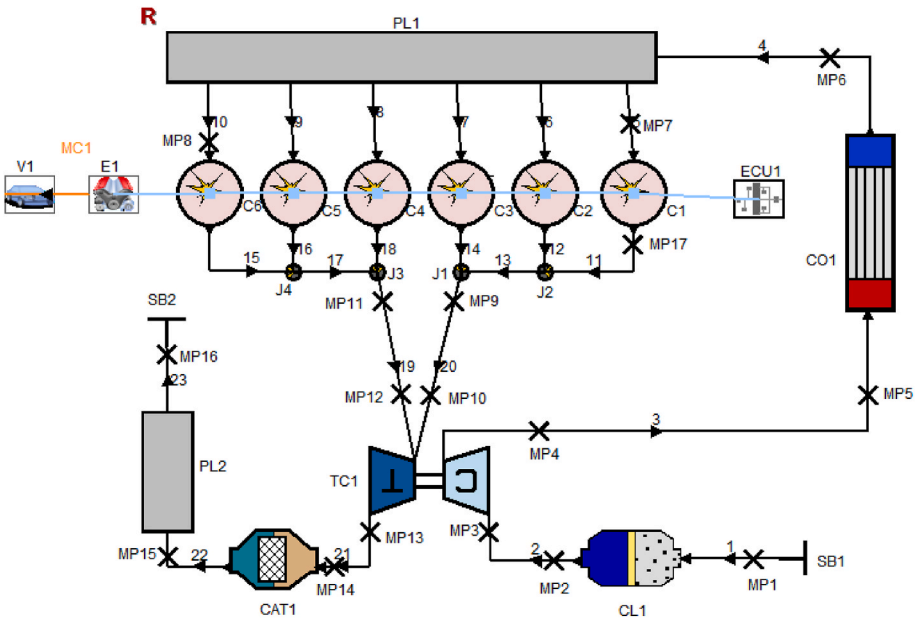


Fig. 3. 1D/0D simulation model of fishing vessel propulsion system in AVL Boost™.

injection at two locations (at intake port and cylinder), dual fuel operation was simulated with the direct injection of fuel mixture (alternative fuel and diesel) into cylinders. With such model simplification only air and potentially residual gases are compressed that is typical for direct injection dual fuel engines.

The combustion process of conventional diesel and dual fuel engine in this study is calculated with the adoption of single Vibe function with two zone modelling approach where thy cylinder mass during the combustion process is divided into burned and unburned zone. The simulation of dual fuel combustion in 1D/0D simulation models is commonly performed with the application of single-, two-, multiple-Vibe functions (Stoumpos et al., 2018) or advanced quasi-dimensional combustion models (De Felice et al., 2025; Frerichs and Eilts, 2022). The modelling of conventional diesel-natural gas dual fuel with the application of single Vibe function was performed in (Lebedevas et al., 2020). For the range of engine load defined by brake mean effective pressure (BMEP) from 2 to 6 bar the Vibe shape parameter was fixed to 0.6 while the combustion duration was varied from 65° to 200° of crank angle as the engine load was lower. The maximum modelling error of indicating parameters was equal to 15 % compared to experimental results. Investigation of different injection parameters on the combustion process of diesel-natural gas was presented in (Kozlov et al., 2019). The modelling of combustion with single Vibe function resulted with range of shape parameter and combustion durations. For engine loads defined by BMEP from 5.5 bar to 8.2 bar the shape parameter was varied in range from 1.2 to 1.53, with the variation of combustion duration from 20° to 70° of crank angle. Hydrogen-gasoline dual fuel combustion was experimentally investigated in (Kiss et al., 2025) together with the validation of single Vibe function with two-zone modelling approach. It was found that Vibe shape parameter ranges from 1.5 to 2.18 with combustion durations around 65° of crank angle.

Introduction of two or multiple Vibe functions increases the number of input parameters such as combustion durations, shape parameters, start of combustion by each Vibe function etc. Multiple Vibe function would lead to better prediction of combustion burning rate creating better preconditions for the emission modelling but set of previously mentioned input parameters should be defined according to reference (preferably experimental) data. Furthermore, input parameters of multiple Vibe function should be modified for each mass substitution ratio of alternative fuel because the behaviour of diffusion and premixed (flame propagation) combustion changes accordingly. Since experimental data with dual fuel combustion of analysed engine and fishing vessel are not available, single Vibe function was applied in this study reducing the number of input parameters to minimum level. Although the absolute values of emissions are affected, general trends of emissions from dual fuel combustion will not be changed significantly by the modification of Vibe parameters, as it was demonstrated in (Duong et al., 2025).

Description of gas composition (species transport) and the calculation of gas properties in this study is based on the classic species transport approach where the mixture is defined by mass fractions of fuel vapor, combustion products and air. Conservation equations for combustion products (CP) and fuel vapor (FV) are solved, while the remaining mass fraction of air (w_{air}) is calculated from the following equation:

$$w_{air} = 1 - w_{FV} - w_{CP}. \tag{3}$$

The calculation of NOx emissions is performed with Zeldovich mechanism where the burned zone, as high-temperature region, was used as input parameter. Six reactions were considered, based on the well-known Zeldovich mechanism (Rao et al., 2022). The specification of calculated reaction rates and coefficients using the Arrhenius-type form are given in Table 3.

The final rate of nitrogen oxide change is calculated as follows:

Table 3
Reactions and coefficients considered for the overall NO_X emission.

	Stoichiometry	Reaction rate $k_i = k_{0,i} \cdot T^a \cdot e^{\left(\frac{-T_{Ai}}{T}\right)}$	$k_0 \left[\frac{mol}{cm^3 \cdot s \cdot K}\right]$	a [−]	T_A [K]
R_1	$N_2 + O = NO + N$	$r_1 = k_1 \cdot c_{N2} \cdot c_O$	$4.93 \cdot 10^{13}$	0.0472	38048.01
R_2	$O_2 + N = NO + O$	$r_2 = k_2 \cdot c_{O2} \cdot c_N$	$1.48 \cdot 10^{8}$	1.5	2859.01
R_3	$N + OH = NO + H$	$r_3 = k_3 \cdot c_{OH} \cdot c_N$	$4.22 \cdot 10^{13}$	0	0
R_4	$N_2O + O = NO + NO$	$r_4 = k_4 \cdot c_{N2O} \cdot c_O$	$4.58 \cdot 10^{13}$	0	12130.6
R_5	$O_2 + N_2 = N_2O + O$	$r_5 = k_5 \cdot c_{O2} \cdot c_{N2}$	$2.25 \cdot 10^{10}$	0.825	50569.7
R_6	$OH + N_2 = N_2O + H$	$r_6 = k_6 \cdot c_{OH} \cdot c_{N2}$	$9.14 \cdot 10^{7}$	1.148	36190.66

$$r_{NO} = C_{PPM} \cdot C_{KM} \cdot 2 \cdot (1-\alpha^2) \cdot \frac{r_1}{1+\alpha \cdot AK_2} \cdot \frac{r_4}{1+AK_4}, \quad (4)$$

where:

$$\alpha = \frac{c_{NO,act}}{c_{NO,equ}} \cdot \frac{1}{C_{PPM}}, AK_2 = \frac{r_1}{r_2+r_3} \text{ and } AK_4 = \frac{r_4}{r_5+r_6} \quad (5)$$

The constant C_{PPM} $(-)$ represents the post-processing multiplier, while C_{KM} $(-)$ is NOx kinetic multiplier for tuning the calculated exhaust gas emission level.

The soot emissions model considers the formation and oxidation mechanism (Schubiger et al., 2002). The soot formation reaction is related to the diffusion combustion rate, while the oxidation mechanism depends on the actual soot mass and available oxygen in the burned zone. A soot formation reaction is related to the combustion rate of diffusion combustion $\frac{dm_{fb,diff}}{dt}$:

$$\frac{dm_{soot,f}}{dt} = A_{S,f} \cdot \frac{dm_{fb,diff}}{dt} \cdot \left(\frac{p}{p_{ref}}\right)^{n_1} \cdot e^{\frac{E_{s,f}}{R_m T}} \quad (6)$$

where $A_{s,f}$ $(-)$ is soot formation tuning parameter, p (Pa) is actual in-cylinder pressure, p_{ref} (Pa) is reference pressure, $E_{s,f}$ (J/mol) is activation energy for soot formation. The soot oxidation reaction depends on the actual soot mass in the cylinder and available oxygen in the burned zone:

$$\frac{dm_{soot,o}}{dt} = A_{S,o} \cdot \frac{1}{\tau_{char}} \cdot m_{soot}^{n_2} \cdot \left(\frac{p_{o2}}{p_{o2,ref}}\right)^{n_3} \cdot e^{\frac{E_{s,o}}{R_m T}} \quad (7)$$

where $A_{s,o}$ $(-)$ is soot oxidation tuning parameter, τ_{char} (s) is characteristic mixing time related to overall heat release rate, m_{soot} (kg) is actual soot mass, p_{O2} (Pa) is partial pressure of oxygen, $p_{O2,ref}$ (Pa) is reference partial pressure of oxygen, $E_{s,o}$ (J/mol) is activation energy for soot oxidation. In both equations (6) and (7) R_m (J/kgK) and T (K) are individual gas constant and temperature of burned zone, respectively. In addition, n_1, n_2, n_3 $(-)$ are fixed model constants.

CO_2 emissions are calculated using a known carbon mass ratio in the fuel and the stoichiometric equation of the carbon oxidation process:

$$1 \text{ kg } C + \frac{32}{12} \text{ kg } O_2 \rightarrow \frac{44}{12} \text{kg } CO_2. \quad (8)$$

Equation (8) indicates that burning of 1 kg of carbon will produce 44/12 kg of carbon dioxide. Total CO_2 emissions for driving cycles are calculated using the following equation:

$$CO_2 \text{ [kg]} = \frac{44}{12} \cdot \text{Fuel consumed [kg]} \cdot \text{Carbon mass fraction [-]}, \quad (9)$$

where carbon mass fractions for each applied fuel and mixtures are specified in Table 4.

In the conventional diesel engine, where diffusion flame is dominant, the shape parameter of Vibe function was set to 1.0 according to AVL Boost user's guide. When the dual fuel combustion of methanol and diesel is considered, the shape parameter was increased gradually as the energy ratio of methanol is higher. At the maximum energy ratio of methanol equal to 80 %, the shape parameter of Vibe function was set to 2.2 that is typical for the combustion governed by the flame propagation. Due to high reactivity and higher laminar flame speed of hydrogen compared to methanol (around 6 times higher), in the cases of dual fuel combustion of diesel and hydrogen, the Vibe shape parameter was fixed to 1.0 for all energy ratios of hydrogen considered in this study.

The main and thermodynamic properties of fuel mixtures used in this study were defined using the BOOST Gas Properties Tool. As the methanol substitution ratio is getting higher, the lower heating value and carbon mass fraction of mixture is decreased. On the other side, higher amounts of hydrogen, increases the lower heating value of mixture with significant decrease of carbon mass fraction that will reflect on CO_2 emissions. Mass substitution ratios (x_{alt}) of alternative fuel are calculated according to the following equation:

Table 4
Overview of fuel properties.

Dual fuel	Label	Energy supstitution ratio (%)	Mass supstitution ratio (%)	Lower heating value (MJ/kg)	Carbon mass fraction (−)
Diesel	D	0	0	42.80	0.862
Methanol (CH_3OH) + Diesel	DF-M-20	20	33.58	35.54	0.683
	DF-M-40	40	57.41	30.36	0.572
	DF-M-60	60	75.21	26.50	0.490
	DF-M-80	80	89.00	23.50	0.426
Hydrogen (H_2) + Diesel	DF-H2-20	20	8.19	49.15	0.770
	DF-H2-40	40	19.22	57.67	0.678
	DF-H2-60	60	34.87	69.75	0.546
	DF-H2-80	80	58.81	88.24	0.346

$$x_{alt} = \frac{\frac{e_{alt}}{LHV_{alt}}}{\frac{e_{alt}}{LHV_{alt}} + \frac{1-e_{alt}}{LHV_{diesel}}}, \quad (10)$$

where e_{alt} represents energy substitution ratio by alternative fuel, while LHV_{alt} and LHV_{diesel} are lower heating values of alternative and diesel fuel, respectively. The lower heating values of diesel, methanol and hydrogen are 42.8, 21.1 and 120 MJ/kg, respectively. Carbon mass fraction of mixture (c_{mix}) specified in Table 4 is calculated using the following formula:

$$c_{mix} = x_{alt} \cdot c_{alt} + (1-x_{alt}) \cdot c_{diesel}, \quad (11)$$

where c_{diesel} and c_{alt} are carbon mass fractions in diesel and alternative fuel, respectively. Carbon mass fraction of diesel is equal to 0.862, while the methanol has carbon mass fraction of 0.375. Hydrogen is considered as carbon free fuel.

4. Results

4.1. Calibration of 1D/0D simulation model

Before the application of dual fuel combustion with alternative fuels the engine simulation model was calibrated using the engine performance data specified by engine manufacturer. The reference engine performance curves plotted in Fig. 4 are defined according to ISO 8665 and SAE J1228 reference conditions and IMCI procedure for rating the power. The maximum engine brake power over engine speed range is plotted in Fig. 4 a). To achieve that simulation results match well with reference results at 100 % of engine load, the fuel quantities injected into cylinder are adopted achieving the air excess ratio around 1.4 as the minimum value.

For the typical propeller curves for this engine given in Fig. 4, the mass of fuel injection defined by ECU element was calibrated for engine speeds from 800 rpm to 1800 rpm. After the calibration of engine simulation model at steady operating conditions, the calibration of transient engine operation over two operating cycles of fishing vessel was made, Fig. 5. The measured vessel velocities plotted in Fig. 5 b) were

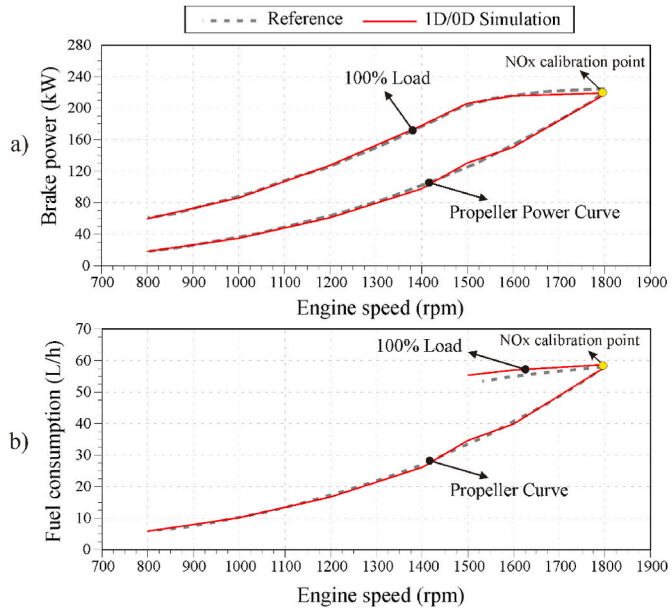


Fig. 4. Validation results at steady state operation – a) comparisons of maximum engine power and engine power required by propeller and b) fuel flow at full load and for typical propeller curve.

imposed into simulation model via Vehicle element (V1) in AVL Boost workspace. The maximum measuring uncertainty of fishing vessel speed is equal to ±15 % leading to maximum averaged errors of ±0.41 kn and ±0.49 kn for operating cycle 1 and operating cycle 2, respectively.

The calculation of drag force of fishing vessel (F_{drag}) is based on the instantaneous vessel speed (v) according to the following equation:

$$F_{drag} = D \cdot v^2, \tag{12}$$

where D (Nh^2/km^2) is user-defined coefficient that was adopted over the time for each operating cycle to match the cumulative fuel consumption. Profiles of adopted D coefficient over the time and comparisons of cumulative fuel consumptions are plotted in Fig. 5 c) and d). Positions of operating points that corresponds to operating cycles are plotted in Fig. 5 a). The average engine load for the operating cycle 1 is equal to 51.1 %, while the operating cycle 2 has lower average engine load equal to 39.7 % that is caused by lower drag force defined by lower drag coefficient D. Due to slightly faster velocity of fishing vessel at operating cycle 2 compared to operating cycle 1, the engine speed are higher, as it can be seen from Fig. 5 a). For the fuel consumptions plotted over the time in Fig. 5d for operating cycle 1 and operating cycle 2, the maximum measuring uncertainty (±0.5 %) of fuel consumptions are equal to ±0.246 L and ±0.627 L, respectively.

At nominal engine speed of 1800 rpm, where the maximum engine brake power of 220 kW is achieved, NOx emission sub-model was calibrated. According to IMO TIER 2 level and for nominal engine speed of 1800 rpm the threshold of specific NOx emission is equal to 7.85 g/kWh. The adoption of NOx kinetic multiplier from default value (equal to 0.64) to 0.30 resulted with simulated level of the specific NOx emission equal to 7.83 g/kWh. The comparisons of specific NOx emissions calculated at engine full load, typical propeller curve and operating points from transient engine operation (from operating cycles) are given in Fig. 6 a).

The comparisons of soot emissions calculated at engine full load, typical propeller curve and operating points from transient engine operation (from operating cycles) are given in Fig. 6 b). The calibration parameters of soot model, soot production and soot consumption constant were kept constant at default values of 1000 and 775, respectively, for all operating range of analysed engine. It can be seen in Fig. 6 b) that full load operating points satisfy the Tier 2 limit expect the minimum engine speed at 800 rpm where the simulated soot result exceeds the limit by approximately 5 %, but only one or two operating points during transient engine operation at operating cycle 2 will reach that region so it can be neglected.

Trawler vessels operate under a cyclical and predictable duty profile that includes distinct phases with varying engine loads (Koričan et al., 2023). A typical operational cycle begins with the vessel traveling to and from fishing grounds at moderate to high engine loads, resulting in relatively high fuel consumption. This is followed by the trawling phase, where the vessel tows heavy nets at slow speeds under steady, moderate engine loads. The trawling phase is energy-intensive and can last for several hours per cycle. Once the net is retrieved, the vessel enters the hauling and processing phase, during which engine load varies depending on the operation of winches, hydraulic systems, and onboard processing equipment. Periods of low-load operation or idling may occur during rest, gear preparation, or while waiting between tows. This variation in engine load throughout the day significantly influences fuel consumption and emissions.

4.2. Environmental assessment

The operational characteristics of a typical trawling cycle using dual-fuel configurations for two operating periods are presented in Table 5. The results indicate a notable interconnection between fuel consumption, emissions, and efficiency. During an operating cycle of 99 min, methanol-diesel blends (DF-M) show an increase in brake-specific fuel consumption as the methanol share increases, leading to higher overall fuel consumption but lower NO_x emissions. In contrast, hydrogen-diesel blends (DF-H2) significantly reduce CO_2 emissions, with fuel consumption decreasing as hydrogen substitution increases. However, NO_x emissions tend to rise, particularly under transient conditions. The comparison between steady and transient operations reveals slight variations, with transient cycles generally showing higher NO_x emissions for hydrogen-diesel blends, possibly due to higher in-cylinder temperatures caused by increased fuel injection quantities under engine acceleration. For an operating cycle of 297.5 min, methanol-diesel blends show a rise in brake specific fuel consumption with higher methanol substitution, leading to increased overall fuel consumption. However, NO_x emissions decrease significantly as the methanol fraction increases, with a more pronounced reduction under transient conditions. Hydrogen-diesel blends demonstrate a considerable reduction in CO_2 emissions, with lower fuel consumption as the hydrogen proportion rises and slight increase in NO_x emissions, particularly in transient operation. Compared to the 99-min cycle, similar efficiency and emissions trends persist, but the longer duration may increase fuel savings and emission reduction benefits, particularly for hydrogen-diesel configurations.

It is well known that premixed hydrogen mixtures at high loads could lead to knock occurrence problems. It was demonstrated in (Scrignoli et al., 2024) that hydrogen-diesel dual fuel engine can operate at speed of 2400 rpm and BMEP of 10.5 bar with hydrogen energy share of 80 % if the start of injection is properly retarded increasing the maximum in-cylinder pressure by 5 % compared to original diesel combustion (from 94 to 99 bar). In analysed two operating cycles of fishing vessel in presented study, the fishing vessel engine is not exposed to high loads. The maximum in-cylinder pressure does not exceed 65 bar, hence the problem with knock occurrence is not expected even with the 80 % of hydrogen energy share.

Fig. 7 illustrates the CO_2 and NO_X emissions from different dual-fuel engine configurations, using hydrogen (DF-H2), methanol (DF-M), and diesel (D) —under two operating cycles (99 min and 297.5 min), comparing transient and steady-state conditions. The analysis of CO_2 emissions shows that emissions decrease as the substitution ratio of hydrogen or methanol increases, with DF-H2 consistently yielding the lowest CO_2 emissions, followed by DF-M, while diesel-only operation results in the highest CO_2 output across both operating cycles. The

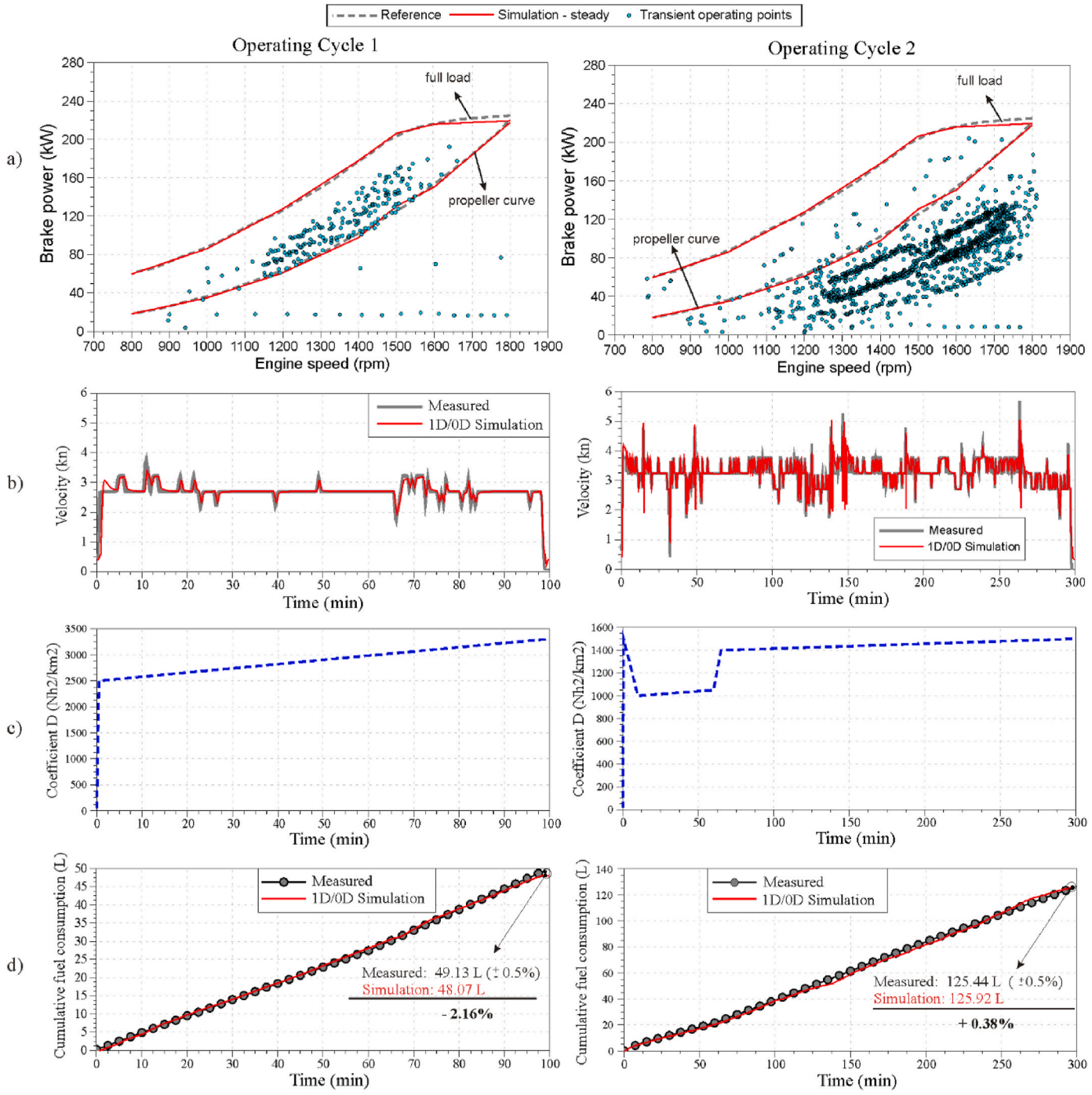


Fig. 5. Validation results over two operating cycles – a) positions of engine operating points, b) comparisons of fishing vessel velocity, c) adopted drag coefficient and d) cumulative fuel consumptions.

difference between transient and steady operating cycles for CO_2 emissions is relatively minor. In contrast, the NO_X emissions show different results. Transient operation consistently leads to higher NO_X emissions than steady-state conditions. DF-H2 configurations tend to produce more NO_X than DF-M, with the diesel baseline exhibiting the highest NO_X values in the short (99 min) cycle, particularly under transient operation. Notably, extending the operating cycle to 297.5 min results in a noticeable reduction in NO_X emissions for all fuel types and operating modes. Overall, while increasing hydrogen or methanol substitution significantly reduces CO_2 emissions, it may lead to elevated NO_X levels, especially under transient conditions and at higher hydrogen substitution rates.

Engine performance and emissions from diesel-methanol marine engine was experimentally and numerically investigated by Karvounis et al. (2025). For the cases of port methanol injection, the maximum methanol energy fraction was equal to 50 %, limited by increased combustion instabilities. On the other hand, direct methanol injection enables knock-free combustion up to 95 % of methanol energy fraction with 85 % of NO_X reduction compared to diesel combustion mode. In this study, for 80 % of methanol energy fraction (DF-M-80 cases), NOx reductions of 82 % and 71 % are achieved for operating cycles with 99 min and 297.5 min, respectively, as it can be seen in Table 5. Similar results regarding NO_X emissions of methanol-diesel combustion are confirmed experimentally (Dierickx et al., 2021). At engine speed of

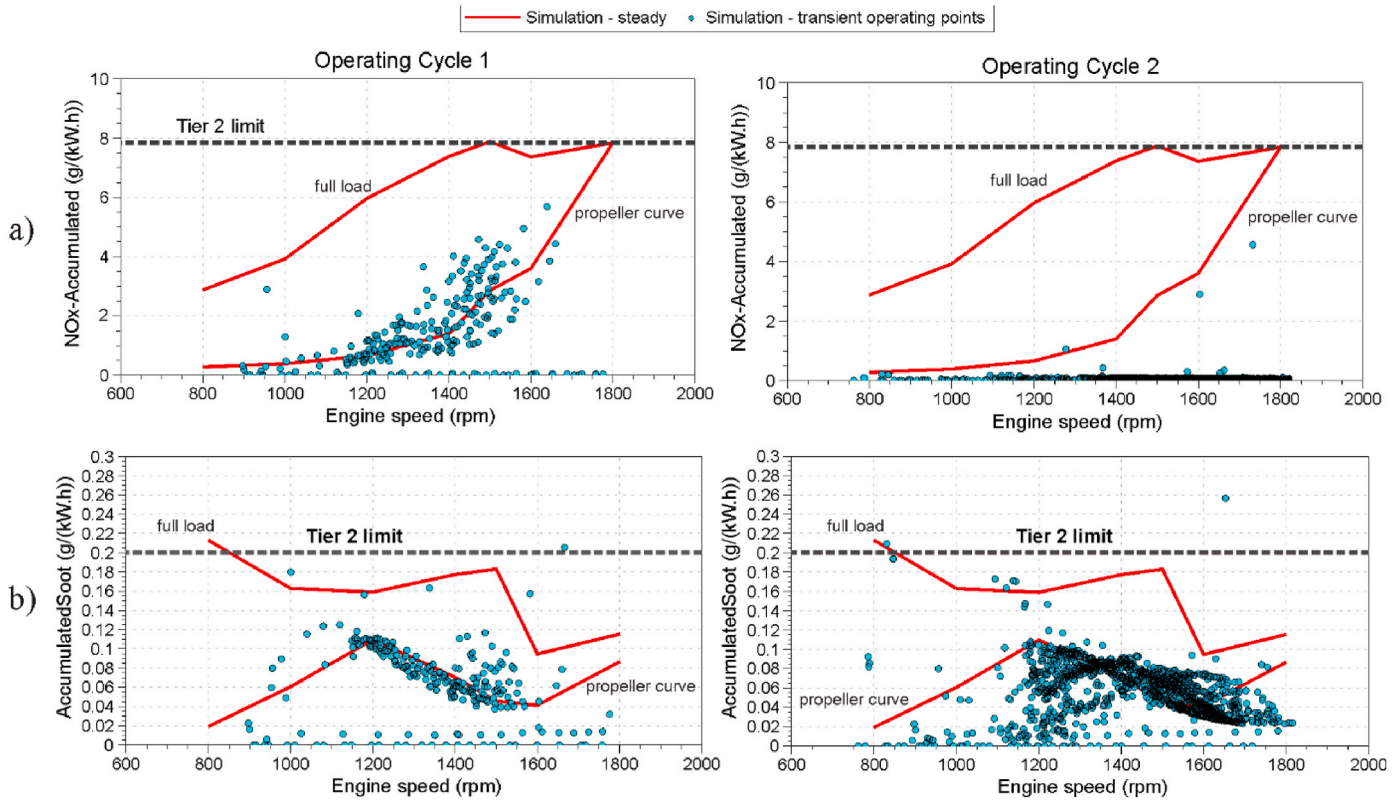


Fig. 6. Calibration of emissions at steady and transient engine operation – a) comparisons of NOx emission, b) soot emission.

Table 5
Operational characteristics on a typical trawling cycle for two operating periods and operating states.

Fuel		BSFC, g/kWh		CO_2, kg/kWh		NOx, g/kWh		Soot, g/kWh	
		Steady	Transient	Steady	Transient	Steady	Transient	Steady	Transient
Operating cycle of 99 min	D	222.28	223.83	0.702	0.707	1.18	1.89	0.0533	0.0733
	DF-M-20	269.97	273.20	0.567	0.573	0.61	0.89	0.0687	0.0940
	DF-M-40	322.83	325.87	0.435	0.438	0.458	0.633	0.0711	0.0962
	DF-M-60	377.60	380.80	0.296	0.298	0.355	0.460	0.0710	0.0964
	DF-M-80	433.15	437.70	0.151	0.152	0.256	0.338	0.0718	0.0953
	DF-H2-20	433.15	193.31	0.541	0.546	0.892	1.31	0.0513	0.0685
	DF-H2-40	191.42	162.84	0.403	0.405	0.940	1.36	0.0419	0.0532
	DF-H2-60	162.08	133.26	0.265	0.267	0.985	1.42	0.0317	0.0408
	DF-H2-80	132.46	104.55	0.132	0.133	1.000	1.47	0.0243	0.0301
Operating cycle of 297.5 min	D	225.16	227.50	0.711	0.719	0.940	0.591	0.0763	0.0881
	DF-M-20	274.47	277.97	0.576	0.583	0.494	0.342	0.0976	0.3267[a]
	DF-M-40	327.73	331.48	0.441	0.446	0.379	0.282	0.1034	0.3703[a]
	DF-M-60	382.8	386.45	0.299	0.303	0.285	0.220	0.1049	0.2866[a]
	DF-M-80	440.24	443.22	0.153	0.154	0.219	0.174	0.1040	0.2360[a]
	DF-H2-20	192.27	196.84	0.543	0.556	0.689	0.472	0.0707	0.2489[a]
	DF-H2-40	163.25	167.11	0.406	0.416	0.712	0.523	0.0585	0.1853
	DF-H2-60	134.12	138.06	0.268	0.276	0.761	0.855	0.0464	0.1644
	DF-H2-80	104.6	107.68	0.132	0.137	0.783	0.897	0.0353	0.1298

[a] value exceeds TIER 2 limit.

1500 rpm and engine load of 3.5 bar the maximum NO_X reduction of 50 % was achieved at maximum methanol energy fractions of 70 %.

Awaga et al. (2024) published the engine performance and emissions of hydrogen-diesel dual fuel combustion where 0 %, 25 % and 50 % of hydrogen energy fraction was investigated. For the sweep of engine speeds (750 rpm–2100 rpm) it was observed that 25 % of hydrogen energy fraction resulted with slightly increased NOx emissions compared to diesel operation, while at 50 % of hydrogen energy fraction NOx emissions are almost twice. In transient engine operation for the operating cycle of 297.5 min the simulation results reveal the similar behaviour. The increase of hydrogen energy ratio above 40 % resulted with NOx emissions higher than diesel only operation. According to simulation results and with the maximum hydrogen energy ratio of 80 % the increase of NOx emission is equal to 50 %.

Results of experimental studies (Saccullo et al., 2018) achieved on the single cylinder engine showed the specific emissions of soot with neat diesel and methanol-diesel combustion. It was shown that addition of methanol reduces soot emissions by 75 %, while the simulation results of soot in this study listed in Table 5 are increased around 25 % in average for all methanol energy fractions in steady and transient engine operation. On the other hand, soot emissions of hydrogen-diesel combustion decreases for steady state engine operations shows logical trends

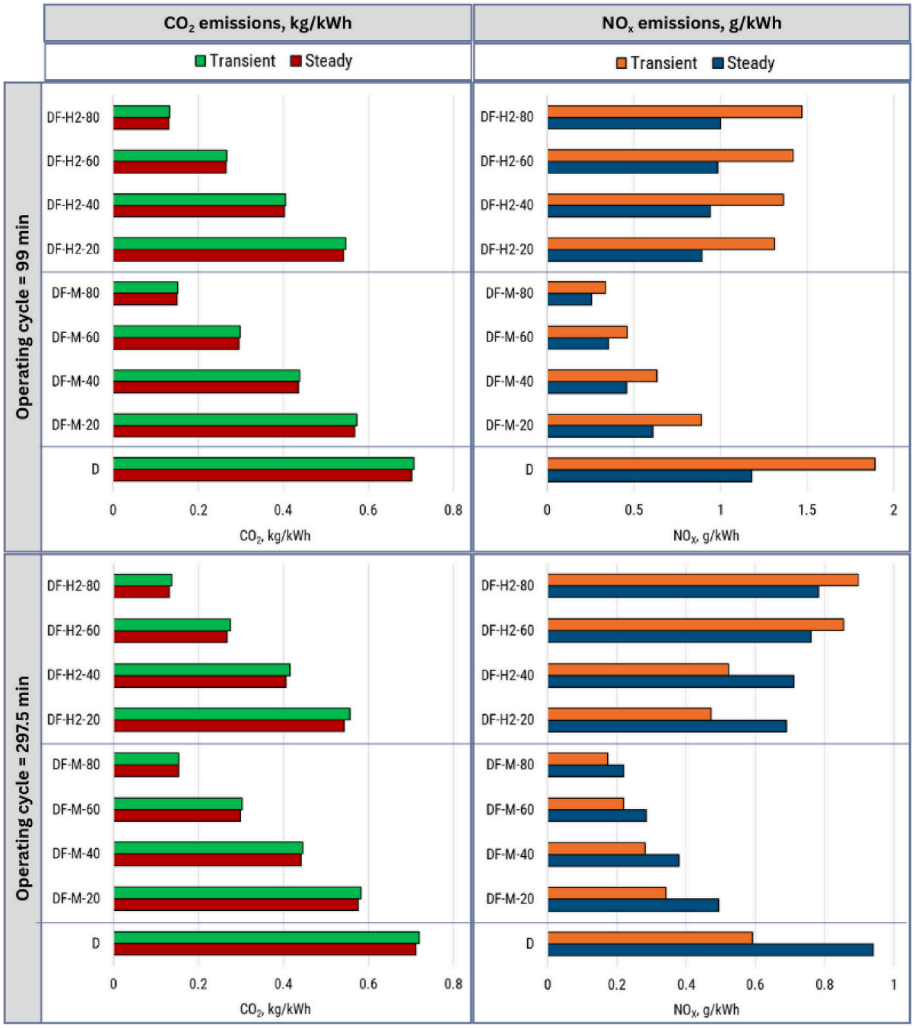


Fig. 7. Environmental assessment under different operating states and duration.

according to literature – the addition of hydrogen decreases soot emission. Ali Abuelnour et al. (2024) confirmed the reduction of 88 % of soot by addition of 50 % of hydrogen. In this study the maximum reduction of soot by 55 % is achieved for the maximum hydrogen energy ratio of 80 %. Bearing in mind that soot model constants were kept fixed for all analysed cases and due to the application of simple combustion model (single Vibe function) the simulation results of steady engine operation are in line with experimentally observed trends of soot emission.

4.3. Analysis of split operating cycle

The simulation of split operating cycle that has two equal 2.5-h net trawling period (Operating Cycle 2) was performed to evaluate the change of fuel consumption and nitrogen oxides emission. The split cycle was imposed into simulation model by means of repeated vessel speed and drag coefficient after first 2.5-h of net trawling period. Profiles of imposed vessel drag coefficient D under continuous and split cycle are plotted in Fig. 8a. Simulation results in cumulative fuel consumptions and cumulative NO_X emissions are compared with continuous cycle and diagrams are plotted in Fig. 8b and c.

In the split operating cycle, decrease in fuel consumption by 8.0 % and decrease of NO_X by 12.78 % are calculated because the engine is exposed to lower load in the second half of operating cycle. In the presented analysis, the period between two equal 2.5-h net trawling periods is neglect, which in real operation is required to remove the catch from the net. Within that process, the vessel main engine will operate at idling and low load conditions, which will decrease the calculated potential in the fuel consumption saving and lowering of NO_X emission. Therefore, the calculated fuel saving and decrease of NO_X emission under split cycle operation represents the maximum potential with split cycle application.

5. Discussion and limitations

Previous research (Koričan et al., 2023; Perčić et al., 2023) of fishing vessels has typically relied on fixed values of SFC, which limits the accuracy of the results. This directly affects the environmental assessment since SFC significantly influences emission intensity calculations. Therefore, neglecting real-time fluctuations in SFC can lead to under- or overestimations of emissions, particularly in dynamic engine operations where load conditions and fuel mix ratios vary substantially.

The current analysis highlights how emission factors (EF) change dynamically with increasing energy substitution, particularly for methanol-diesel and hydrogen-diesel dual-fuel configurations. The results for both 99 min and 297.5 min operating cycles are illustrated in Fig. 9. The figure illustrates the relationship between energy substitution levels and emissions characteristics, specifically CO_2 and NO_X emissions, as well as their respective EF under both steady and transient operating cycles. As energy substitution increases through methanol (DF-M) or hydrogen (DF-H2), CO_2 emissions steadily decline in both operating states. This reduction is more pronounced with methanol up to 80 % substitution, but there is a noticeable rise in CO_2 emissions when

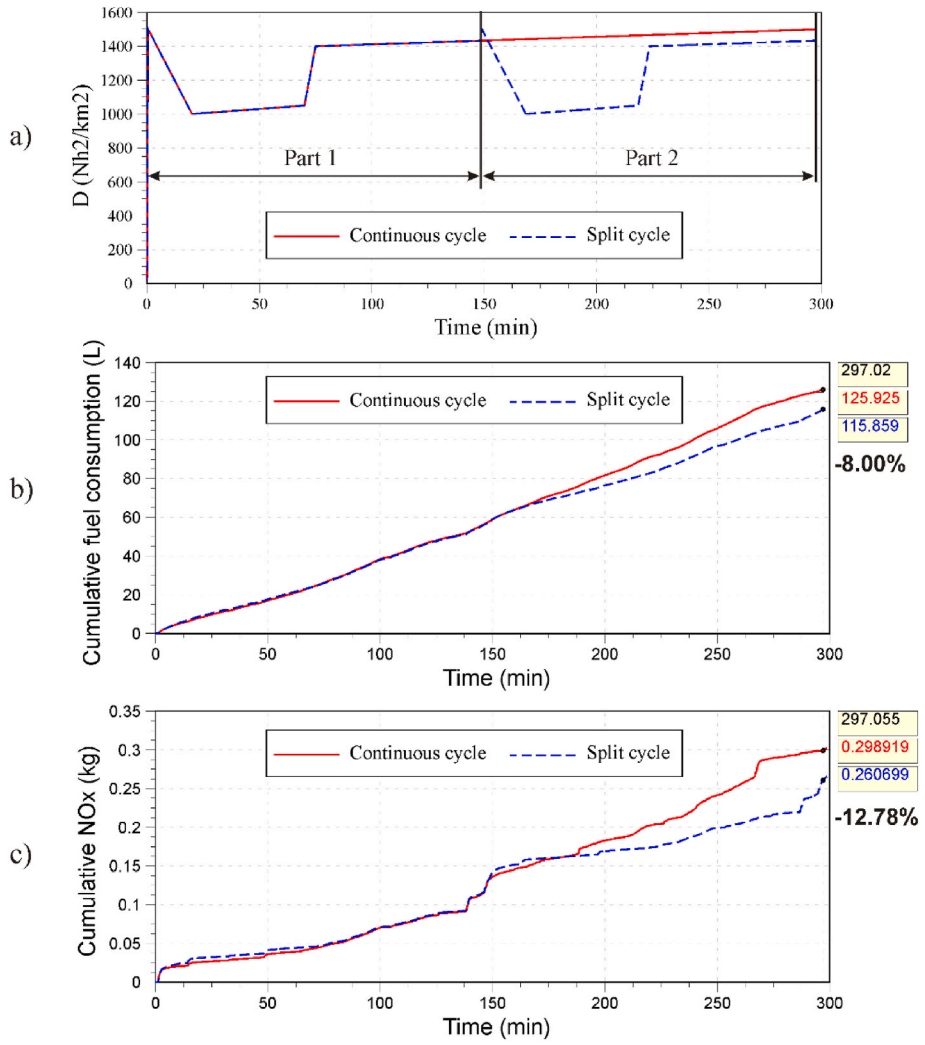


Fig. 8. Comparisons of simulation results for continuous and split Operating Cycle 2: a) definition of drag coefficient D, b) cumulative fuel consumptions, c) cumulative nitrogen oxide emissions.

transitioning to hydrogen at the 20 % level, which then declines again with higher hydrogen ratios. This pattern is mirrored in the EF for CO_2, indicating improved carbon footprint with higher substitution, though the switch from methanol to hydrogen introduces a slight temporary increase in CO_2 intensity.

In case of NO_X emissions, shown on the right side, a reverse trend is evident. The NO_X emissions initially decrease with increasing methanol substitution, reaching a minimum at DF-M80 in both cycles. However, upon transitioning to hydrogen blends, NO_X emissions begin to rise consistently with higher substitution ratios. This is particularly evident in the EF NO_X, which remains relatively low during methanol substitution but climbs steeply with increased hydrogen content. Even more so in transient operation, where the EF reaches its peak at DF-H2-80. For energy substitution ratios of diesel by hydrogen equal to 40 % and more, NOx emissions exceed values of diesel only operation because the in-cylinder temperatures are getting higher. By considering these variations and limits, this study provides a more realistic assessment of fuel performance and emissions, addressing a critical gap in previous methodologies.

Increased NO_X emissions potentially could be reduced directly inside the combustion chamber (raw emissions) with recirculation of exhaust gases (EGR) or addition of water to methanol. Dierickx et al. (2023) presented experimental results where the performance and emissions of a marine dual-fuel engine was operated with methanol-water blends. By increasing the water content, the NO_X emissions were additionaly reduced due to cooling effect inside the cylinder. On the other hand, the application of exhaust aftertreatment systems, such as Selective Catalytic Reduction – SCR can additionally decrease NO_X emissions, but this option requires modification of exhaust line and additional costs in potential retrofiting of existing marine diesel engines to operate in dual-fuel combustion mode.

According to Wang et al. (2024) the engine low load operation with methanol-diesel dual fuel can be achieved with minimum compression ratio of 14.5 that is equal to compression ratio of selected marine engine (see Table 2) in this study. The precondition for potential retrofitting of analysed marine engine in this study satisfies the compression ratio requirements.

Limitations of study:

- With higher methanol energy fractions the flame propagation dominates, and combustion instabilities become higher. The cyclic variations of combustion related parameters were not considered in the presented study.
- Higher substitution ratios of diesel by hydrogen at higher engine loads increases engine knock tendency that was not analysed in the presented study. In the selected illustrative example of fishing vessel, the maximum in-cylinder pressure does not exceed 65 bar, hence the knock-free operation is expected.
- Start of combustion defined by fuel injection timings were not optimized for the engine efficiency and emissions.

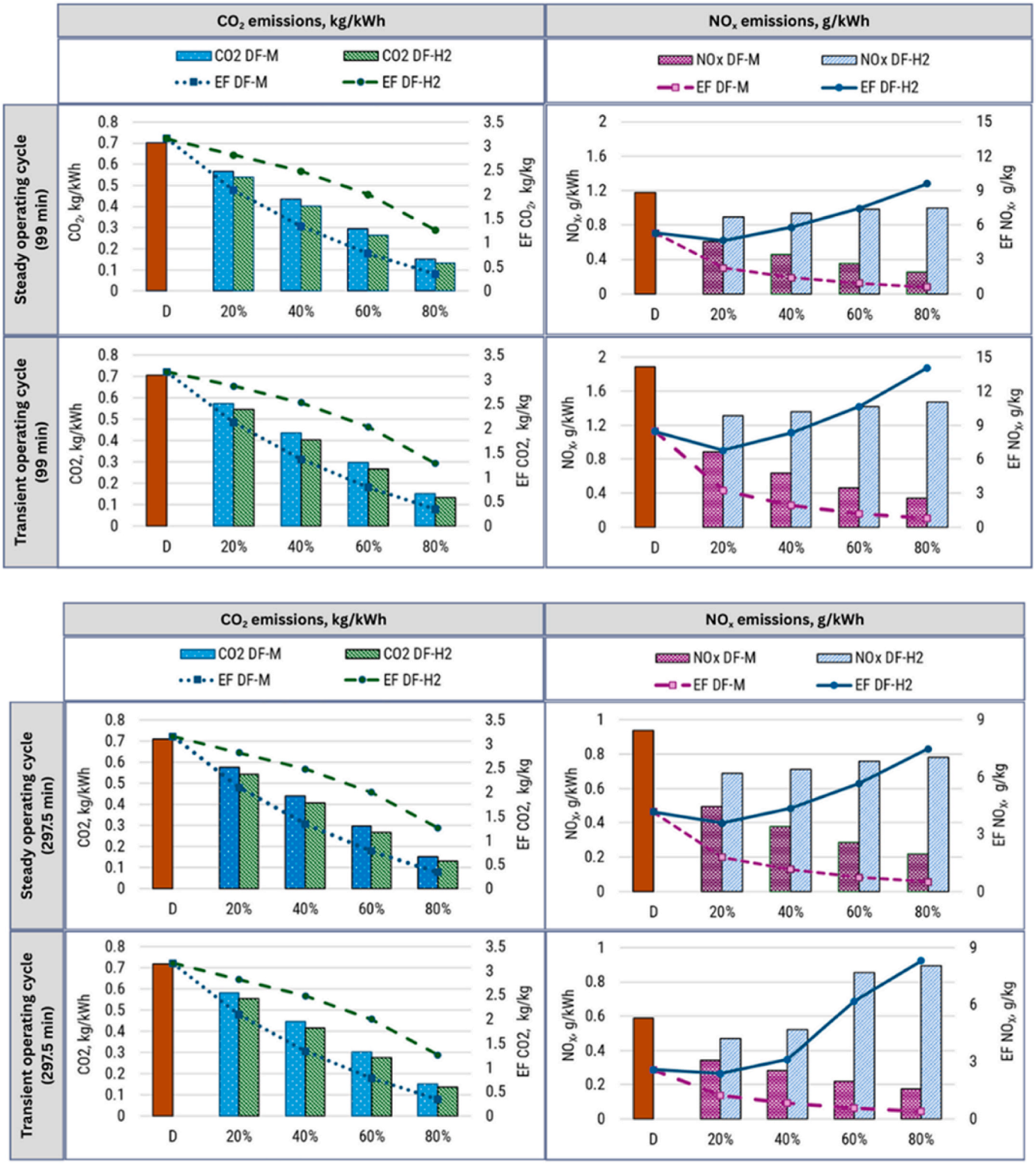


Fig. 9. Relationships between energy substitution levels and emission characteristics.

- Although the methanol has significant heat of evaporation, the cooling effect of methanol injection is fully neglected that potentially lead to lower in-cylinder temperatures and reduced NOx emissions.
- The influence of EGR and exhaust aftertreatment systems (SCR) is not considered on the tail emissions. The presented emission results correspond to engine raw emissions.
- Prediction of soot emissions trends with methanol-diesel dual fuel combustion is opposite to trends from the experimental studies due to application of single Vibe function. Multiple Vibe functions or quasi-dimensional combustion models are required to better predict soot emissions.
- The influence of trawling speed and pull duration on the quality of the catch is not considered.

The analysis assumes a direct proportionality between catch quantity and total operating time, standardizing each operating cycle as consisting of two equal 2.5-h haul periods within a 5-h cycle. This simplification allows for a focused assessment of fuel consumption and emissions. However, it is recognized that variations in fishing practices, such as changes in speed and duration, can significantly affect catch efficiency and, consequently, broader operational performance.

6. Conclusion

This study presents a calibrated and validated 1D/0D engine simulation model for evaluating the performance and environmental impact of dual-fuel combustion using methanol and hydrogen as alternative fuels in fishing vessel operations. The model reproduces engine behaviour across steady- and transient operating cycles by accounting for real-world variations in engine load and vessel dynamics in a reliable way. Calibration based on manufacturer specifications and measured vessel data ensured reliable model validation basis and replication of both power output and fuel consumption patterns.

The environmental assessment reveals clear trade-offs between emissions and efficiency for dual-fuel configurations:

- Steady state engine operation can be used for the calculation of CO_2 emissions, while transient engine operation is required to capture NOx trends;
- Methanol-diesel blends significantly reduce NO_X emissions: at highest substitution ratio of 80 % the maximum NOx reduction is equal to 82 %;
- Methanol-diesel blends lead to increased brake specific fuel consumptions due to reduced lower heating value of fuel mixtures compared to diesel only operation;
- Methanol- and Hydrogen-diesel blends consistently reduce CO_2 emissions as the substitutions of methanol and hydrogen increases. The maximum CO_2 reductions (at 80 % of diesel substitution ratio) for methanol-diesel and hydrogen-diesel are equal to 78.5 % and 81.1 %, respectively.
- Hydrogen-diesel blends result in lower brake specific fuel consumption, however, cause a rise in NO_X emissions, particularly under transient conditions. At energy substitution ratios above 40 % with hydrogen, the NOx emissions exceed levels achieved with diesel only operation.
- The higher combustion temperatures and dynamic instability contribute to the increase in NO_X;
- Soot prediction in methanol-diesel dual fuel combustion is not captured correctly and the opposite trend is observed compared to results from other relevant publications. Hydrogen-diesel dual fuel combustion decreases soot levels and the maximum decrease of 55 % is achieved at substitution ratio of 80 %. More comprehensive combustion and soot models are required for better prediction of soot production and oxidation process.
- Extended operation over a 297.5-min cycle demonstrates greater potential for emission reductions and fuel savings, particularly for hydrogen-diesel configurations;
- Simulating a split-cycle operation showed up to 8 % fuel savings and a 12.78 % reduction in NO_x emissions;
- The study also highlights the significant role of dynamically varying specific fuel consumption (SFC) in accurately quantifying emissions.

In conclusion, methanol emerges as a viable alternative fuel that provides a significant advantage in reducing NO_X emissions, which is essential for meeting increasingly stringent regulatory standards in the maritime sector. Methanol's relatively low emission profile, together with its potential for easy integration into existing engine technologies, makes it an attractive option for vessels aiming to comply with current and future emission regulations. This makes it particularly optimal for industries facing compliance challenges in heavily regulated regions. On the other hand, hydrogen offers a clear pathway towards achieving the main goal of decarbonization. As a fuel with no carbon emissions during combustion, hydrogen represents a key solution in the transition towards a low-carbon maritime sector. While hydrogen infrastructure and storage solutions pose challenges, its potential to drastically reduce the carbon footprint of maritime operations makes it a critical player in the long-term vision of sustainable shipping.

The study shows that adoption of favourable engine performance and refining operational strategies will be crucial to achieving the best system performance with alternative fuels. Future research should advance these efforts by integrating more sophisticated combustion modelling, such as multiple Vibe functions or quasi-dimensional combustion models capable of predicting soot formation, alongside simulations involving a wider range of alternative fuels, including emerging e-fuel blends. Such developments, combined with techno-economic assessments, will be essential for defining optimal technical solutions and operational strategies that support the long-term decarbonization and sustainability of fishing vessel fleets.

CRediT authorship contribution statement

Momir Sjerić: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marija Koričan:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Nikola Vladimir:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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