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Technical and Economic Feasibility Study on Reducing CO_2 Emissions of Dutch Beam Trawlers

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ABSTRACT

This paper examines the technical and economic influence of CO_2 reduction measures on the design and operation of Dutch beam trawlers. This is done by means of a parametric model used to assess the influence on the overall design of the vessel. Technical feasibility is determined by meeting operational effectiveness requirements, maximum added draught, maximum added length, and a reduction of CO_2 emission by at least 40%. Secondly the model evaluates the new energy carrier and fish storage layout as a result of additional required volume. Additional volume is gained within the net store, fish hold, or by hull extension. Additionally, various propeller configurations, waste heat recovery, and regenerative braking systems are explored to reduce energy consumption. The economic performance is assessed using yearly operational requirements, capital expenses of configuration, and total cost of ownership.

KEY WORDS

Beam trawlers; feasibility study; parametric modeling; zero-emission

INTRODUCTION

The most recent estimates in the Fourth International Maritime Organization (IMO) Greenhouse Gas (GHG) Study 2020 show that GHG emissions of shipping have increased by 9.6% between 2012 and 2018 (IMO, 2020), while the IMO strives to reduce CO_2 emissions by at least 40% by 2030, pursuing efforts towards net zero by 2050, compared to 2008 (IMO, 2023). Although a Dutch beam trawler has a gross tonnage below or just above 400GT and the IMO regulations do not apply to it, there is nevertheless an aim to reduce GHGs of these vessels. The last decade the Dutch beam trawler fleet has been confronted with a lot of developments (MEPC, 2024) which has led to the reduction of profitability of the vessels. Two developments stand out in the last decade, namely: (1) BREXIT, which has resulted in a reduction of available fishing ground, and (2) the ban on pulse fishing, which is a method of fishing which reduced the operational expenses by around 30-40%. Due to the current state of the fishing fleet the Dutch government has introduced a plan called “Noordzee Visie (Northsea Vision)” (Rijsksdienst voor Ondernemend, 2019) which aims to reduce the environmental impact of the Dutch fishing fleet. This plan consists of buying out weak companies and investing money in the form of a subsidy to make the remaining fishing vessels more sustainable.

To continue fishing a Dutch beam trawler has to comply with these regulations, thus requiring implementing the use of sustainable fuels together with energy saving technologies. Vessel owners want to implement these technologies without sacrificing operational effectiveness. Therefore, this study aims to assess the technical and economic feasibility of reducing the CO_2 emissions of Dutch beam trawlers to meet the 2030 IMO CO_2 emission regulations, while maintaining vessel operational effectiveness.

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LITERATURE

With the buyout and high fuel costs on the horizon studies have been done on the reduction of CO_2 emissions by means of alternative energy carriers on new build (beam) trawlers. These research topics concern: feasibility study fishing on natural gas ('t Hart, 2009), LNG potential energy source (Taal and Hoefnagel, 2012) and Design Green shrimp trawler (van Urk, 2012). This studies are limited to other fishing vessel types and only consider gas-like fuels. There are mainly three ways to reduce the emitted emission of a vessel: (1) reducing the energy consumption of the vessel, (2) after treatment of the rest product of energy converter or by (3) changing to an alternative fuel. All the mentioned and open source studies are done on new build beam trawlers, discuss one methods to reduce CO_2, and do not combine all three options and aspects together. Additionally, and the economic perspective has been missing from previous literature. Looking at emissions and fishing regulations there is large future uncertainty driven by future availability fishing grounds and alternative fuel characteristics. It is thus necessary to get insight in the performance of multiple propulsion configurations on economic and technical performance. The review below covers: (1) determining the current state and operation of a Dutch beam trawler, (2) exploring methods to reduce the CO_2 emissions, and (3) establishing requirements for an assessment model.

Vessel State

The latest study (Wageningen Marine & Research, 2023) showed the average age of the 284 active Dutch beam trawlers to be 32 years (build 1990), with 75% being older than 20 years. The vessels are powered by a conventional engine room set up. For these vessels this means the main engine is a MGO fueled 4-stroke medium speed internal combustion engine, and is indirectly coupled to the propeller by means of a gearbox. The installed Pb varies between 1000kW and 1450kW. The vessels average characteristics range from: Lpp: 35-42m, $B_{moulded}$: 6-9m, T_{mid}: 3-4.5m, D_{prop}: 2-3m and Prop-speed: 180−280rpm. The main energy consumers besides the engine propulsion the propeller onboard are the ice & cooling machines, safety & communication, and the winch. From which the cooling system is responsible for the preservation of caught fish and the winch for the setting and hauling of the nets.

The state of the art of beam trawlers limits itself to optimized propeller and diesel engine configurations but does not go any further. The operational profile of the vessel can be divided into the short and long cycle. The long cycle is the time from sailing out from port, the fishing and the return into port. The short cycle is the fishing cycle covering the repetition of setting, fishing and hauling the nets. Two types of long cycles exist in the Dutch fleet: a 100hr and a 160 hour per week, based on geographic and demographic preferences within the Netherlands. The short cycle has an average duration of 2.5 hours.

Emission Reduction Exploration

The energy converters, energy carriers and emission reduction methods identified in Table 1 have the highest potential in achieving the stated goals.

Table 1: Combination of systems, similar numbers indicate technical combinations

Converter	Energy Carrier	Energy Reduction
Diesel ICE (1)	MGO (1) HVO (1) FAME (1)	Propeller (1,2,3,4) - 3.4m 4 blade - 3.4m 5 blade - 4.0m 4 blade - 4.0m 5 blade
DF ICE (2)	Methanol (2)	Orcan, WHR (1,2,3)
LT PEMFC (3)	Hydrogen (3)	SRC, WHR (1,2,3)
NMC-Li battery (4)		Winch (1,2,3,4) - Regenerative braking - Operational optimization

The four energy converters identified demonstrate promising potential for implementation on a beam trawler. These converters were selected based on their capacity to reduce CO_2 emissions while ensuring technical reliability.

- ***MGO ICE*:** This engine was considered for its cost-effectiveness and its proven track record in efficiently converting chemical energy into mechanical or electrical energy (DNV, 2020; Streng et al, 2022).
- ***DF ICE*:** The DF (Dual Fuel) technology was chosen as it has already been validated by several engine manufacturers. Furthermore, its utilization of methanol fuel offers the potential to significantly decrease CO_2 emissions (Dierickx et al, 2021; Pendle Government, 2018).

- ***LT PEMFC*:** The Low-Temperature Proton Exchange Membrane Fuel Cell (LT PEMFC) was selected due to its reliability, high energy density, rapid response to load variations, and a simplified system compared to high-temperature fuel cells (Leon, 2008; Welaya et al, 2011).
- ***Nickel Manganese Cobalt-Lithium (NMC-Li) Batteries***: These batteries were preferred over other options because of their high energy density, extended cycle life, and relatively fast charging capability (Freudenberg E-power systems, 2022).

Additionally, five energy carriers are employed, carefully selected based on their ability to exhibit low Tank-To-Wake (TTW) emissions and ensure minimal safety risks for both the crew and the environment.

- ***MGO:*** MGO is being considered to assess its feasibility in meeting IMO targets without transitioning to alternative fuels.
- ***HVO and FAME***: Hydrotreated Vegetable Oil (HVO) and Fatty Acid Methyl Ester (FAME) are highly regarded by IMO for their exceptionally low TTW emissions due to their bio-based production (IMO, 2023). Their similarity to Marine Diesel Oil (MDO) makes their application relatively straightforward (DNV, 2019).
- ***Methanol***: Methanol is partially classified as a drop-in fuel, and its lower carbon content provides the potential to reduce TTW emissions.
- ***Hydrogen***: Hydrogen, chosen for its zero TTW emissions, is a favored fuel option. Hydrogen in liquid form is preferred due to its higher storage efficiency compared to compressed hydrogen, attributed to the significant reduction in volume resulting from its low temperature (DNV, 2022).

At last three types of energy reducing methods are explored. (1) Propeller: due to its high rotational speeds and high blade loading it is found that there is potential for efficiency improvement by increasing the diameter of the propeller, which would reduce blade loading and rotational speed, leading to an overall increase in efficiency (Laurens et al, 2013). (2) Winch: with the application of regenerative braking on the winch a small amount of electrical energy can be recovered during the setting of the nets. Secondly by optimizing the winch operation the required propulsion power during setting and hauling can be reduced. (3) Waste heat recovery (WHR): depending on the propulsion setup, energy can be recovered from exhaust gas or cooling water (Mat Nawi et al, 2019; Benvenuto, et al, 2016; Ouyang et al, 2020).

Combination of Systems

The proposed configurations consist of various combinations of energy converters, energy carriers, and energy consumption reduction strategies. However, certain combinations are not feasible due to system working principles. With the exception of the original propulsion configuration, all other combinations are designed to be either diesel-electric or fully electric, aligning with the Dutch subsidy regulations outlined in the Noordzee Visie. The calculations are designed to store the maximum amount of the main energy carrier on board, considering a 40% reduction in CO_2 emissions. The remaining required energy is stored as the secondary energy carrier. These hybrid combinations of energy carriers are chosen based on the assumption that they are the most economically feasible. The combination of Hydrogen and NMC-Li for example will result in significant capital investments, and complex combination of systems. HVO and FAME already achieve 40% CO_2 and are therefore not used in the hybrid configurations.

In addition to the mono-fueled configurations, four hybrid configurations are explored. The selection of these hybrid combinations is based on the goal of achieving the lowest initial investment while still achieving a 40% reduction in CO_2 emissions. Consequently, combinations involving HVO, FAME, Hydrogen, and batteries are not chosen, as they already comply with the TTW fraction requirements. The following four combinations remain:

1. MGO-Hydrogen (liquid) (MGO-H2(l))
2. MGO-Nickel Manganese Cobalt-Lithium (MGO-NMC-Li)
3. DF-Hydrogen (liquid) (DF-H2(l))
4. DF-Nickel Manganese Cobalt-Lithium (DF-NMC-Li)

The fraction of delivered energy in each combination is determined by using the maximum amount of MGO or DF, with the remaining energy supplied by the second energy carrier.

METHOD

To evaluate the potential of various combinations of systems, an assessment model was developed (Figure 1), consisting of three main components: literature, technical, and economical. The literature section gathered inputs from specific system characteristics found in a literature study. The technical segment involved calculations to determine the required energy and new vessel dimensions for different storage options, ensuring compliance with all necessary requirements. In the economic part, proposed configurations that met the requirements were evaluated using three performance indicators: capital expenses, operational expenses, and total cost of ownership.

The primary focus of this research was to assess the technical and economic feasibility of reducing CO_2 emissions in a beam trawler. For this purpose, a parametric assessment model was employed. This method assigned points to various criteria and evaluated their fulfillment to assess the viability of the proposed solution. The model considered crucial factors such as emission reduction potential, cost-effectiveness, and alignment with existing infrastructure and regulations. By aggregating scores assigned to each criterion, a comprehensive and objective evaluation of CO_2 reduction measures was achieved. This parametric approach offered a systematic and transparent decision-making process, facilitating the selection of the most suitable emission reduction strategies for beam trawlers while considering both technical and economic aspects.

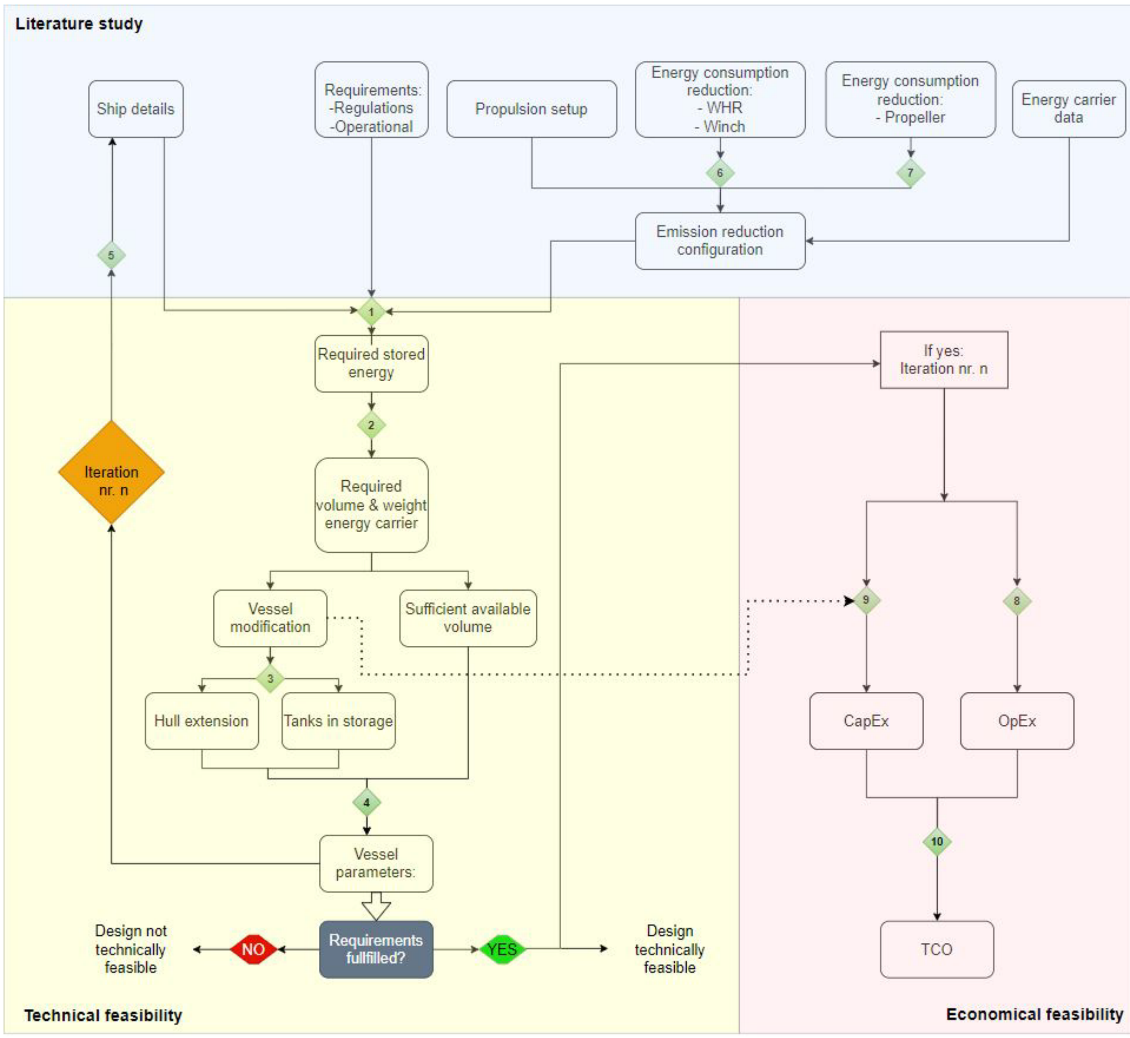

Figure 1. Flowchart of the assessment model.

Technical Feasibility Assessment

In this phase of the assessment, calculations are performed to transform the operational profile and propulsion configuration into new vessel parameters. By considering the system characteristics, vessel data, and operational requirements, the necessary energy per long cycle, volume of energy carrier, weight of energy carrier, and weight of propulsion configuration are determined. To accommodate the calculated volume of energy carrier, including the tank storage arrangement (See Figure 2), various storage methods are suggested. These methods involve combining the original storage tanks with additional volumes such as the net store, fish hold, or creating new storage space if the hull is extended.

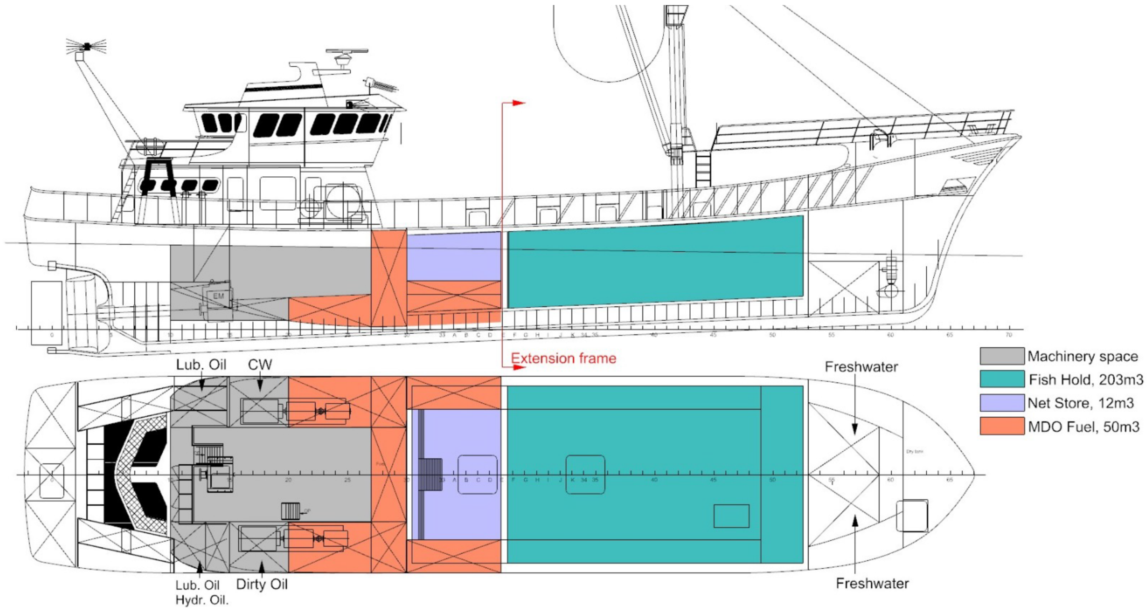

Figure 2: Original tank plan (Padmos, 1987)

Examining the energy density and storage arrangements of drop-in fuels such as MGO, HVO, and FAME requires relatively straightforward investigation. However, when dealing with energy carriers like methanol and liquid hydrogen, specific tank storage arrangements become necessary. In order to estimate the optimal position and quantity of tanks, this research took into account the average Dutch beam trawler, its energy carrier consumption, and hull dimensions. Additionally, the requirements for cofferdams and cryogenic tanks were considered, ultimately determining the average energy density, including the storage tank, used in this study.

Different organizations employ diverse formulas, often incorporating non-empirical values and correction factors, to calculate emission reduction. However, approaches like EEXI, EEDI, and CII, which work with emission ratios per ton of cargo per mile, are unsuitable for fishing vessels due to their limited transportation of goods, primarily consisting of a few tons of fish. Moreover, these ratios often use generalized correction factors that may not be applicable to specific sectors or may lack relevant data, leading to an insufficient understanding of the actual impact of various configurations.

To address these concerns, the assessment of CO_2 emission reduction for fishing vessels will be presented as a percentage relative to the original emission during the long cycle. The focus will be on considering TTW emissions, as Dutch, EU, and IMO regulations calculate, penalize, and evaluate emissions based on this criterion. It is important to note that fuel producers bear the responsibility for well-to-tank (WTT) emissions, and well-to-tank (WTT) emissions, being a separate study, are beyond the scope of this study.

Once the new estimated hull parameters are established, the configuration is examined for its technical feasibility. To be deemed feasible, the configurations must meet various types of requirements.

(1) Operational effectiveness requirements
- Towing capacity
- Endurance
- Fish hold capacity
- Cooling
- Winch
- Storage area

(2) Maximum 0.3m added average draught
(3) Maximum 3m hull extension
(4) Minimum 40% CO_2emission reduction

The maximum added draught and length of a vessel are unique to each vessel and determined by factors like minimum required freeboard, maximum GT, seaworthiness, and stability. If a configuration fails to meet these specific requirements, it is considered technically infeasible. Conversely, if it fulfills these criteria, it is deemed technically feasible, and the assessment model proceeds to evaluate its economic feasibility.

Economic feasibility assessment

This part assesses the economic performance of the configurations based on three indicators: (1) Operational expenses, (2) Capital expenses, and (3) Total cost of ownership.

Operational expenses

The operational expenses is the summation of the yearly costs of energy carrier consumption, the paid tax on CO_2 emission to the Dutch government, and the maintenance (Equation 1).

$$OpEx = Energy\ Carrier + CO_2\ emission\ taxes + maintenance \qquad [1]$$

Using:

- Energy Carrier, required amount of energy carrier per year multiplied by price
- CO_2 emission taxes, CO_2 emission per year multiplied by tax price
- Maintenance, the yearly costs required to keep propulsion configuration and ship in good and reliable condition.

Maintenance costs

To obtain the most accurate estimate of the expected costs per propulsion configuration, the annual maintenance costs need to be determined. These costs will always be an approximation as they depend on various variables such as operational hours, whether the work is performed in-house or by a subcontractor, etc. Additionally, predicting breakdowns is challenging. However, through the expertise of Padmos and insights from case studies, an attempt has been made to determine an annual cost estimate for ship maintenance.

Capital expenses

With the propulsion configurations that meet the requirements, an estimation can be made on the system prices and vessel retrofitting prices. The propulsion configuration system prices can be estimated using average e/kW fractions. The retrofitting prices of the vessel are difficult to estimate, since they are vessel specific. Steel prices and labour prices are fixed but the required amount of hours and steel are difficult to estimate. The capital costs of retrofitting are significant and therefore must be included in the economic feasibility. The company's history in vessel retrofitting is used to estimate working hours for the different retrofitting options. With the cross section drawings and the weight of steel the added weight of the extension section is calculated. With an average price on steel welding, cutting and pre-forming costs this results in the overall costs to make the section. The CapEx is built up as the sum of propulsion configurations costs, propeller, winch modifications, WHR and vessel extension costs (see Equation 2).

$$CapEx = Propulstion\ configuration + Energy\ saving\ devices + Hull\ extnesion \qquad [2]$$

Total cost of ownership (TCO)

TCO is one widely used approaches in the analysis of economic performance (see Equation 3). TCO takes into account not only the upfront investment costs but also the operational and maintenance expenses over the system's lifetime. A new propulsion configuration may require significant investment upfront, but its long-term cost implications are equally crucial. TCO analysis helps in identifying potential cost savings over the operational lifespan of the system. For instance, a propulsion configuration with higher fuel efficiency and lower maintenance requirements may result in substantial cost reductions over time, offsetting the initial investment. TCO analysis allows for a fair comparison of different propulsion configurations (Terun et al, 2022). By calculating and comparing the total costs associated with each option, decision-makers can identify the most economically viable solution.

$$TCO_{yearly} = CapEx + OpEx \qquad [3]$$

- TCO_{yearly}, the yearly total cost of ownership[e/year]
- *Capex*, the capital expenditures[e]
- *Opex*, the operational expenditures[e/year]

In the context of the new propulsion configuration, the vessel's expected lifetime is considered to be 15 operational years. Consequently, the residual value of the investment, or the remaining value of the system after its useful life, is expected to be negligible or zero. This expectation arises from factors such as technological obsolescence, wear and tear, and the introduction of newer, more efficient propulsion technologies over time. Given the vessel's expected lifetime of 15 operational years, the TCO analysis typically focuses on this relatively short time horizon. Since the remaining value of the investment is negligible or zero by the end of this period, including it in the TCO analysis would not significantly impact the overall economic assessment. Only at a later stage when a new build vessel is included into the configurations, a remaining value will be included since this vessels lifetime is more than 15 years. The remaining value is determined according to Equation 4.

$$TCO_{yearly,remaining} = CapEx + OpEx - remaining\ value \quad [4]$$

CASE STUDY

To obtain a realistic picture of the technically and economically feasibility of the configurations, a case study is conducted on an existing beam trawler. The vessel has the following characteristics (Table 2), and as can be seen from the literature it matches the average Dutch beam trawler parameters.

Table 2. Case vessel particulars

Lpp	33.75m
Beam	7.5m
Draught	3m
Displacement	500 tons
Block Coefficient	0.6
Main engine	1200kW Stork Werkspoor
Propeller diameter	2.5
Winch	100kW

Given the significant impact of operational expenses on the economic feasibility of the configuration, it is necessary to conduct scenarios with varying energy carrier prices and CO_2 emission tax prices. This analysis aims to determine whether the most promising configurations also perform well under different circumstances. By exploring different scenarios, insights can be gained into the robustness and versatility of the potential configurations beyond their primary conditions. Within this study three scenarios are explored: (1) high energy carrier price, and (2) high emission tax price, and (3) forecasted energy carrier and emission tax prices. The last scenario will be used to actually find the answer to the problem of this research.

Energy Carrier Prices

Although best estimates are used on forecasted carrier prices, the last decade showed large deviations from forecasted prices due to pandemics or wars (Olusanya et al. 2021; Pavlenko et al, 2020). By considering a case in which with high energy carrier prices, it allows for an analysis of the economic viability of different propulsion configurations under various cost conditions. The projection for 2050 is increased and decreased by 30% to find the influence of the price of the energy carrier on the economic feasibility of the beam trawler vessel. A 30% uncertainty is chosen after considering the enormous volatility that energy prices have shown.

Emission Tax Prices

The Dutch Government imposes taxes or levies on carbon emissions to incentivize emission reductions. This regulation has been set until 2030; however, this research aims to further explore the economic performance of the configuration. Therefore, there will be a need to make assumptions about the price trajectory post-2030 (Enerdata, 2023), introducing uncertainty into the model. To assess the model's sensitivity to these uncertainties, a scenario is applied assuming a high emission price. By evaluating this scenario with different emission tax prices, it helps in understanding the cost implications of environmental regulations and their influence on the economic viability of the proposed propulsion configurations. The scenario proposed will work with a upper limit of 50% above predicted prices. A 50% uncertainty is chosen after considering the enormous volatility that future regulations have shown. After finding the sensitivity of the model with Scenario 1 and scenario 2, the last scenario (3) uses the prices for both energy carrier prices and emission tax as forecasted in Table 3 and 4.

Table 3. Energy carrier price current and future, [e/GJ]

	Fuel Costs 2022	Fuels Costs 2050	Source
MGO	17	17	(LR, 2023)
HVO	31	31	(DNV, 2019)
FAME	28	28	(DNV GL, 2019)
Methanol	39	27	(Pothaar, 2022)
Hydrogen	70	33	(IEA, 2022, 2023)
Electricity	27	10	(GRO, 2020)

Table 4. Statutory price trajectory of carbon levy in 2021 (OECD, 2021)

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Levy rate (€ / tonne CO_2)	30	40.56	51.12	61.68	68.12	76.42	83.21	89.72	94.20	103.92

RESULTS

The results of the assessment model are presented for different configurations applied to the case beam trawler, sailing with both the 100hr and the continuous long cycle. In the economic evaluation, it is assumed that the retrofitted case vessel will have an operational lifespan of 15 years. The model generates various outputs, from which the required amount of energy per configuration per long cycle is the first value calculated. This is then converted into the necessary volume and weight. In this section, the required volume, including the storage tank, is presented to provide an overview of the quantities involved and to understand the impact of specific energy reduction methods. The outcome is presented in Table 5 and 6. The required volumes mentioned here are including storage tank.

Table 5. Required storage volume [m^3] for mono fuels configurations. Red indicates more volume than available.

			100 hr long cycle					Continuous long cycle				
			Propeller					Propeller				
Converter	Fuel	Config.	Original	T.1	T. 2	T. 3	T. 4	Original	T. 1	T. 2	T.3	T.4
ICE	MGO	D-D	22	18	15	18	15	36	29	25	29	25
ICE	MGO	D-E	23	19	16	19	16	38	30	26	30	26
ICE	HVO	D-E	25	21	18	21	18	42	33	28	33	28
ICE	FAME	D-E	25	20	17	20	17	41	33	28	33	28
ICE	DF	D-E	73	59	50	59	50	121	96	81	96	81
PEMFC	Hydrogen	E	117	93	79	93	79	191	151	128	151	128
Battery	NMC-lithium	E	232	188	161	188	161	380	305	259	305	259

Table 6. Required storage volume[m^3] hybrid configurations. Red indicates more volume than available.

			100 hr long cycle					Continuous long cycle				
			Propeller					Propeller				
Main energy carrier	Sec. energy carrier	Config.	Original	T.1	T. 2	T. 3	T. 4	Original	T. 1	T. 2	T.3	T.4
MGO	Hydrogen (1)	D-E	63	41	27	41	27	103	65	42	65	42
MGO	NMC-Li	D-E	99	61	37	61	37	163	97	58	97	58
Methanol	Hydrogen (1)	D-E	89	66	54	66	54	145	107	88	107	88
Methanol	NMC-Li	D-E	114	75	54	75	54	186	120	88	120	88

Both long cycles

None of the mono battery configurations are deemed feasible as they exceed the maximum added draught and extension length limitations. However, fuels like HVO and FAME show technical feasibility due to their similarity to MDO, provided the IMO continues to consider them as zero-emission fuels. Regarding the hybrid propulsion configurations, both MGO-H2(l) and DF-H2(l) are technically feasible for all propeller types, including the original propeller. This is mainly attributed to the relatively high energy density of methanol and MGO when compared to liquid H2.

It is worth noting that in all situations, the presence or absence of waste heat recovery (WHR) or regenerative braking, or a combination of these systems, does not directly determine whether the 40% CO_2 emission reduction target is met or not (see Table 7). However, this does not imply that installing these systems would not be beneficial. While they may contribute to additional complexity, volume, and weight in the overall machinery configuration, they may still provide other advantages and improvements.

Table 7: CO_2 emission reduction, green: configurations technical feasible

			Propeller				
Converter	Fuel	Conf.	Original	1	2	3	4
ICE	MGO	D-D	0%	19%	31%	19%	31%
ICE	MGO	D-E	-4%	16%	28%	16%	28%
ICE	HVO	D-E	90%	92%	93%	92%	93%
ICE	FAME	D-E	93%	94%	95%	94%	95%
ICE	DF	D-E	16%	32%	42%	32%	42%
PEMFC	Hydrogen	E	100%	100%	100%	100%	100%
Battery	NMC-Lithium	E	100%	100%	100%	100%	100%

100hr long cycle

The dual fuel configuration can achieve a 40% reduction in CO_2 emissions only when combined with the application of propeller type 2(4.0D). This is because carbon is still present in methanol and the pilot fuel, necessitating a larger diameter propeller to reduce energy consumption during the cycle. For a mono-fuel hydrogen configuration, upgrading the propeller to type 1 and type 2 is required to prevent exceeding the maximum extension limits. On the other hand, the hybrid configuration MGO-NMC-Li is feasible for all propellers, primarily due to MGO's high energy density, which requires only a small amount of energy from batteries. However, the hybrid configuration DF-NMC-Li is feasible only with propeller type 2, owing to the lower energy density of the batteries and methanol in comparison to MGO.

Continuous long cycle

The DF configuration can be feasible if combined with a type 2 propeller, even though it requires hull extension or storage in the fish hold. However, using H2(l) as a mono fuel is not technically feasible for any propeller type, as it exceeds the extension length or results in too much lost volume in the fish hold. The technically feasible hybrid configurations are generally similar to the 100hr long cycle, with the exception of DF-NMC-Li. This configuration requires additional volume of methanol compared to MGO, leading to the need for additional energy from batteries. Consequently, DF-NMC-Li is only feasible with the type 2 propeller.

Since the mono fuels use the same emission factor for both 100hr and continuous long cycles, their CO_2 emission reductions are equal. As previously mentioned, the hybrid fueled configurations are designed to achieve a 40% CO_2 reduction, and thus, their emission reductions are not visualized, as they all achieve the same reduction target of 40%. For the WHR systems, the battery is not taken into account since it does not have enough heat flow in the exhaust.

If it is found that the proposed configuration meets the requirements, it is considered technically feasible. Subsequently, further analysis will be conducted to assess the economic performance of the different configurations. The unfeasible configurations will be excluded from the scenarios which follow in the upcoming sections. Table 8 summarizes the technical feasibly propulsion configurations. Based on these developments it is assumed that using a larger diameter propeller is highly cost-effective regardless of the chosen energy carrier and thus it was decided to further analyze the configuration with the type 2 and type 4 propeller applied. Figure 3 demonstrates the economic performance of the 100-hour and continuous long cycle, combined with either a type 2 or type 4 propeller, for all technical feasible propulsion configurations. Figure 4 represents the total cost of owner ship, minus the remaining value of the ship including its propulsion configuration, (Equation 4).

Table 8. Technically feasible configurations

			100 hr long cycle	Continuous long cycle
	Fuel	Config.	Propeller type	Propeller type
Mono	HVO	D-E	Original, 1,2,3,4	Original, 1,2,3,4
	FAME	D-E	Original, 1,2,3,4	Original, 1,2,3,4
	DF	D-E	2,4	2,4
	Hydrogen	E	1,2,3,4	-
Hybrid	MGO-H2	D-E	All	All
	MGO-NMC-Li	D-E	2,4	2,4
	DF-H2	D-E	All	All
	DF-NMC-Li	D-E	1,2,3,4	2,4

A number of trends can clearly be spotted for the long term 15 year projection in Figure 3. First, the new build vessel surpasses all retrofit configurations in performance, primarily due to two factors. Firstly, the maintenance costs of the hull, including auxiliary systems, are significantly lower compared to retrofit configurations due to the age of the hull and systems. Secondly, fuel costs are low because MGO is relatively inexpensive, and the energy consumption is minimized due to the hull being optimized for a 4.0 meter diameter propeller. In contrast, the DF hybrid configurations yield poorer results compared to the MDO hybrid configurations. This is directly attributed to methanol being a more expensive fuel than MGO, and the carbon emission tax not compensating for the equal amount of emissions generated by both fuels. Although the HVO and FAME show promising numbers, they still exhibit a significant operational increase compared to the original configuration. However, over the long term, this difference diminishes as the emission tax rises. The TCO analysis for the 100-hour long cycle indicates that while the new build vessel has low operational costs, its performance is somewhat hindered by a high TCO resulting from substantial capital expenses in 2023. Despite higher operational expenses, the HVO and FAME demonstrate promising TCO lines due to being drop-in fuels, which require lower capital expenses. The MDO-Hydrogen, despite having higher capital expenses compared to fuels like MGO, HVO, FAME, or DF, shows good results owing to the low forecasted electricity prices.

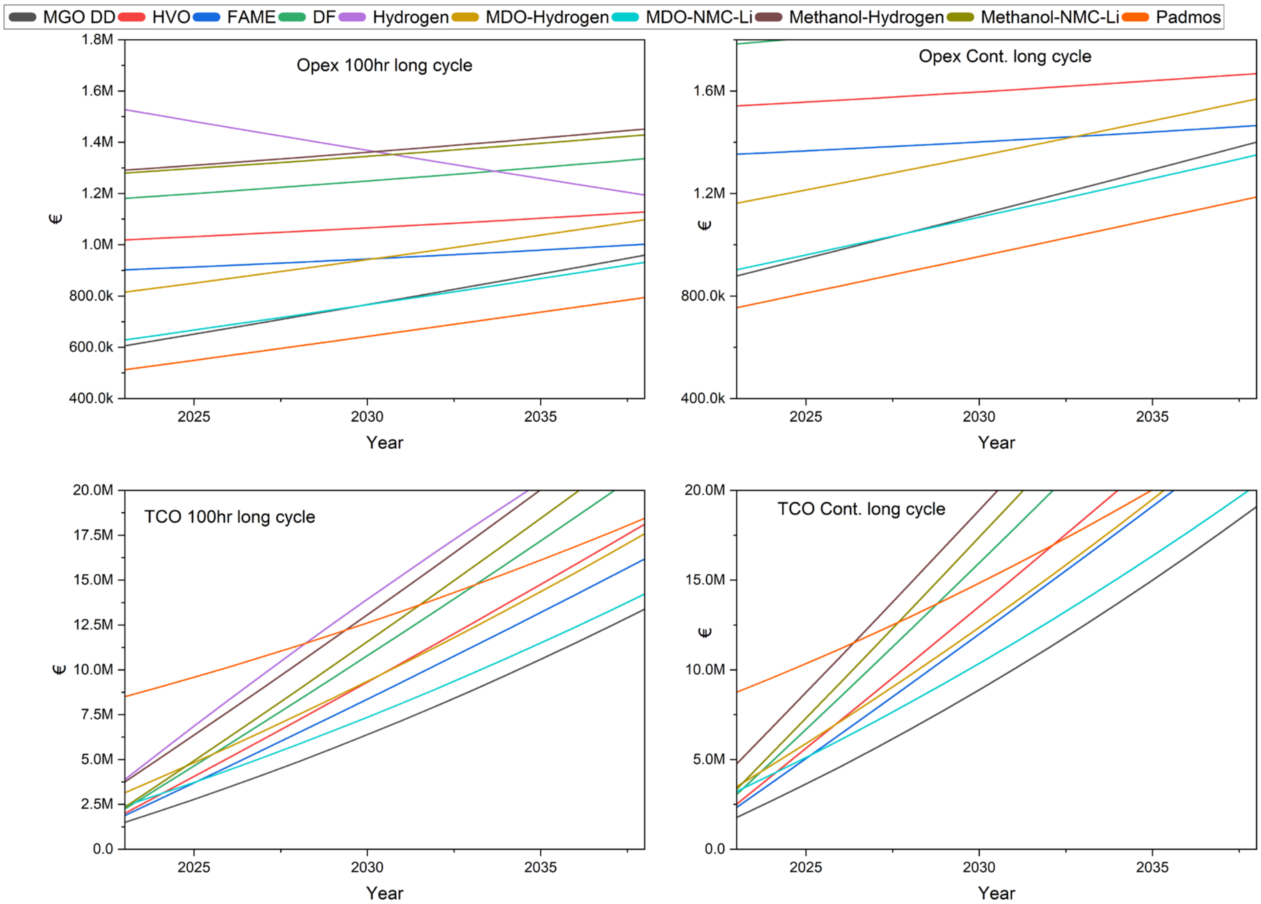

Figure 3: Opex and TCO, for type 2 propeller, 100hr and continuous long cycles, including new build vessel. The MGO DD is the reference to original costs

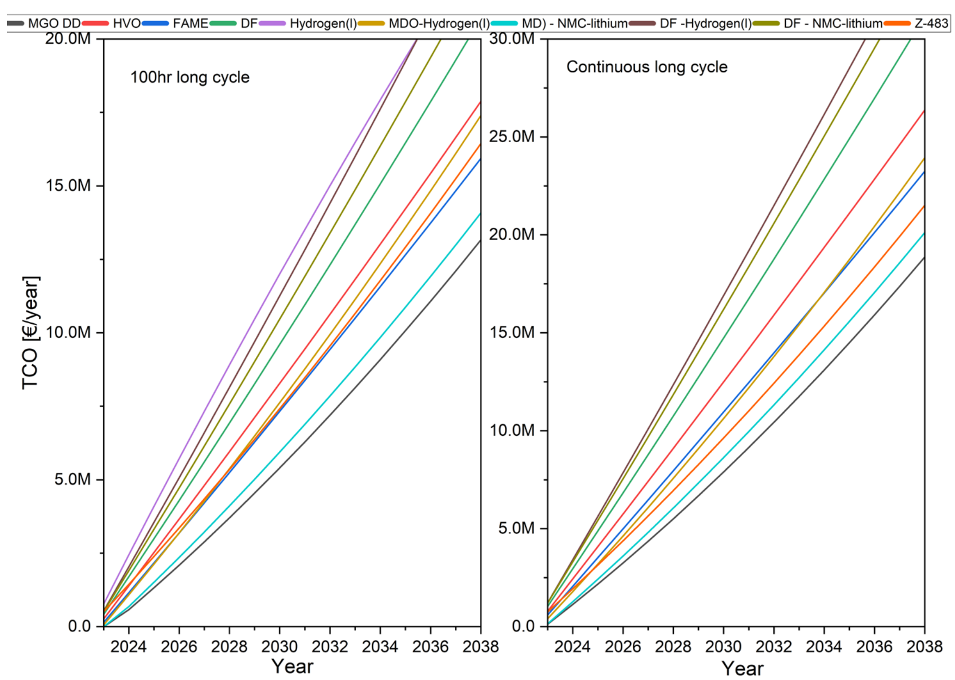

Figure 4: TCO – remaining value, for type 2 propeller including new build vessel. The MGO DD is the reference to original costs

Based on Figure 4 a short description is provided on what can be concluded when including the remaining value of ship and propulsion configuration into the TCO. In contraction to Figure 3 the high capital expenses in year 2023 are roughly included for in these figures. The hybrid MDO-NMC Li option shows promising performance despite its high capital expenses in 2023, this is again assumed to be caused by the low forecasted electricity. It is important to note that the average battery life is 15 years for the two long cycles, depending on the number and types of charges and charges. Therefore if, for any reason, there is a desire to proceed with the vessel, it would require a significant capital investment for the battery configurations. This is not the case for the other options. The options for mono hydrogen can be concluded to be technically or economically not feasible using the forecasted parameters from Table 3. The drop in fuels HVO and FAME actually show to be a very good option, but as mentioned their TTW factor is very sensitive to interpretation of IMO regulations, and thus could result in not being technically feasibly in 2030 when regulations change. To eliminate this uncertainty, an alternative option could be chosen, such as methanol. The main drawback of this option is the currently predicted higher energy carrier prices, which consequently increase the TCO.

CONCLUSIONS

This study employed an assessment model to evaluate various technical configurations of energy carriers, energy converters, and energy reduction methods on Dutch beam trawlers. The findings include analyses performed on different emission reduction techniques for a case vessel operating under either a continuous or 100-hour operational profile.

Technical Feasibility

Both long cycles:
None of the mono battery configurations are feasible due to exceeding the maximum added draught and extension length. However, fuels such as HVO and FAME are technically feasible as long as they are considered zero emission fuels by the IMO. The hybrid propulsion configurations MGO-H2(l) and DF-H2(l) are technically feasible for all propeller types, including the original propeller, due to the relatively higher energy density of Methanol and MGO compared to liquid H2. It can also be concluded that the implementation of WHR or regenerative braking systems, or a combination of both, does not determine whether the 40% CO_2 emission reduction target is met or not. However, installing these systems will contribute to additional complexity, volume, and weight of the overall machinery configuration.

100hr long cycle:
Dual fuel configuration only achieves the 40% CO_2 emission reduction target when combined with propeller type 2(4.0D) to reduce energy consumption. The mono-fuel hydrogen configuration requires propeller upgrades to prevent exceeding the maximum extension. The hybrid configuration MGO-NMC-Li is feasible for all propellers due to the high energy density of MGO, requiring only a small amount of energy from batteries. The hybrid configuration DF-NMC-Li is only feasible with propeller type 2 due to the low energy density of the batteries and methanol.

Continuous long cycle:
The DF configuration, when combined with a type 2 propeller, results in a feasible configuration, although hull extension or storage in the fish hold may be required. The mono fuel H2(l) is not technically feasible for any propeller type due to exceeding the extension length or losing volume in the fish hold. The technically feasible hybrid configurations are similar to the 100hr long cycle, except for DF-NMC-Li, which requires additional volume due to methanol requirements. The energy scale of batteries is such that this hybrid configuration is only feasible with a type 2 propeller.

Economic feasibility
Depending on the amount of available financial resources, available subsidy, and to what extent one is willing to take risks, the following conclusions can be made for different categories of initial capital expenses:

€0-€2.5M
The cheapest option to meet the 2030 regulations is the switch to bio-diesels HVO and FAME. Because these options are fully drop-in, there is no need for significant investments in system and vessel conversion, which applies to both types of long cycles. However, a major drawback of this strategy is the sensitivity to future regulations. This is partly due to the fact that the low CO_2 emissions for these fuels are entirely determined by regulations and the limited availability of raw materials. As a result, it is possible that within a short period, this option will no longer ensure IMO compliance.

A second option that can be recommended for any type of fuel and long cycles is to increase the propeller nozzle diameter. Although the Orcan WHR is estimated to have a payback period of 8-9 years (100-hour cycle) and 5 years (continuous cycle), the investment of approximately €250k is still significant and does not determine compliance with the IMO regulations. Although in the long run the Orcan will result in a reduction of TCO compared to not applying it.

For both long cycles an option which requires more initial investments although less sensitive to regulations and can be cheaper in the long run is the conversion to methanol dual fuel configuration or to hybrid MDO-battery option, this applies to these configurations with 4.0m diameter propeller. The methanol option requires a lower investment, but the MDO-battery option outperforms it despite the high initial investment, thanks to the low predicted operational costs mainly caused by low forecasted electricity prices.

€2.5M+
In addition to the retrofit options, this option also includes the possibility of building a new ship. Once again, it is recommended to use a larger propeller for all configurations. Looking at Figure 3 and 4, it can be observed that in the long term, both types of long cycles show that the hybrid MDO-battery and the new build options deliver the best results in terms of TCO. For both options, it is again noted that they will be less sensitive to future prices of alternative fuels or the impact of (inter)national regulations on tax emissions.

In the assessment between the retrofit option to MDO-battery and the newbuild, it should be considered that after the assumed 15-year lifetime, the retrofit option will have virtually no remaining value, and the hull of the ship will be technically written off due to its age. This is not the case for the newbuild option, which still holds significant remaining value and is technically capable of many more years of service, provided it is well-maintained. As calculated with this model, no attempt has been made to calculate the labor hours required for installing the new propulsion configuration. However, the mentioned newbuild price does include the total cost of materials and labor. As a result, the lines for retrofit and new build may give a distorted picture. Therefore, despite the ease of saying it and the possibility of achieving it financially, committing the company to a large debt for many years, a newbuild ship is considered a better option when considering costs and lifespan.

Energy carrier storage
Due to practical considerations, it is not advised to use both the net store and fish hold to store the energy carrier. The costs to extend the vessel are very small compared to the costs for new propulsion configurations. This trend means that if one decides to extend the vessel, the extension length is not that important when looking at costs. This also reinforces why you wouldn't want to use a net store if you extend, since the costs to prevent giving up such a practical volume are very low.

The practical influence of using the fish hold is the reduction of storage volume for fish boxes. The practical influence of hull extension is a potential increase in operational costs due to increased hull resistance. The increase in operational costs, in reference to the original configuration, is very small. Only in the absence of financial resources would the choice be made to store the energy carrier in the fish hold. However, if an owner is convinced to have an excessively spacious fish hold and only a small additional volume is needed for energy carrier storage, then the fish hold can also be used.

CONTRIBUTION STATEMENT

Arnoud de bruin: Conceptualization; Investigation, Methodology, Software, Writing – Original Draft. **Walter van Harberden:** Conceptualization; resources; supervision; writing – review and editing. **Austin A. Kana:** Conceptualization; supervision; writing – review and editing.

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