Designing the zero emission vessels of the future: Technologic, economic and environmental aspects

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One of the major challenges facing the maritime sector today is the transition to zero emission carbon-neutral vessels. In particular, work vessels such as dredging vessels are required to operate worldwide and under heavy conditions. These vessels have a high power density, limited on-board space, require often a large autonomy, and therefore will need very energy dense fuels. This article presents an environmental and economic assessment of four cutter suction dredger drive system design alternatives with the life cycle performance assessment tool. This tool includes the most important environmental factors as well as the net present value. The effect of emission costs and fuel price developments may be taken into account with scenarios, and this article illustrates that they have a large effect on the economic viability of future zero emission vessels. A combination of clean fuels, new prime mover technologies, efficient design and effective system integration has the potential to achieve zero emissions while maintaining the vessels' functionality. However, technology alone cannot solve the complex challenge of energy transition in the maritime sector. In order to make zero emission designs economically viable, a system wide integration is needed, meaning cooperation in the value chain and effective policies.

Keywords: Life cycle performance assessment, zero emission vessels, alternative fuels, energy efficiency, emission costs

1. Introduction

1.1. The challenge of decarbonisation

The decarbonisation of the world's entire energy system is one of the major challenges of the 21st century. Fossil fuels such as coal, oil & gas supplied 81% of the world's primary energy demand in 2017 and resulted in a total carbon dioxide (CO_2) emission of 32.6 Gt [26]. The Paris Agreement has the aim to limit the global temperature rise due to global warming limited to 1.5–2°C compared to the pre-industrial

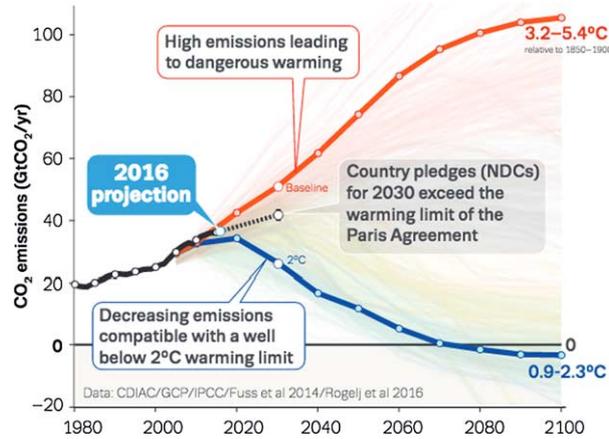[*]Corresponding author. E-mail: btw.mestemaker@royalihc.com.

Fig. 1. CO_2 emission scenarios up to 2100 [21].

era [53]. Figure 1 highlights two possible CO_2 emission pathways up to 2100 and their effect on the average temperature on Earth compared to the pre-industrial era. The baseline (business-as-usual) scenario results in a temperature increase of 3.2–5.4°C, while the Paris Agreement pathway results in an increase of 0.9–2.3°C. The Paris Agreement requires a sharp decrease of CO_2 emissions and possibly negative CO_2 emissions after 2080.

The International Maritime Organisation (IMO) mainly focussed on the reduction of harmful emissions e.g. sulphur oxides (SO_X), nitrogen oxides (NO_X) and particulate matter (PM) emissions from shipping. In addition, the IMO has currently two energy efficiency measures in place to reduce CO_2 emissions from ships. These are the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). The EEDI applies to new ships from the largest and most energy intensive vessel types, covering about 85% of the CO_2 emissions from international shipping. It requires a 30% CO_2 reduction in grams per tonne mile for vessels built in 2025 compared to the reference value (average from 2000 to 2010) [27].

Greenhouse gas (GHG) emission reduction is gaining importance within the IMO, even though the Paris Agreement does not include the shipping sector. IMO has adopted an initial strategy on the reduction of greenhouse gas emissions from ships [28] during the 72nd meeting of the Marine Environment Protection Committee (MEPC) in April 2018. The initial IMO GHG strategy has the objective to reduce the total GHG emissions of shipping with at least 50% in 2050 compared to the 2008 level and aims to pursue efforts to phase GHG emissions out entirely. This 50% CO_2 reduction is in line with the proposal of the International Chamber of Shipping [29].

The shipping sector emitted 854 Mt of CO_2 emissions in 2017, about 2.6% of the total global amount of CO_2 emissions in 2017 [26]. The CO_2 emissions of shipping are expected to increase in the future for several reasons. The shipping volume is

expected to grow with 32% until 2030 (compared to 2016) [13] and the maritime fleet size will likely increase with 35% in deadweight by 2050 [27]. The long economic lifetime of vessels about 25–30 years, results in a slow pickup of alternative (cleaner) fuels due to the fuel dependent retrofit costs.

Work vessels present a particularly difficult challenge. For example, dredging vessels are often required to operate worldwide and under heavy conditions. These vessels have a high power density, limited on-board space, require often a large autonomy, and therefore will need very energy dense fuels. The alternatives are needed for the maritime sector and for work vessels in particular include:

- alternative renewable fuels;
- novel cleaner prime movers;
- efficient designs;
- system integration at both the vessel and the value chain level (i.a. the fuel logistics & availability and clear policy).

1.2. Alternative fuels

Several alternative fuels or energy carriers are considered in literature to replace fossil fuels in the maritime sector [14,16,29,38,43]. Each of these alternatives has their own issues regarding the sufficient availability for the maritime sector, the transport & bunkering logistics, the status of the renewable production processes and the fuel & investment costs. Table 1 provides an overview of the technology readiness level (TRL), the possible prime movers, the total cost of ownership (TCO) and emissions of a vessel operating on these alternatives. NASA developed the TRL system to assess the maturity of a technology with certain criteria for each level from 1 to 9 as explained by Mankins (2004) [39]. The emissions in Table 1 include the GHG and hazardous tank-to-propeller (TTP) emissions, however the well-to-tank (WTT) emissions are not considered in the table. The "+" and the "++" signs indicate higher emissions of 25% and 50% respectively, the "−" and the "−−" signs indicate lower emissions of 25% and 50% respectively and the "0" indicates no nett emissions. For the TCO, the "+" and "++" signs indicate lower costs while the "−" and "−−" signs indicate higher costs. The alternative fuels may be placed in four groups:

- transition fuels: fossil fuels emitting less harmful emissions (NO_X, SO_X & PM) and possibly less GHG emissions;
- bio-based fuels: fuel with carbon from biomass emitting nett less GHG emissions;
- renewable e-fuels: fuels with carbon captured from the environment for example via exhaust gas capture or direct air capture (DAC);
- carbon-free fuels/energy carriers such as hydrogen (compressed, liquefied), ammonia (NH_3), reversible metal hydrides (MH_2), alkali metal hydrides (such as sodium borohydride ($NaBH_4$)), iron powder (Fe) and batteries.

Table 1
Alternative fuel characteristics and integration aspects [4]

Fuel	TRL	Prime mover	TCO	Emissions
GTL (syn. diesel)	8	CI/FC	−−	++
LNG/CNG	9	DF/SI/FC	++	+
LPG	9	DF/SI/FC	+	+
MeOH	8	DF/SI/FC	++	−
DME	6	CI/FC	++	−
HVO (biodiesel)	8	CI/FC	++	−−
Biogas (NG)	8	DF/SI/FC	++	−−
BioMeOH	7	DF/SI/FC	++	−−
BioDME	6	CI/FC	+	−−
BioEtOH	9	SI/FC	++	−−
Ren. MeOH	7	DF/SI/FC	+	−−
LH_2	9	DF/SI/FC	−	0
NH_3	5	FC	+	0
$NaBH_4$	3	DF/SI/FC	−−	0
Fe	3	n/a	−−	0
Li-ion	9	n/a	−−	0

CI: compression ignition internal combustion engine (ICE), DF: dual fuel ICE, SI: spark ignited ICE & FC: fuel cell (type depends on fuel).

Figure 2 shows the energy storage density per mass and per volume for several energy carriers including their storage system. These properties are independent of the fuels origin (fossil, biomass, e-fuel/renewable or a blend). Biofuels may be a future fuel option for the maritime sector, but should be produced 100% renewable and not compete with food production. The production processes of biofuels, renewable e-fuels and the carbon-free fuels are still in development, making it difficult to predict which will be the future fuel for (work) vessels. Brynolf et al. (2018) [2] concluded that methane is the least costly e-fuel to make, followed by methanol, dimethyl ether, gasoline and diesel, but these estimations have uncertainties. Renewable methane can theoretically be produced with 80% efficiency based on the lower heating value (LHV) using a solid oxide electrolysis cell for co-electrolysis [35], but the technology is still in development. The process requires CO_2, but this is also the case for the production of other hydrocarbon fuels (e.g. methanol, DME & diesel).

Hydrogen (H_2) in the form of liquefied hydrogen (LH_2) or compressed gaseous hydrogen (CGH_2) is an option for vessels operating close to the coast or on inland waterways. These do not require a large autonomy as they can refuel on a more regular and if required daily basis. The low energy density (Fig. 2) of hydrogen limits its use on work vessels as these usually have no fixed route, have a high power density, have limited space for fuel storage and require a large autonomy.

Ammonia (NH_3) has a higher energy density than hydrogen and does not require CO_2 as a feedstock unlike renewable hydrocarbon e-fuels. Ammonia is currently not
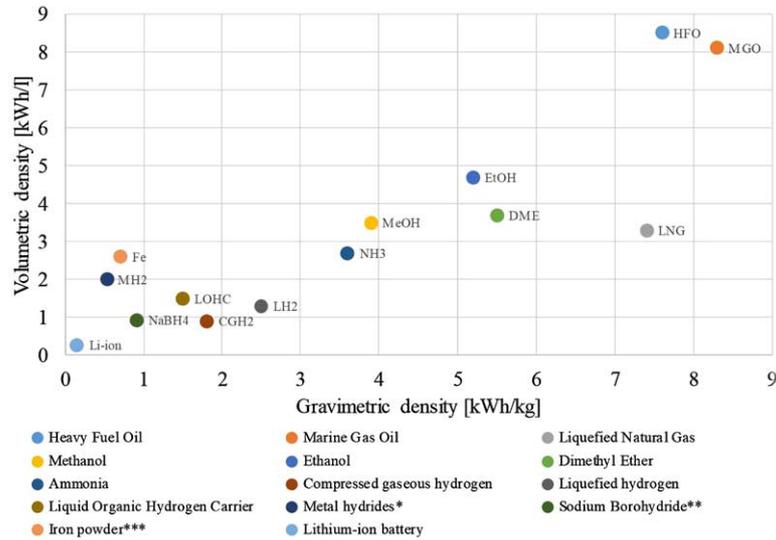
Fig. 2. Volumetric and gravimetric energy density of logistic fuels including the tank system [41]. *Low temperature AB2, Ovonic, **fuel 30, wet spent fuel (reactor not included), ***spent fuel (reactor not included).

used in commercial applications as a fuel, due to among others its high toxicity and its about 5 times lower laminar flame speed than methane (CH_4) [32] which makes it difficult to combust in an engine. The application of ammonia as an energy carrier is currently researched in several projects such as the EU project ShipFC in which a 2 MW ammonia fuel cell will be retrofitted on the offshore support vessel Viking Energy [18]. Ammonia was also used as a fuel during the 2nd World War to power commercial busses in Belgium due to a diesel shortage [34].

Solid energy carriers are being investigated as an alternative fuel for the maritime sector. Figure 2 shows three options, namely reversible metal hydrides (MH_2), an alkali metal hydrides e.g. sodium borohydride ($NaBH_4$) and iron powder (Fe). The energy density of $NaBH_4$ in Fig. 2 is based on the wet spent fuel ($NaBO_2$) as this has a higher mass [56]. Storing the fuel in a dry form may increase the energy density, but results in additional energy consumption due to the need to produce fresh water onboard for the hydrogen release reaction. The used fuel may be stored dry, but this requires the drying and thus additional energy consumption. The energy density does not include the required hydrogen release reactor for $NaBH_4$. The efficient recycling of the sodium metaborate ($NaBO_2$) to the usable $NaBH_4$ still posses an issue [36]. The iron powder (Fe) energy density is based on the used fuel as this in the form of haematite (Fe_2O_3) is about 43% heavier than the unused fuel due to the additional bound oxygen atoms [33]. The combustion chamber required for iron powder is not included in the energy density of this fuel.

Literature [14,16,29,38,43] also mentions nuclear, solar and wind power, but these are not included here. Work vessels often operate globally under unpredictable sea conditions and require a reliable and stable power source with a high energy density. This rules out solar and wind power as the main energy source, but, they can play an auxiliary role. Wind (assisted) power with for example a Flettner rotor can reduce fuel consumption on some types of work vessels by reducing the required propulsion power. Nuclear power is not a likely power source for commercial shipping as it is a controversial technology due to its social acceptance and high capital costs. Work vessels usually operate close to the coast and enter harbours frequently, thus its application is not expected for these vessels. Nuclear power is probably limited to military applications and to vessels that operate very remotely with no bunkering infrastructure.

1.3. Prime movers

The shift from heavy fuel oil (HFO) to alternatives allows for the application of novel prime movers with a higher efficiency and lower emissions. The diesel engine is currently the predominant prime mover in the maritime sector, but the natural gas fuelled pilot ignited dual fuel engine has been gaining traction recently. The prime movers considered for (future) maritime application can be divided in two categories, namely internal combustion engines and fuel cells. Gas turbines are continuous internal combustion engines, but are not common for maritime application due to their low efficiency in the required power range.

Reciprocating internal combustion engines can be split in compression ignition (CI), pilot ignited gas-diesel (GD), pilot ignited dual fuel (DF) and spark ignited (SI) engines. Table 1 showed that CI engines can be used for high Cetane number (CN) fuels such as marine diesel oil (MDO) or marine gasoil (MGO), biodiesel either hydrotreated vegetable oil (HVO) or fatty acid methyl esters (FAME), gas-to-liquid (GTL) also known as synthetic diesel and (bio)dimethyl ether (DME). Fuels with a low CN have a too large ignition delay and cannot be used in the CI engines [25]. Combusting ammonia in a CI engine requires a compression ratio of more than 35 to achieve the auto ignition temperature in the cylinder [11,37].

Low CN fuels such as methanol (MeOH), ethanol (EtOH), liquefied petroleum gas (LPG) and natural gas either liquefied (LNG) or compressed (CNG) require an external ignition source to start the combustion process. DF and SI engines add the main energy source to the fresh airflow either in the inlet port, the inlet receiver or before the compressor [19]. This air-fuel mixture is ignited in the cylinder with either a diesel pilot (in a DF engine) or a spark plug (in a SI engine). SI engines general have pre-combustion chambers with a richer air-fuel mixture to ensure combustion in the main chamber. Using a pre-chamber allows these engine to run on more lean mixtures, resulting in a higher engine efficiency and lower NO_X emissions. Injecting the fuel in the inlet receiver or before the compressor of engines with a valve overlap results in fuel slip. For some fuels, such as methane, this has a negative impact on the

GHG emissions of these engines. Therefore, most modern dual fuel engines inject the fuel in the inlet receiver and time it based on the exhaust valve closure. These engines may still have fuel slip due to an incomplete combustion as there are dead spots in the cylinder which the flame front may not reach [7].

The GD engine alternatively injects the main energy source at high pressure in the cylinder through the flame created by the combustion of the pilot fuel [19]. This combustion method may be applied for the same fuels as the DF and SI processes indicated in Table 1. The GD process results in a diesel like combustion and transient response. It prevents the occurrence of knocking and misfiring, but does result in NO_X emissions similar to those of diesel engines.

Fuel cells are an alternative prime mover with less harmful emissions, less noise and higher efficiencies than internal combustion engines, but at the cost of a slower transient response and a lower tolerance for fuel impurities [55]. The most promising fuel cell types for maritime applications are the low temperature proton exchange membrane fuel cell (LT-PEMFC), the high temperature proton exchange membrane fuel cell (HT-PEMFC) and the solid oxide fuel cell (SOFC) [52].

Table 2 provides an overview of the characteristics of these three fuel cell types. LT-PEMFCs are used by car manufacturers as a primary mover due to the high power density and the good transient capability for a fuel cell, but hydrogen with a high purity is required as a fuel. For the maritime application of LT-PEMFCs, the main issues to be solved are the on-board availability of pure hydrogen and the possible failure mechanisms in a marine environment due to for example the saline air [30].

SOFCs have a higher tolerance for fuel impurity, allowing for operation on light hydrocarbons such as natural gas [54]. The high temperature of the SOFC also allows for reforming in the stack and operation on ammonia, which can be cracked in the stack [9]. However, SOFCs have a low power density and a slow transient response

Table 2
Overview of the characteristics of various fuel cell technologies [55]

Property	Unit	LT-PEMFC	HT-PEMFC	SOFC
Operating temperature	°C	65–85	140–180	500–1000
Electrical efficiency (LHV)	%	40–60	30–40	50–65
Fuel requirements		99.9999% H_2	CO < 3%	S < 20 ppm
Gravimetric power density	W/kg	125–750	25–150	8–80
Volumetric power density	W/l	50–400	15–120	4–32
Stack life time		5–20 kh	10–30 kh	20–90 kh
System life time		$\geqslant$10 years with stack replacement		
Cold start-up time		<10 s	10–60 min.	>30 min.
Load transients (0 to 100%)		seconds	<5 min.	<15 min.
Current capital cost	€/kW	1000–2500	3000–5000	3500–15000
Projected capital cost	€/kW	50–500	100–1000	200–2000
Maritime TRL		6–7	5–6	4–5
Cooling medium		Liquid	Liquid	Air

to prevent thermal stress in the stack [45]. SOFCs are generally applied on land in mission critical systems such as data centres and in combined heat and power systems. Maritime application of SOFCs requires an increase of the power density and a reduction of the cost price per kilowatt.

HT-PEMFCs are an alternative for both as these have a higher tolerance to carbon monoxide (CO) than the LT-PEMFCs and a faster transient response than the SOFC, but at a lower efficiency [6]. A possible implementation of HT-PEMFCs is to replace auxiliary engines, which generally have a lower power than the main engines. The HT-PEMFC may be used to operate on the reformate of a fuel which is easy to reform such as methanol [31]. Fuels that require higher temperatures to reform such as methane should not be combined with HT-PEMFCs as the operating temperature is not high enough to reform the fuel and the need for external heat would further decrease the efficiency.

1.4. Energy efficiency measures

Efficient vessel designs may be combined with novel fuels and prime movers to further decrease the CO_2 emissions. More efficient vessels require less fuel, which can increase its autonomy or reduce its size. Therefore, improving the energy efficiency of vessels is required for the successful implementation of alternative fuels with a lower energy density.

Bouman et al. (2017) [1] made a review regarding the state-of-art of measures to reduce GHG emissions from shipping. Figure 3 shows their results for 22 measures distributed in 5 categories. Some of these measures are mutually exclusive, but others can be combined. Current technologies make it possible to reduce CO_2 emissions with 50–60% for freight transport without including the effect of renewable fuels.

The improvement from these measures is smaller for work vessels such as trailing suction hopper dredgers (TSHDs) as the dedicated mission equipment requires a significant part of the installed power [10,49]. The propulsion system of TSHDs accounts for about 50% of the total power requirement. Therefore, improvement to both the power generation system and the propulsion system are important.

Improving the hull shape of a TSHD may reduce resistance with approximately 15% on top of the about 30% reduction achieved for TSHD's during the last 25 years [41]. The propeller efficiency may be improved significantly by applying CFD for more accurate propeller flow calculations of new designs. This results in a better efficiency at a certain thrust to speed ratio and a propeller which does not cavitate during normal operation. The new Wageningen C4-40 propeller has a maximum efficiency of 78% at a P/D of 1.4 [8], a 30% efficiency improvement compared to the 60% efficiency of current propellers. The combination of using light weight materials (±5%), hull shape optimisation (±15%), a more efficiency propeller (±23%) and measures to reduce resistance such as hull coatings (±5%) results in a propulsion system efficiency improvement of a TSHD of about 40%.
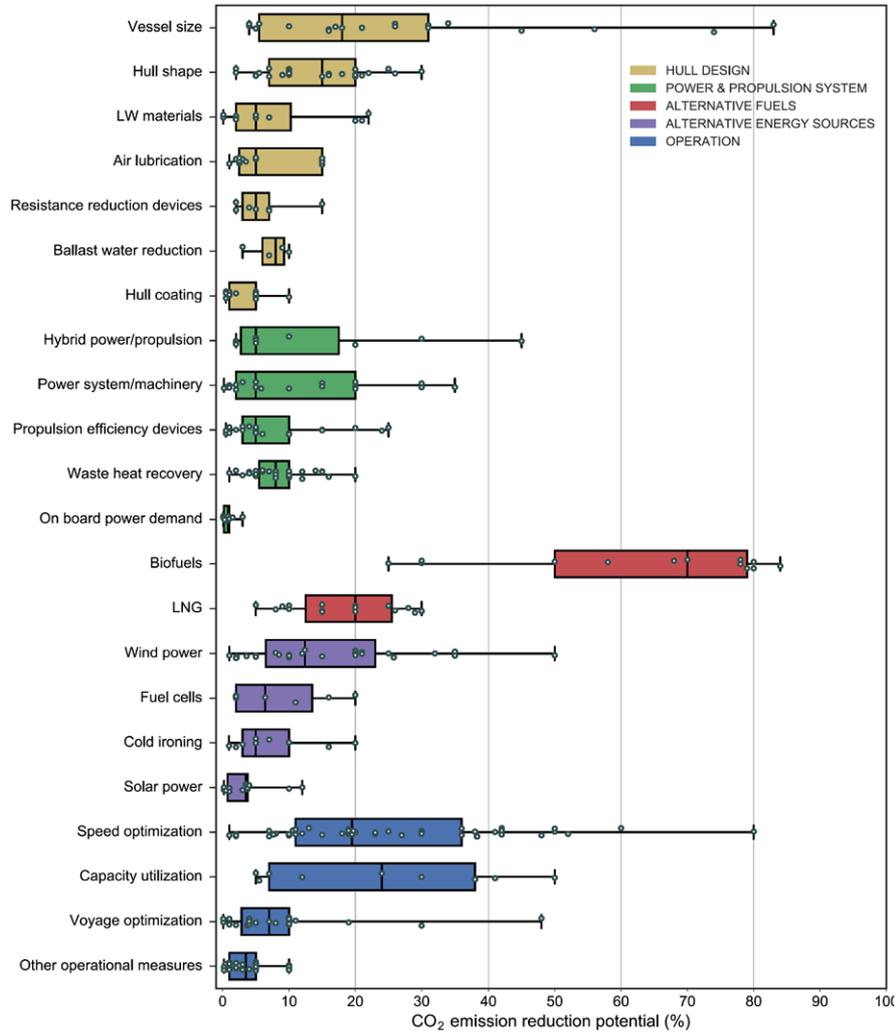
Fig. 3. CO_2 emission reduction potential as published by Bouman et al. (2017) [1].

The power generation system efficiency of a TSHD may increase with about 20% by combining a hybrid power system with fuel cells and waste heat recovery based on the results of Bouman et al. (2017) [1]. The total fuel efficiency improvement of a TSHD varies between 30% to 40% for a propulsion system energy consumption of 33–67%.

Cutter suction dredgers (CSDs) have a different load profile than TSHDs and a 4.4–24% fuel consumption reduction is possibly by hybridising the drive system

[20]. The power generation system efficiency may increase with 10–20% by applying fuel cells in combination with a waste heat recovery (WHR) system [1]. Thus, the total fuel efficiency improvement that may be achieved for a CSD varies between 14% to 40% depending on the operational profile.

1.5. System integration

The drive systems of zero emission vessels with the new energy carriers and novel prime movers require four changes from a system integration perspective, namely design for operational profile, electrification, hybridisation and modularisation. Further, not only the vessel, but also the whole value chain must be integrated, so that zero emission vessels can operate economically with alternative cleaner fuels.

Design for operational profile means the installed power will match the usual power requirements, and is not defined based on a "design point" of an extreme situation that may rarely occur. This extreme situation must be considered as well and measures must be taken to ensure the safety of the vessel and crew in such situations.

Electrification is necessary for the application of novel prime movers such as fuel cell systems, energy storage systems (ESS) and energy recovery devices such as WHR systems based on steam or on an Organic Rankine cycle (ORC) as all of these systems produce either DC or AC power [50,59].

Hybridisation (with an ESS) allows for the use of prime movers with a slower transient response than diesel engines [15,17]. During large load fluctuations an ESS may be used to prevent e.g. a DF engine from changing to diesel operation or prevent a spark-ignited engine from stalling [40]. SOFCs require hybridisation as their dynamic behaviour is limited due to the internal thermal gradients of the cells. LT-PEMFCs have a better dynamic response, but large load variations will significantly reduce the lifetime of the fuel cell due to problems with membrane humidification and gas starvation [47]. For vessels with a low (average) engine load due to dynamic positioning requirements, an ESS may be used as a spinning reserve, delivering power during the failure of an engine or switchboard. This would allow fewer engines to operate and the operating engines will have a higher average engine load, reducing the specific fuel consumption. Fewer running hours and higher engine loads also reduce engine wear and maintenance costs.

Modularisation of future drive systems will allow the flexibility to optimize the drive system for each task the work vessel has to perform based on the operational profile. Drive systems are generally designed for the most extreme situation they could encounter during its operation, while this situation is not very common [22]. This results in overpowered and suboptimal vessels from a fuel consumption perspective as the specific fuel consumption of engines increases at part and low load. Modular power supply units that can be switched on and off as required can overcome this problem and it allows to exchange drive components with limited costs when they become outdated (e.g. for emission purposes).

The integration of the value chain means that zero emission vessels can operate with economic viability and without major limitations. For example, they can bunker their fuel of choice near their operational area. Currently, alternative cleaner fuels are produced in small amounts and the fuels logistics network is underdeveloped, limiting their introduction for maritime applications [48]. Vessel owners need to go to great lengths to organise the fuel supply on their own. The same challenge holds for spare parts and maintenance for novel (often more complex) drive systems, for which crews and maintenance operators need special training. In the view of the multiple alternatives ahead (multiple fuels, multiple prime movers), a wide cooperation is needed at the value chain level, to make sure the energy transition can occur at bearable costs, so systems integration is also needed at a global maritime level. Further, policies that stimulate the cleaner technologies need to come in place, in order to shift the economic balance [24]. A current example is the discussions on the tax exemption of maritime fuels and the introduction of carbon and emission pricing. The effect of a clean design and wide system integration including policies is illustrated in the next section with the example of four design alternatives for self propelled CSD.

2. Methods

2.1. Design alternatives

Designing future proof zero emission vessels is a complex task, involving many choices and a comprehensive systems perspective that the maritime sector still needs to develop. Efforts have been made into developing tools that help designers make these choices and access their effect with limited effort at an early stage. Such a tool is the Life Cycle Performance Assessment (LCPA) tool, described in the next section.

In order to illustrate the effect of design, fuel and prime mover choice, efficiency measures and system integration, four design alternatives of a self-propelled CSD are described and assessed on their environmental performance and economic viability. DF engines using LNG as the main fuel and MDO as the pilot fuel resemble the baseline design. The choice for LNG leads to lower harmful emissions and lower CO_2 emissions. Therefore, DF engines fuelled with LNG are the first transition step towards clean zero emission vessels. Fossil LNG is selected as the use of this fuel is increasing in the maritime sector and renewable LNG is currently not available in sufficiency amounts.

DF engines are capable of operating in two modes, the "gas mode", where main fuel is LNG using diesel as pilot fuel, and the "diesel mode", where the main fuel is diesel. DF engines switch to diesel mode when subjected to large transient loads. Large load fluctuations are common when dredging of materials such as hard packed

sand or rock with a cutter suction dredgers [40,49]. The switch to diesel mode protects the engine from damage, but results in higher emissions than in the gas mode, as the main fuel used is diesel and not natural gas. In order to eliminate the need to switch to diesel mode, two options are available:

- use a hybrid drive system with an energy storage system for peak shaving in order to accommodate the large transient loads;
- use more engines in parallel to decrease the load change per engine.

The most sustainable option to currently power a vessel is a fuel cell which is fuelled with hydrogen produced from renewable energy. Hydrogen has been selected as it can be produced with available technology (TRL 9) and there are currently several hydrogen fuelled vessels being built powered by either fuel cells or engines. Renewable methane or other renewable hydrocarbon fuels are not considered in this study as these require a carbon source from either biomass and/or DAC and the technologies to produce these fuels are not yet mature (Table 1). When renewable hydrocarbon fuels become available, they are likely more expensive than renewable hydrogen as this is used in their production process. Therefore, four design alternatives were evaluated for the work vessel:

- baseline DF LNG: the DF engines change from gas mode to diesel mode during large transient loads;
- hybrid DF LNG: improved version of the baseline design using a flywheel to achieve peak shaving with minimum installed power and operational conditions in gas mode, a DF LNG power supply is used;
- more engines: add one extra engine (3 engines in total) in order to guaranteed operational conditions in gas mode only for the DF power supply;
- future design: hydrogen fuelled fuel cell system with a hybrid drive system able to do peak shaving using a flywheel and batteries. Fuel cell systems should operate with limited dynamic loads for maximum efficiency and lifetime of the stacks. This design is expected to score the best on the environmental performance.

2.2. Vessel weight, materials & investment costs

The baseline vessel design weighs about 15,000 metric tons and the distribution of materials can be found in Table 3. The hybrid LNG and the More Engines designs are assumed to have nearly identical weight and the Future design is assumed to be 10% heavier, due to the relative large weight of hydrogen storage systems. This is a rough estimation and at this early stage, it is not very significant, because the materials have limited impact in the assessment. Besides, this type of vessel spends a significant amount of time not sailing or at a very low speed, so the impact of weight on fuel consumption is considered very limited. The material composition used in the assessment has been limited to simplify the modelling as this has a limited impact on the total results.

Table 3

Material composition and weight of the baseline vessel

Material	Mass (mt)
Steel (85%)	12,800
Copper (5%)	750
Others (10%)	1,450
Total	15,000

Regarding the investment costs, the Hybrid and More Engines designs cost 5% more than the baseline, the Future design costs 40% more. This is only a rough estimation, required to show eventual effects of initial costs of design alternatives.

2.3. Operational phase modelling

The operational phase is modelled in a simplified way as a 30 year use phase. A use phase from 2025 to 2055 is chosen as the used fuel and emission costs are known for this time period. The energy consumption of the alternatives is modelled according to the operational profiles below [42,44]:

- the baseline DF design operates 15% of the time in diesel mode;
- the Hybrid DF LNG uses 1% more fuel compared to the baseline and operates 100% of the time in gas mode;
- more engines DF LNG uses 11% more fuel and operates 100% of the time in gas mode;
- future design Hydrogen Fuel Cell is estimated to use 30% less fuel compared to the baseline. Fuel cell systems are known to have a higher efficiency than internal combustion engines. Combining fuel cells with a hybrid system, optimal installed power for the operational profile and a WHR system, may achieve a reduction of at least 30% in fuel consumption for the same functionality. The chosen fuel is hydrogen produced from excess offshore wind energy.

2.4. LCPA method

The LCPA method was developed in the FP7 EU-funded project JOULES based in the life cycle assessment (LCA) methodology standard ISO 14040 [23,57]. The LCPA method is a simplified screening LCA capable evaluating the environmental performance of design alternatives for maritime equipment at an early stage. Six relevant aspects for the maritime sector were defined. These key performance indicators (KPIs) are included in the method and are calculated with widely accepted methods for each of them [51,57,58]. The chosen environmental indicators are consistent with results from previously performed screening LCAs for applications in which large amounts of fossil fuels are used such as the transport sector [3,5]. The net present value (NPV) has been added as an economic indicator, resulting in the following KPIs measured over the entire life cycle of the vessel:

- global warming potential (GWP) in [tCO_2-eq]: calculated with the CO_2 and CH_4 emissions with an GWP attributed to methane of 28 [46];
- acidification potential (AP) in [tSO_2-eq]: based on the amounts of SO_X, NH_3, HCl and NO_X emissions;
- aerosol formation potential (AFP) in [$tPM_{2.5}$-eq]: caused by PM, SO_X and NO_X emissions;
- cumulative energy demand (CED) in [MWh]: the total required by a process or product over the entire life-cycle;
- eutrophication potential (EP) in [tPO_4-eq]: resulting from NH_3 and NO_X emissions;
- net present value (NPV) in [€]: calculated with the standard method and a 10% discount rate.

The LCPA tool structure is displayed in Fig. 4 with the characterisation of all emissions and energy consumption in impact categories. The method makes an inventory of all materials flowing into the system, the energy flows and the emissions produced by the system.

The LCPA method includes the three phases of a product during its lifetime, namely: production, operation and end-of-life. It also includes the energy used and emissions produced during the material production and fuels production (well-to-tank energy and emissions). An estimation of the maintenance costs is also included in the calculation. Therefore, the LCPA can be used during the early stages of the design process to get a rough estimation of the vessel's performance during its entire life cycle.
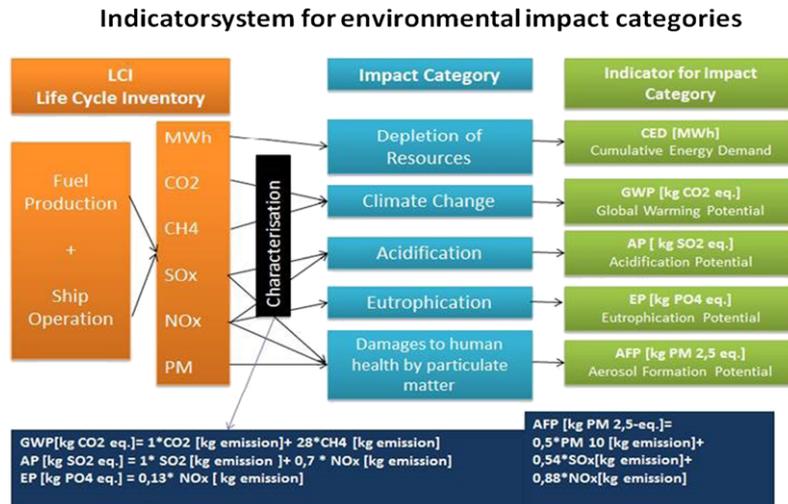

Fig. 4. LCPA tool schematic from input to KPI [51].

Table 4

MDO prices used for period 2025 to 2050 [51,57,58]

Date	Costs (USD/mt)		
	Low	Middle	High
1-1-2025	554.4	792.9	1465.2
1-1-2030	558.6	920.7	1678.5
1-1-2035	621.0	1061.1	1909.8
1-1-2040	659.7	1234.8	2185.2
1-1-2045	692.1	1375.2	2416.5
1-1-2050	724.5	1483.2	2647.8

Table 5

LNG prices used for period 2025 to 2050 [51,57,58]

Date	Costs (€/MWh)		
	Low	Middle	High
1-1-2025	29.4	51.0	62.9
1-1-2030	29.9	49.2	67.8
1-1-2035	30.0	51.8	69.2
1-1-2040	33.8	59.3	80.4
1-1-2045	37.7	66.9	91.7
1-1-2050	41.5	75.6	102.9

2.5. Scenarios, fuel costs & emission costs

The LCPA tool has the option to work with various scenarios related to fuel price and emission costs (also called external costs). These scenarios can be used to show the profitability of the design alternatives and the conditions required for a design to be economically viable. Two scenarios based on those of the International Energy Agency (IEA) [26] are used, where the most extreme conditions are described, namely:

- business as usual: fossil fuel is cheap, clean fuels expensive and absence of emission costs;
- sustainable development: higher fossil fuel costs and emission taxes resulting in better viability of clean fuels.

Tables 4, 5, 6, 7 & 8 show the fuel (MDO, LNG & LH_2) and emission costs (CO_2, SO_X, NO_X & PM) as used in the LCPA tool [4].

2.6. End-of-life

The end-of-life phase of the four concepts has been modelled as the scrapping and recovery of materials from the vessel. The costs of scrapping are estimated at a lump

Table 6

LH$_2$ prices for period 2025 to 2050 (produced from excess offshore wind energy) [51,57,58]

Date	Costs (€/kg)
1-1-2025	5.7
1-1-2030	5.2
1-1-2035	4.7
1-1-2040	4.2
1-1-2045	3.8
1-1-2050	3.3

Table 7

CO$_2$ price ranges for period 2025 to 2050 [51,57,58]

Date	CO$_2$-equivalent cost (€/mt)		
	Low	Middle	High
1-1-2020	50	105	160
1-1-2030	70	145	215
1-1-2040	95	190	290
1-1-2040	130	260	390

Table 8

SO$_X$, NO$_X$ and PM emission prices for period 2025 to 2050 [51,57,58]

Date	SO$_X$ (€/mt)	NO$_X$ (€/mt)	PM (€/mt)
1-1-2020	9,200	8,000	23,700
1-1-2030	9,200	8,000	23,700
1-1-2040	9,200	8,000	23,700
1-1-2040	9,200	8,000	23,700

sum of € 1,000,000.– for all design alternatives. It is assumed that 100% of the steel content and 60% of the copper content is recovered during scrapping. The remaining materials are disposed as waste.

3. Results

3.1. Business-as-usual scenario

The results of the LCPA assessment are presented for the business as usual case in Table 9. The business as usual scenario uses the low fuel costs as defined in Tables 4, 5, & 6 and assumes that there are no external costs (i.e. emission costs). Figures 5 to 10 show the major emissions relevant for the maritime sector for both the business as

Table 9
Impact category KPI results, relative to the baseline (business as usual scenario)

Property	Baseline DF	Hybrid DF	More engines	Hydrogen fuel cell
NPV	100	93.0	81.4	55.6
AFP	100	63.6	69.3	5.5
AP	100	59.7	65.0	7.4
GWP	100	95.9	103.5	16.9
CED	100	100.5	109.3	118.5
EP	100	68.5	74.5	2.2
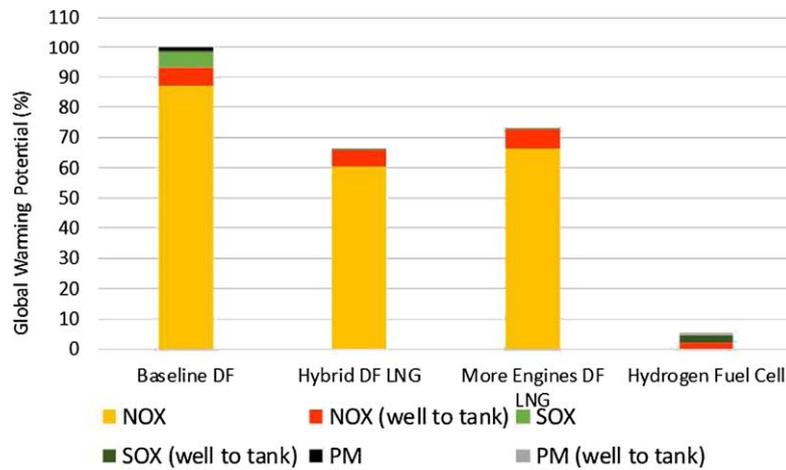
Fig. 5. Amounts of the harmful emissions NO_X, SO_X and PM during the lifecycle.

usual and the sustainable development scenario. The results show that all alternative designs score better than the baseline for most impact categories, except for the NPV value. The More engines alternative scores worse for the GWP due to additional fuel consumption at low engine load [42].

The following sections show the spider web diagram visualisation of the LCPAs KPIs and go into detail in the global warming potential and external costs aspects. These show that the hydrogen fuel cell design alternative scores much better than the other design alternatives on all environmental KPIs except for the cumulative energy demand KPI. It seems that a higher energy consumption compared to fossil fuels is the trade-off required for using clean renewable fuels.

Figure 5 shows the amount of harmful emissions produced from well-to-propeller (WTP) split between the WTT and the TTP emissions. The hydrogen design alternative has only limited emissions, which originate from the offshore wind infrastructure required to produce renewable hydrogen, but has no harmful emissions during operation.
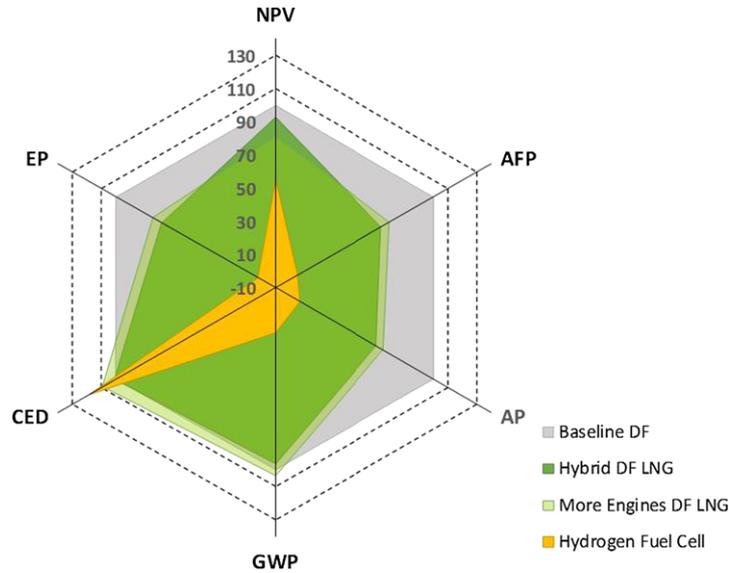
Fig. 6. Spider web diagram showing the KPIs performance, scenario business-as-usual.

3.2. *Spider web diagram visualisation*

The spider web diagram of the design alternatives is shown in Fig. 6. The baseline is in grey as backgrounds, and all KPIs are compared to the baseline, which is scaled to 100%. More than 100% is an improvement for the NPV and for the other KPIs less than 100% is an improvement. This figure shows that the "Hybrid DF" design has a slight advantage compared with the "More engines DF".

The best environmental performance is originated by the Hydrogen fuel cell, as it could be expected, as the hydrogen is produced from offshore wind, so the emissions over the lifecycle are very low. All alternatives score worse in the CED as they require more fuel in the case of the "Hybrid" and "More engines", and in the case of "Hydrogen Fuel Cell, the production of hydrogen from electrolysis requires a large amount of energy. The environmental performance of the Hybrid DF is expected to be better in reality, as the effect of engine load in the emissions is not captured with full detail in the LCPA tool.

All design alternatives score lower in the NPV (the economic indicator) than the Baseline DF, as the initial investment and higher fuel costs of hydrogen have a negative impact on the economic aspect. Hydrogen production from renewable sources requires more energy than fossil LNG production, what is also visible in the CED axis.

The cumulative costs over the lifecycle, shown in Fig. 7 are in this scenario 165% for the Fuel Cell Hydrogen vessel compared to the Baseline DF design, as the higher
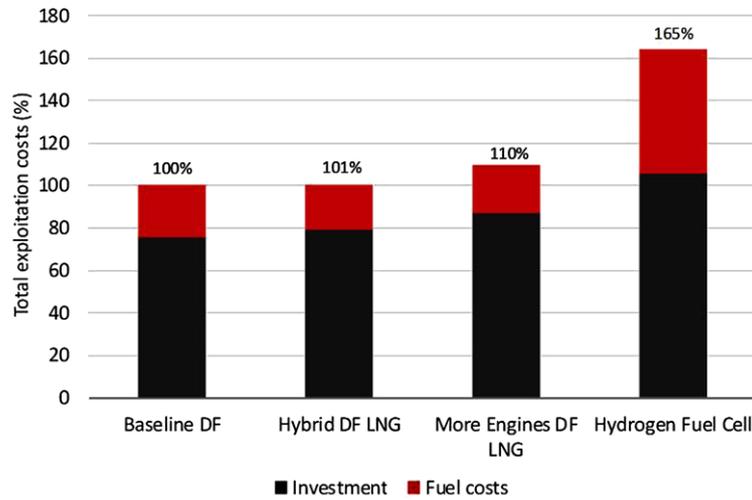
Fig. 7. Cumulative costs of investment and fuel, scenario business-as-usual.

investment costs add up to the higher fuel costs. The higher efficiency is not able to compensate sufficiently for the fuel cost

3.3. Global warming potential

The global warming potential is highlighted here in more detail, due to the recent policy developments on reduction of CO_2 emissions. Figure 8 shows that the Hybrid DF design has a slightly better performance in this KPI, even having a slightly higher fuel consumption, as it is known that LNG produces less CO_2 emissions per kWh than diesel. Even when accounting for some CH_4 emissions (methane slip), the result of eliminating the time that the engine changes to diesel mode results in a lower total GWP score [42]. The total GWP of the More Engines design is higher due to the lower engine efficiency at low load and the higher methane slip emissions as calculated in Mestemaker et al. (2019) [42]. The Hydrogen Fuel Cell design has some CO_2 and CH_4 emissions, which are originated by the upstream processes, the materials production and infrastructure of the offshore wind installation.

3.4. Sustainable development scenario

The sustainable development scenario is based on the scenario sketched by the IEA [26] in which fossil fuels and emissions are taxed. In addition, local governments may impose constraints on dredging in tenders to favour solutions with lower emissions and higher costs over those with higher emissions and lower costs by placing a value on the emissions emitted during the dredging works. This scenario uses
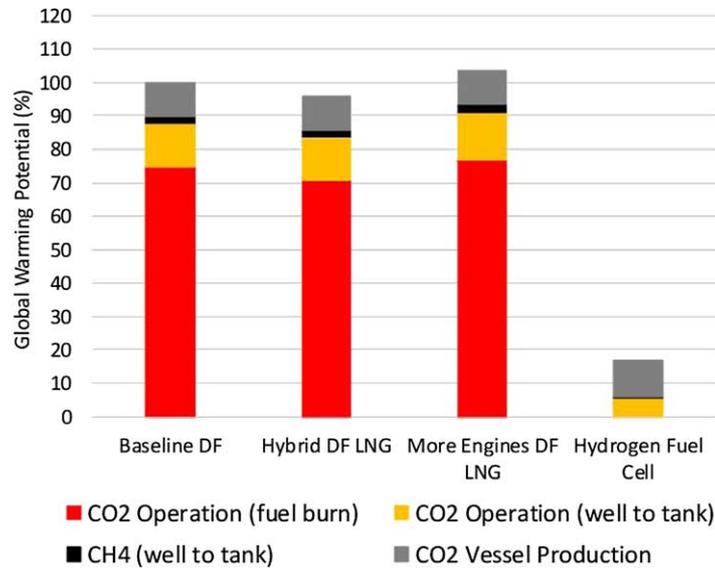
Fig. 8. Global warming potential over the lifecycle.

the high fossil fuel costs as defined in Tables 4 & 5, the middle fuel costs for hydrogen from Table 6 and assumes that there are external costs. These external costs consists of the high CO_2 price as defined in Table 7 and the SO_X, NO_X & PM costs as provided in Table 8.

The introduction of high fossil fuel costs and high emission costs result in a different score for the NPV, where the hydrogen fuel cell vessel scores the best as shown in Fig. 9. The other scores remain unchanged, as only the costs change. In this situation, the hydrogen fuel cell vessel has an NPV of 108%, compared to the baseline DF design. This is the cumulative effect of the fuel savings due to the high efficiency of the fuel cell system and the savings on the emission costs of CO_2 and the harmful emissions: NO_X, SO_X & PM. The effect of the fuel and emissions costs in this scenario is show in Fig. 10. This figure illustrates the important impact of the economic-environmental policies of attributing costs to emissions on the economic viability of cleaner vessels. Figures 7 and 10 do not include the revenues, as the assumption in the LCPA model is that these are the same for all vessel design alternatives.

In Fig. 7, the best choice in economic terms is the baseline design, closely followed by the hybrid DF. The hydrogen fuel cell design is the least attractive due to high technology costs and high fuel costs compared to LNG. For the sustainable development scenario, Fig. 10, the result is opposite and the hydrogen fuel cell and the hybrid DF LNG designs are the most economically viable as these have lower emission costs. Therefore, in a future scenario where fossil fuels are costly and emissions are taxed, the cleanest technology also becomes the most economic viable. When comparing both figures, it seems that in an uncertain future, choosing a clean fossil
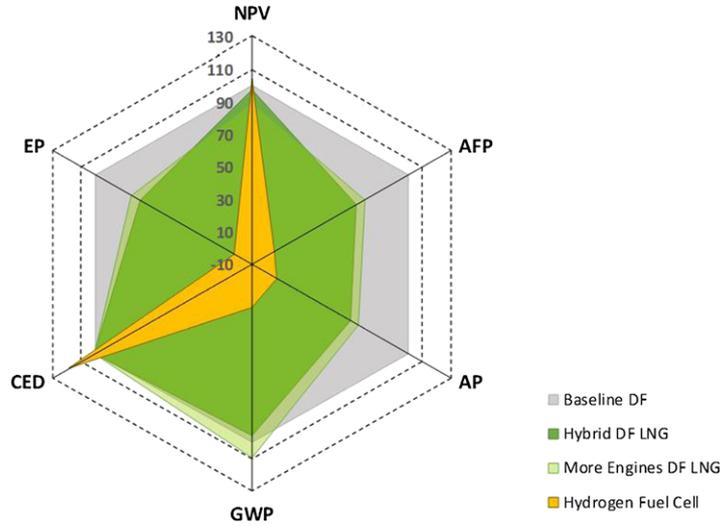
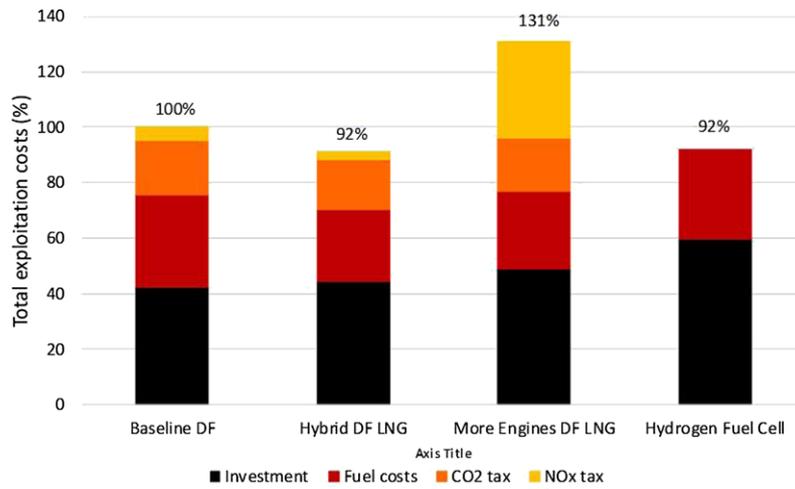Fig. 9. Spider web diagram showing the KPIs performance, sustainable development scenario.

Fig. 10. Cumulative costs of investment, fuel and emissions, sustainable development scenario.

fuel with high efficiency drive system (i.e. the hybrid DF concept) might strike a good compromise.

The implementation of emission taxes alone may not be enough to provide cleaner concepts with a financial advantage over more polluting drive system designs. Figure 10 shows that the LNG fuelled hybrid concept has the same cumulative costs as the renewable hydrogen fuel cell design in the sustainable development scenario de-

spite the higher emissions of the hybrid system design (Fig. 5). If policy makers want to stimulate a change to a zero emission maritime sector, new policy is required consisting of subsidies and/or more strict legislation. New legislation may not be limited to new-built vessels, but could include the existing fleet as vessels generally have a lifetime of 25–30 years [12]. This legislation may limit both GHG emissions (CO_2 & CH_4) and harmfull emissions (SO_X, NO_X & PM). Additionally, policy makers may include specific demands in tender processes as well as prohibit vessels from operating in certain areas.

These results should not be taken as a conclusion as they are obtained with simplifications and a prognoses of price and tax developments. But, it is demonstrated that the LCPA tool can be used at an early design stage to make a first assessment of design alternatives. The design parameters need to be carefully analysed in each case in order to reach a robust conclusion. A more detailed modelling of the drive system is required to compare the harmful emissions, this requires the inclusion of the dynamic aspects of the driveline behaviour such as studied by Mestemaker et al. (2020) [40].

4. Conclusions

The energy transition poses complex vessel design problems with multiple factors, but this is not only a challenge in the sense of technology and design. In order to achieve zero emissions with economic viability, wide cooperation and effective legislation are needed for the maritime sector. The results presented in this article illustrate that design alternatives can be modelled at an early stage and evaluated using the life cycle performance assessment methodology. This approach is able to translate the effects of design choices and provides a first indication of the environmental and economic performance of the vessel over the entire lifetime, and thereby assists designers and ship operators to choose fuels and driveline designs at an early design stage.

The operational phase is the most important in the environmental performance of work vessels, and all vessel types and accounts for more than 90% of the total environmental impact of the whole life cycle of the vessel. The design of efficient vessels has a positive effect on the environmental performance, especially when considering greenhouse gas emissions. The combination of efficient designs and clean fuels has a tremendous potential for future vessels aiming to achieve zero emission as is shown in this article.

At an early stage, some details seem to be very important, while others are less important. The vessel weight and materials composition do not require detailed modelling for a self-propelled cutter suction dredger. However the costs, the fuel consumption and emissions do require detailed modelling. This is required in order to capture the economic and environmental performance accurately and to be able to compare the design alternatives on a sound basis.

The possibility of using scenarios with variations in fuel prices and emission costs is very valuable as well. In this article, the large effect of scenario variables is illustrated, resulting in the economic viability of either a fossil-fuel-based technology or a zero-emission-based technology. Next to the technological developments, policies are required in order to stimulate the (maritime) energy transition and create a level playing field for the maritime industry. Ship owners striving for clean innovations should be rewarded and the economic viability of the sector should be safeguarded on the long term.

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Abbreviations

AFP	aerosol formation potential
AP	acidification potential
CED	cumulative energy demand
CGH_2	compressed gaseous hydrogen
CH_4	methane
CI	compression ignition
CN	Cetane number
CNG	compressed natural gas
CO_2	carbon dioxide
CO	carbon monoxide
CSD	cutter suction dredgers
DAC	direct air capture
DF	dual fuel
DME	dimethyl ether
EEDI	Energy Efficiency Design Index
EP	eutrophication potential (EP)
ESS	energy storage systems
EtOH	ethanol
FAME	fatty acid methyl esters
FC	fuel cell
Fe	iron (powder)
Fe_2O_3	haematite
GD	gas-diesel
GHG	greenhouse gas
GTL	gas-to-liquid
GWP	global warming potential
H_2	hydrogen
HCl	hydrogen cloride
HFO	heavy fuel oil

HT-PEMFC	high temperature proton exchange membrane fuel cell
HVO	hydrotreated vegetable oil
ICE	internal combustion engine
IEA	International Energy Agency
IMO	International Maritime Organisation
KPI	key performance indicator
LCA	life cycle assessment
LCPA	Life Cycle Performance Assessment
LH_2	liquefied hydrogen
LHV	lower heating value
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LT-PEMFC	low temperature proton exchange membrane fuel cell
MDO	marine diesel oil
MeOH	methanol
MEPC	Marine Environment Protection Committee
MH_2	(reversible) metal hydrides
MGO	marine gasoil
$NaBH_4$	sodium borohydride
$NaBO_2$	sodium metaborate
NH_3	ammonia
NO_X	nitrogen oxides
NPV	net present value
ORC	Organic Rankine cycle
PM	particulate matter
PO_4	phosphate
SEEMP	Ship Energy Efficiency Management Plan
SI	spark ignited
SOFC	solid oxide fuel cell
SO_X	sulphur oxides
TCO	total cost of ownership
TRL	technology readiness level
TSHD	trailing suction hopper dredger
TTP	tank-to-propeller
WHR	waste heat recovery
WTP	well-to-propeller
WTT	well-to-tank