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TNO report

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Validation scheme for the Green Deal for Shipping, Inland Shipping and Ports (C-230) - Validation of alternative fuels, hydrogen in a combustion engine

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Samenvatting

Met de op 19 juli 2019 gepubliceerde Green Deal Zeevaart, Binnenvaart en Havens (C-230) is invulling gegeven aan de belofte in het Regeerakkoord van het Kabinet Rutte III om de verduurzaming van de zeevaart en de binnenvaart een impuls te geven. Als onderdeel binnen deze Green Deal is er vanuit de Rijksoverheid financiering beschikbaar gesteld (2020-2024, max 1M€ per jaar) waarmee de maritieme sector kan werken aan validatie van duurzame maritieme oplossingen.

Met valideren wordt bedoeld: Een onafhankelijke toetsing van de prestatieclaim (% emissiereductie) van de ontwikkelaar, gegeven de toepassing op een schip in bepaalde operationele condities. Op basis hiervan kan worden vastgesteld of een toepassing van deze oplossingen effectief is voor bepaalde scheepstypen onder bepaalde operationele condities. Dit is van belang voor de (MKB) ontwikkelaars die in deze scheepstechnieken investeren, maar ook voor de werven die daarmee beter kunnen onderbouwen hoeveel duurzamer het geïntegreerde scheepsontwerp zal zijn. Ook helpt het reders/scheepseigenaren te kiezen voor de best passende (retrofit) oplossing voor hun vloot.

Als voorbereiding op de validatie is een aantal stappen uitgevoerd. In een eerste fase is door TNO en MARIN een vooronderzoek gedaan naar de reikwijdte van de validatieregeling alsmede is een overzicht van validatietechnieken gemaakt. In een vervolg hierop is een overzicht gemaakt van relevante referentieschepen en is een eerste verkenning gemaakt van de marktrijpheid en verwachte reductiepotentie van verschillende referentietechnieken. Daarnaast is door NMT input verzameld bij nautische stakeholders over hun verwachtingen rondom de impact en haalbaarheid van verschillende emissiereductietechnieken. Op basis van deze input is als eerste techniek voor de validatieregeling het gebruik van alternatieve brandstoffen in een verbrandingsmotor gekozen.

Dit rapport beschrijft een eerste gedeeltelijke validatie casestudie voor H2 ICE (Internal Combustion Engine). Om dit in context te kunnen zien, werd ook een exploratief onderzoek naar verbrandingsmotoroplossingen op basis van andere alternatieve brandstoffen uitgevoerd en beschreven.

Het onderzoek werd uitgevoerd in drie fases die ook terug te vinden zijn in de verschillende hoofdstukken:

- Hoofdstuk 2 beschrijft de exploratieve studie;
- Hoofdstuk 3 inventariseert en onderzoekt de haalbaarheid van H2-ICE in maritieme applicaties;
- Hoofdstuk 4 beschrijft de eerste testresultaten met een H2-ICE set-up.

Tenslotte worden de verschillende resultaten en conclusies gecombineerd in hoofdstuk 5.

De volgende conclusies vatten de bevindingen van het huidige project samen:

Verkenningsstudie voor vermogens-, voortstuwings- en energie- (VVE-) systemen op basis van alternatieve brandstof met verbrandingsmotor

- De resultaten in dit deel van de studie zijn gebaseerd op de momenteel vastgestelde operationele referentieprofielen; andere operationele profielen leiden tot andere conclusies.
- De grootte en het gewicht van de VVE-componenten, de kosten en de emissies zijn gebaseerd op de huidige kennis van de sector. Gedetailleerde onderzoeken waarin bijv. OEM's worden geraadpleegd om ontwerpen en informatie voor specifieke VVE-systeemcomponenten te verstrekken, kan tot verschillende resultaten leiden.
- Het monteren van op alternatieve brandstoffen (lagere energiedichtheid) gebaseerde VVE-systemen in kleine schepen met een relatief groot VVE-systeem in vergelijking met de scheepsgrootte, resulteert in aanzienlijk grotere schepen (tot twee keer zo groot in het geval van waterstof) om het nieuwe VVE-systeem te integreren of in een aanzienlijke vermindering van de autonomie van het schip. Voor de grotere schepen, zoals ‘general cargo’, is de consequentie van een op alternatieve brandstof gebaseerde VVE-systeem beperkt tot ongeveer 15% van de scheepsgrootte als de autonomie ongewijzigd blijft.
- De kosten van deze nieuwe systemen zijn afhankelijk van de CapEx en OpEx balans. Het rapport geeft richtlijnen over prijsniveaus, maar let ervoor op dat deze niveaus sterk afhangen van de ‘feedstock’ in het geval van brandstoffen (OpEx), van de ontwikkeling van de verbrandingsmotortechnieken en de van noodzaak van o.a. nabehandeling om TIER III te bereiken. Daarom moeten deze prijsniveaus met zorg overwogen worden. Bovendien houdt deze analyse geen rekening met wat het toegevoegde effect is van de kosten van de scheepsromp en uitrusting wanneer het schip moet worden vergroot zodat de energie- en vermogenssystemen passen.
- Het potentieel voor broeikasgasemissiereductie is het laagst voor de LG-oplossingen, voornamelijk vanwege de methaanslipbijdrage. Met HVO zou een reductie van ongeveer 60% kunnen worden bereikt. Met de andere brandstoffen (bio en synthetisch) zouden in theorie reducties van ongeveer 90-95% kunnen worden bereikt, maar het TRL niveau is afhankelijk van het systeem. Zoals ook blijkt uit de inventarisatie en haalbaarheid voor H2 ICE in maritieme applicaties moeten de technologieën met hoge emissiereductieniveaus nog enige ontwikkeling ondergaan (althans in het geval van waterstof). Biomethanol die tertiaire afvalstromen gebruikt, vertoont een lagere emissie dan e-methanol, omdat gebruik wordt gemaakt van optimale afvalstromen.

Inventarisatie en haalbaarheid voor H2 ICE in maritieme applicaties

- De H2-ICE-ontwikkelingen gaan snel met de belangrijkste onderzoeks- en ontwikkelingsactiviteiten voor maritieme toepassingen in Europa en in mindere mate in Japan. Veel van de erkende fabrikanten van maritieme motoren zijn actief in H2-ICE ontwikkeling met zowel dual fuel H2-ICE concepten als mono fuel concepten.
- De gepresenteerde H2-ICE-concepten zijn allemaal haalbaar voor toepassing in maritieme toepassingen, maar niet alle concepten kunnen momenteel worden toegepast over het volledige motorbedrijfsbereik.

- Momenteel heeft het conventionele dual fuel-verbrandingsconcept het hoogste TRL niveau voor maritieme toepassingen. Gemiddelde CO_2-reducties in de grootteorde van 40-60% zijn haalbaar zonder de uitstoot van vervuilende stoffen te compromitteren. Standaard diesel nabehandeling is van toepassing. De mogelijkheid om terug te vallen op conventionele dieselverbranding wordt beschouwd als een belangrijk voordeel van dit concept voor maritieme toepassingen. Ontwikkeling van andere verbrandingsconcepten kan verdere CO_2-reducties tot meer dan 90% mogelijk maken
- Monofuel H2-ICE-concepten zijn technisch haalbaar met het potentieel om een klimaatneutrale oplossing te realiseren. Het potentieel om dure nabehandelingssystemen te elimineren is het grootst voor deze concepten.
- De toepassing van waterstoftechnologie met directe injectie is geïdentificeerd als een belangrijke factor voor het vergroten van het belastingsbereik van de motor en het elimineren van het terugslagrisico (backfiring). Momenteel is deze technologie nog niet marktrijp en verdere technologische ontwikkeling is gewenst.
- Het gebruik van waterstof als brandstof voor verbrandingsmotoren leidt niet noodzakelijkerwijs tot een verlies van ‘transient respons’ ten opzichte van de basis dieselmotor. Voor een vergelijkbare ‘transient respons’ moet mogelijk het ‘charging system’ van de motor worden aangepast. Om de haalbaarheid te onderzoeken van een verbrandingsconcept voor een specifieke toepassing met betrekking tot ‘transient respons’, moeten exacte gegevens over de beoogde motordynamiek beschikbaar gemaakt worden.
- Op motorniveau heeft het geselecteerde motorconcept voornamelijk invloed op de CapEx door de noodzaak van nabehandelingstechnologie. Overige componentkosten worden als marginaal beschouwd ten opzichte van basismotorkosten en verschillen niet veel tussen de verschillende motorconcepten. Voor de implementatie van de waterstofverbrandingsmotor wordt verwacht dat de kosten voor waterstofopslag dominant zullen zijn, vergelijkbaar met de toepassing van waterstofbrandstofceltechnologie. Resultaten uit de verkenningsstudie (hoofdstuk 2) laten zien dat de motor CapEx varieert tussen 10 en 50% van de totale kosten van motoren en opslag, afhankelijk van het type schip en het missieprofiel.
- Een betrouwbare en veilige werking van de H2 verbrandingsmotor moet in de ontwerpfase van de motor worden aangepakt. De interactie van waterstof met metalen vereist een doordachte materiaalkeuze. Bovendien heeft waterstof slechte smerende eigenschappen waarmee rekening moet worden gehouden bij het ontwerpen of selecteren van motorcomponenten zoals kleppen, klepdichtingen en componenten van het brandstofinjectiesysteem.
- Veiligheidsvoorschriften specifiek voor H2-ICE zijn in ontwikkeling. Momenteel moet rekening worden gehouden met de vereisten die zijn vermeld in de IMO IGF-code voor gasmotoren (CNG / LNG) en brandstoffen met een laag vlampunt. De gevolgen van het scheepsontwerp volgens deze voorschriften zijn daarmee gelijkaardig aan die voor CNG/LNG schepen met betrekking tot waterstofopslag, ventilatiesystemen, gasdetectie en gebieden gemarkeerd als ATEX-zones.

Specifieke voorschriften op motorniveau zijn voornamelijk gericht op het voorkomen van ophoping van waterstof in het uitlaatsysteem, de vloeistoffen in het hulpsysteem (olie, koelwater) of het motorcarter dat kan resulteren in een brandbaar / explosief waterstof / luchtmengsel. Hiermee kan tijdens het ontwerpen van de motor rekening worden gehouden door gebruik te maken van speciale hardware zoals bijv. positieve carter ventilatie. Tijdens het draaien van de motor moet er monitoring aanwezig zijn om slechte verbranding of ontstekingsfouten te detecteren.

- Waterstof kan worden geproduceerd uit verschillende grondstofroutes. De waterstofverbrandingsmotor vertoont een relatief hoge tolerantie voor de gebruikte waterstofkwaliteit. Waterstof met zuiverheid 3.0 (zuiverheid 99,9%) kan veilig worden gebruikt. Als zodanig is de waterstof ICE niet erg selectief met betrekking tot de bron van waterstof.

<u>Testresultaten van een dual fuel H2 ICE set-up</u>

- Het retrofitten van dieselmotoren om te werken op een dual fuel waterstofmengsel leidt tot een aanzienlijke vermindering van de TTW-CO_2-uitstoot.
- Speciale aandacht moet worden besteed om te voorkomen dat de NO_x-emissies stijgen tot onaanvaardbare limieten. Aangetoond werd dat de NO_x-uitstoot op een niveau kan worden gehouden dat vergelijkbaar is met de originele dieselmotor door de timing van de dieselinjectie te vertragen. De vertraging van de timing van de dieselinjectie leidt niet tot een significante daling van de motorprestaties of efficiëntie.
- Een tweede manier om de NO_x-uitstoot in de motor te verminderen, is het gebruik van uitlaatgasrecirculatie (EGR). De eerste tests met een EGR-systeem lieten een afname van de NO_x-uitstoot zien tot de dieselreferentiewaarden voor mengverhoudingen tot 50% H2.
- NO_x-emissiegrenswaarden moeten worden gerespecteerd om te voldoen aan de huidige en toekomstige regelgeving. Verdere motoraanpassingen zoals EGR of aanpassing aan nabehandelingssystemen zoals SCR (Selective Catalytic Reduction) zijn dus een noodzakelijk onderdeel van de implementatie.

Tenslotte worden nog een aantal aanbevelingen gemaakt voor mogelijke vervolgstappen of uit te werken onderzoeksvragen.

Bovenstaande conclusies en aanbevelingen vervangen de uitspraken in het rapport en in de tabellen en figuren met resultaten niet.

Contents

1 Introduction

On the 19th of July 2019 the Green Deal was published by the Dutch government. Green Deal is part of the Dutch government's initiatives that aim to realise the Paris agreements' goal of limiting global warming to at least two degrees Celsius. The Green Deal initiative's purpose is to speed up the process of making both inland and maritime shipping more sustainable by funding research.
This research aims to validate the effectiveness and feasibility of possible solutions that spurt the maritime sector's sustainability, with reduction of CO_2-emissions being the main pillar.

TNO and MARIN are investigating possible solutions for CO_2-reduction and ways to validate them. The H2 ICE (Internal Combustion Engine) is one of these solutions and will be further discussed in this report. To provide a context to the H2-ICE solution the study includes an explorative study into ICE solutions using a wider variety of alternative fuels.

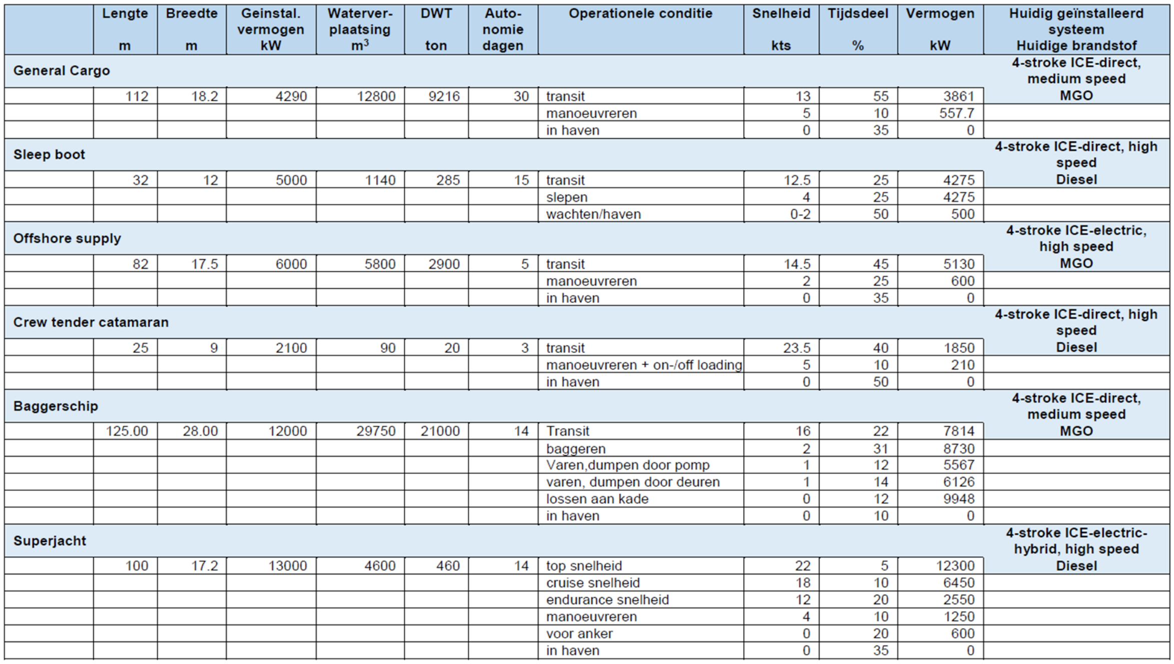
The research consisted of three work packages. WP1 (chapter 2) focusses on the explorative study on ICE alternative fuel solutions. WP2.1 (chapter 3) investigates the feasibility for a H2-ICE setup. WP2.2 (chapter 4) provides the first test results with a H2-ICE setup, In chapter 5 the results of the work packages are combined and conclusions and recommendations are presented.

2 Exploration of energy and power system solutions using internal combustion engines as prime mover

2.1 Introduction

In this section of the report, an explorative study on possible ICE-based ship Power, Propulsion & Energy (PPE)[1] systems is presented for six reference vessels in the GD-Validation, being a general cargo vessel, a tug boat, an offshore supply vessel, a crew tender catamaran, a dredger and a yacht (see Table 1). These vessels are representative for vessels of Dutch Fleet Owners or that are regarded as important market segments for the Dutch maritime industry. More on the details (size, operational profile, ..) can be found in Report 32360-2-SHIPS as published end of 2020 [15].

Table 1: Reference vessels and their mission profile, copy table 2-5 from Report 32360-2-SHIPS.



	Lengte m	Breedte m	Geinstal. vermogen kW	Waterver-plaatsing m^3	DWT ton	Auto-nomie dagen	Operationele conditie	Snelheid kts	Tijdsdeel %	Vermogen kW	Huidig geïnstalleerd systeem Huidige brandstof
General Cargo											**4-stroke ICE-direct, medium speed MGO**
	112	18.2	4290	12800	9216	30	transit	13	55	3861	
							manoeuvreren	5	10	557.7	
							in haven	0	35	0	
Sleep boot											**4-stroke ICE-direct, high speed Diesel**
	32	12	5000	1140	285	15	transit	12.5	25	4275	
							slepen	4	25	4275	
							wachten/haven	0-2	50	500	
Offshore supply											**4-stroke ICE-electric, high speed MGO**
	82	17.5	6000	5800	2900	5	transit	14.5	45	5130	
							manoeuvreren	2	25	600	
							in haven	0	35	0	
Crew tender catamaran											**4-stroke ICE-direct, high speed Diesel**
	25	9	2100	90	20	3	transit	23.5	40	1850	
							manoeuvreren + on-/off loading	5	10	210	
							in haven	0	50	0	
Baggerschip											**4-stroke ICE-direct, medium speed MGO**
	125.00	28.00	12000	29750	21000	14	Transit	16	22	7814	
							baggeren	2	31	8730	
							Varen,dumpen door pomp	1	12	5567	
							varen, dumpen door deuren	1	14	6126	
							lossen aan kade	0	12	9948	
							in haven	0	10	0	
Superjacht											**4-stroke ICE-electric-hybrid, high speed Diesel**
	100	17.2	13000	4600	460	14	top snelheid	22	5	12300	
							cruise snelheid	18	10	6450	
							endurance snelheid	12	20	2550	
							manoeuvreren	4	10	1250	
							voor anker	0	20	600	
							in haven	0	35	0	

Based on the results of the previous study, the following energy carriers are taken into account in this exploration:

- Diesel(E590)/MGO (as per reference ship),
- Methanol,
- Hydrogen (gaseous, stored at 700 bar)[2],
- Ammonia, and
- Liquified gas.

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[1] Note, the ship PPE system is in some parts of the sector called “power train” or, more general, “engine room (arrangement)”.

[2] It has to be noted that 700 bar pressurized hydrogen storage is currently not applied in the maritime industry, most applications to date are (still) around 350 bar, leading to a lower energy density.

All solutions use 5% diesel/MGO as pilot fuel. Note, in case bio- or e-diesel is used the resulting emissions could be lower. As will become clear in section 3, operating at high percentages of hydrogen is hard to reach at this moment. The percentage of pilot fuel that can be reached depends on the main fuel used, the technical readiness of the ICE combustion-technology and dynamic loading of the system.

To provide insight in the possible emission reduction and costs aspects multiple production routes and feedstocks are analysed:

- Fossil based,
- Biological (or recycling of municipal waste), and
- e-fuels (synthetic).

The values used in this report represent a range for each energy carrier. Appendix A provides the specification of the fuels used in this study. The appendix refers to data on https://sustainablepower.application.marin.nl/ for which input from several sources is used to fill the database. For sake of simplicity and uniformity only the link to this site is mentioned in the References of this report. Note, the values are subject to change over time due to changing techniques and economic circumstances. At this moment for the energy carrier costs (OpEx) a range is accounted for in the analysis. For e.g. CapEx this could also be done, but proper data is not abundantly available.

This results in the following energy carriers:

Fossil fuels	**Biological fuels**	**E-fuels**
Diesel (E590)/MGO	HVO	E-Diesel
Methanol	Bio-Methanol	E-Methanol
Hydrogen	-	Hydrogen
Ammonia	-	E-Ammonia
LNG	Bio-LNG	E-LNG

When considering ship and mission profile the PPE solutions in section 2 are studied with respect to:

- **System and weight volume** in relation to the ship's displacement and volume of the hull (incl. freeboard);
- **CapEx** of the system (engine costs and energy carrier storage costst) and **OpEx** of the energy carrier, maintenance of systems is not considered mainly because good data is scarce to be able to make a fair comparison;
- **CapEx and OpEx** for a period of 20 years. This is not the complete Total Costs of Ownership (TCO), because some costs are not accounted for. Still, this gives a good first indication.
- **GHG Emission** from **Well to Wake** reduction potential. Hazardous emissions are set at Tier III;

All results are made relative to a diesel solution for the specific ship type. That diesel reference matches the required autonomy of the operational profile and therefore the resulting bunker volume might be smaller than the bunker in the existing ships. In other words: the existing ships might be able to sail multiple missions on one diesel bunker volume. However, for comparison reasons we reduce the bunker volume of the reference to exactly match the mission autonomy.

The new PPE solutions can be constructed based on three strategies:

1. Define the PPE system keeping the ship and operation as is. This means internal space for e.g. cargo or auxiliary equipment will reduce due to lower energy density of alternative fuels.
2. Define the PPE system keeping ship internal space and operation as is. This means the ship will grow in size.
3. Define the PPE system keeping ship internal space and ship as is. This means the ships' autonomy will reduce.

Those three options are referred to as 'no design, 'free design' and fixed design', respectively. The results will be discussed in the following sub sections.

2.2 Methodology and considerations

2.2.1 Systematic approach

In order to prevent that energy carriers are compared in a similar way, a systematic approach is required. This means that all systems are compared with identical system boundaries. Each energy carrier needs its own systems to deliver power and among carriers these systems differ significantly. Basically, the system boundary is the ship power, propulsion and energy system. Each system needs to deliver a certain amount of power to the propeller and to the auxiliary consumers. These lie just outside the system boundary. The system boundary is visualised in Figure 1. The arrows in this figure represent the ingoing (energy carrier) and outgoing (thrust, ships services, emission) entities. All the boxes within the boundary need to be defined for each carrier: energy storage information (how is the carrier stored on-board), pre-treatment and distribution (what must happen with the stored energy carrier before the engine can use it), energy conversion (the engine required to convert energy to power), after-treatment (what exhaust gas systems are needed to comply with regulations), and power distribution and drives (what systems are needed in order to deliver the power to the propeller and auxiliary services).

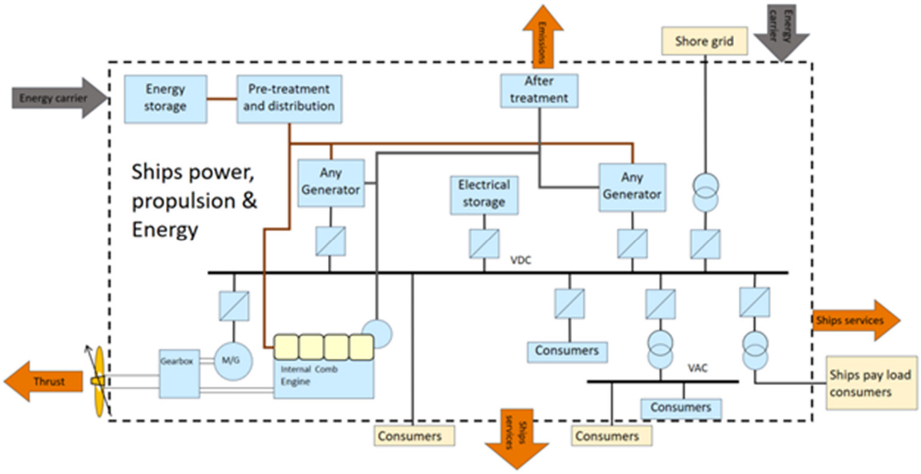

Figure 1: Generic system boundary.

Table 2 gives an overview of the power systems considered here and the subsystems which they consist of.

The subsystems are partly dictated by the physical properties, but distinct choices are made as well. The table is a simplification of an actual system, as more systems are required in order to deliver power. However, the focus is set to those systems which have a significant impact on volume, weight, capital investment or efficiency. These properties are specified in Appendix A.

2.2.2 *Energy storage*

Ammonia and methane (natural gas) are typically stored in a liquid form to increase their contained energy density. Hydrogen may also be stored in liquid form for optimal energy density, but it was chosen to consider (gaseous) compressed storage at 700 bar. The motivation for this is the TRL, for gaseous storage a higher TRL is attained. And the focus of this project is on relatively high-TRL systems.

2.2.3 *Pre-treatment and distribution*

Pre-treatment and distribution systems are separately installed systems required to prepare the energy carrier for application in the energy conversion system (the engine). Liquefied fuels (LNG, Ammonia) will be evaporated in order to return them in a gaseous state, and highly compressed fuels need to be expanded to a pressure suitable for transportation within the ship (H_2). Pressurizing diesel fuel prior to injection is not considered a pre-treatment system as this is performed by the engine block (and thus part of the engine system).

2.2.4 *Energy conversion*

For diesel fuelled ships a distinction is made between hi-speed engines and medium-speed engines as per Table 1.

All alternative energy carriers are combusted in a dual fuel medium-speed combustion engine. The combustion engine was set as a strict boundary of this study (because they are further developed than fuel cells and opens up possibilities for refit). The dual fuel option was chosen because it allows compressed ignited engines to be used which are currently the most widespread. This will also allow the subject ship to fall back on diesel fuel when alternatives are unavailable.
For ammonia it is also the only feasible combustion method. Lastly, the available data for engines running on alternative fuel in a dual-fuel mode is currently constrained to medium-speed engines, therefore all alternatives use medium-speed engines in this study. For LNG fuels, a spark ignited dual-fuel engine is used, which can run both in compressed ignited and in spark ignited (otto cycle). This is the most commonly applied 4-stroke medium speed engine. For methanol and hydrogen, the DF-otto cycle may also be of interest. However, this has been left out of scope for this chapter as the study is simplified to one engine technology per energy carrier. The motivation here is that the current demonstrators with methanol and hydrogen are running in a compressed ignited cycle. Chapter 3 will explain the various engine cycles in more detail.

2.2.5 *Exhaust after treatment*

Here the requirement is set to the IMO Tier III emission level. All systems must comply with this, and therefore require after-treatment systems to reduce NO_x levels. Dual fuel LNG engines that can run in a spark ignited cycle do not require after-treatment [**19**]. Methanol and hydrogen might also avoid SCR after treatment, but to date this is not known as their NO_x emission are thus far higher than Tier III levels (in dual-fuel setup).

WP2 will elaborate on this further for the case of hydrogen. For ammonia SCR will be required [**17**].

2.2.6 *Power distribution and drives*

All power systems feature ICE-direct propulsion, meaning direct mechanical transmission of power from engine to propellor shaft. Some specific ships under consideration will typically not feature ICE direct propulsion, however, for simplification and comparison purposes this has been kept the same amongst the fleet at this moment. Because all engines will have diesel pilot fuel, ICE-direct is expected to be feasible, also in transient conditions. Auxiliaries are assumed to be powered via a PTO on the main engine.

Table 2: Adopted PPE system configuration per energy carrier.

Power systems	**Energy storage**	**Pre-treatment and distribution**	**Energy conversion**	**Exhaust after-treatment**	**Power distribution and drives**
Diesel (E590) / e-Diesel / Bio-diesel	Liquid, ambient temperature	None	Hi-speed / medium speed CI engine[3]	SCR system and soot filter	ICE-direct
Methanol	Liquid, ambient temperature	None	Dual-fuel medium-speed CI engine	SCR system	ICE-direct
LNG / e-LG / LBG	Liquid, stored in highly insulated tank at -162°C	Evaporation	Dual-fuel medium-speed SI-engine	None	ICE-direct
Ammonia	Liquid, stored at -35°C	Evaporation	Dual-fuel medium-speed CI engine	SCR system	ICE-direct
Hydrogen	Gaseous, compressed to 700 bar	Expansion	Dual-fuel medium-speed CI engine	SCR system	ICE-direct

2.2.7 *PPE system metrics*

Table 3 gives a summary of the metrics of the ship’s power propulsion and energy system. For complete insight into how these metrics have been derived please refer to Appendix A. The metrics are based on the current state of the techniques. Note, the power density in this context refers to more than the engine; it also takes into account subsystems. It is more common to us l (or kg) per kW and not the other way around (kW per l or kW per kg), because subsystems now can have to density 0 instead of infinity.

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[3] Application of hi-speed or medium-speed depends on ship type: Megayacht, Crew Tender Catamaran, Tug are considered to have hi-speed engines, whereas the General Cargo, Offshore Supply and Dredger are considered to have medium-speed engines. This only differs for diesel as for the alternative systems only data on medium-speed engines was available.

Table 3: Summary of PPE system metrics.

	Contained Energy density		Power density		Energy CapEx	Power CapEx	Chain efficiency
	MJ/l	MJ/kg	l/kW	kg/kW	€/kWh	€/kW	%
Diesel hi-speed	34.0	30.1	19.8	5.9	0.6	799	37%
MGO med-speed	33.2	29.6	25.0	9.5	0.6	886	43%
Methanol	14.6	15.3	31.0	16.1	0.9	998	48%
LNG	13.6	30.4	19.9	8.2	2	650	47%
Ammonia	10.4	12.6	32.0	17.4	1.1	1198	48%
Hydrogen	3.3	7.1	31.0	16.5	9.4	1098	47%

Clearly the large challenge is visible in energy and power density and CapEx when going to fuels other than diesel. However, the chain efficiency increases substantial. The contained energy density shows LNG is close to diesel in gravimetric density. Volumetric however, LNG is much less compact. Typically methanol has half the density of diesel, ammonia slight less then methanol and hydrogen is factors lower than diesel. This ranking will also become visible when evaluating the different ships and their PPE solutions, especially for cases where the energy carrier amount is leading. In that case also LNG solutions might be more expensive than ammonia solutions due to the large CapEx on energy storage. In power density the differences compared to diesel are much smaller. Here ammonia is slightly heavier and larger compared to hydrogen, because of the pre- and after treatment systems. The CapEx for the LNG PPE system is relatively low because those engines are becoming more mainstream and expensive after treatment is not needed. For the long term, it is expected that prices for the PPE solutions for ammonia, hydrogen and methanol will also decrease over time.

Table 4: Energy carrier OpEx. Range indicated: low, middle, high for the year 2030.

€/GJ	Fossil			Biofuel/carbon recycled			E-fuel		
	Low	Middle	High	Low	Middle	High	Low	Middle	High
EN590 / HVO / e-Diesel	9	12	19	14	23	35	28	30	62
LNG / LBG / e-LG	8	9	11	12	15	35	28	31	59
Methanol	14	16	18	16	23	32	28	31	66
H2	21	25	30	-	-	-	27	31	51
Ammonia	14	25	30	-	-	-	28	30	56

For the OPEX a large bandwidth is used, identifying the uncertainties in future development of the prices. The expected 2030 price level is taken in the analysis to account for future price changes.

The price development for the long term for fossil feedstocks will depend on several factors like economic growth (especially in upcoming Asian economies), the oil and gas supply as well as environmental policy measures such as CO_2 allowance fees.

A scenario analysis by EIA [**1**] found that different developments of supply and policy measures such as introduction of carbon taxes have most impact on price development.

The production costs of several kinds of biofuels depend, among others, on the feedstock prices, and the capital expenditures. Currently, prices are considerably higher than that fossil fuels. There is however downward potential in price development. IEA Bioenergy (2020) [**2**] considers lower prices due to improvements in production technologies and lower CapEx in production due to lower financing costs in case of considerable upscaling of production.

The production cost of e-fuels depends strongly on the costs of the respective feedstocks: electricity, hydrogen and carbon dioxide. With water being an abundant resource, the cost of hydrogen production by electrolysis depends primarily on the price of electric energy. The price of carbon dioxide varies strongly and its development in the future is rather uncertain [**3**].

Table 5: Energy carrier WtW CO_2eq emissions.

g/MJ	Fossil	Biofuel/ carbon recycled (used in analysis)	Biofuel/ carbon recycled (actual range feedstocks)	E-fuel
EN590/HVO/e-Diesel	85.8	33.5	13 - 58	10
LNG/Bio-LNG/e-LNG	93.5	55[1]	33 – 55[1]	25.5[1]
Methanol	84.2	4.4	4.4 - 18	10
H_2	115.2		-	10
Ammonia	96.8		-	10

[1] Including emission of methane slip (20 g CO_{2eq}/MJ) taking into account a 100 year period.

The effect of the solution on CO_2-emissions depends both on the energy carrier as well as the production pathway. Hydrogen generated via electrolysis, for example, has very low CO_2-emissions from a well-to-wake perspective. However, when using hydrogen from a fossil production chain, CO_2-emissions are higher than when using the reference fuels.

Note that fuels based on the biological route consists of a large number of possibilities; including different feedstocks (e.g. food crops, lignocellulosic biomass, solid waste), processing techniques (hydrolyse, pyrolysis, gasification) and upgrading. Therefore, there is a wide range in emission reduction. Table 5 presents some examples of differences in well-to-tank emissions for different feedstock routes. For this analysis, we initially used waste materials as feedstock (tertiary streams) for methanol and secondary for bio-LNG. An additional analysis of different feedstocks mentioned in JRC (2020) [4] found these figures were at the low and high end of the spectrum.

For the carbon containing e-fuels, use of Direct Air Capture as source for CO_2 was considered. The CO_2-emissions from the WTT chain depend on the production location of the e-fuel and the downstream supply chain.

The LG-systems result in the highest CO_2-eq emissions; in these emissions also methane slip is accounted for 20 g CO_2eq/kWh (100 year) (JRC 2020) [4].
It is expected that (some of) the metrics provided in Table 1 and Appendix A will improve over time.

Globally, the following may be expected:

- Hydrogen storage in gaseous form will not increase to a much higher energy density, because the 700 bar storage used in this study, is the maximal physical density that has been applied in other (transport)industries; some applications exist of 900 bar, but they are very limited).
- Instead, hydrogen storage is expected to develop towards liquid storage. Subsequently, its volumetric storage energy density will increase to about 5.0 MJ/l, and the gravimetric density to 8.7 MJ/kg. This is an improvement of 50% in volume and 23% in weight with respect to the metrics used in this study;
- Other carriers are limited by their physical properties, and cannot have higher densities than reported here;
- Capital costs for power systems may improve – but these depend largely on whether SCR will be required. As SCR systems are currently developed as custom-made add-ons, they are costly, whereas when they will become a more integrated package – there is a large potential for cost reduction;
- Capital costs for energy storage systems are not expected to change significantly as they are mostly related to the fact that the density is less and thus more storage is needed;
- The chain efficiencies that were used in this study also represent relatively optimal scenarios in which the system is loaded effectively and optimised for efficiency. Higher efficiencies are only expected when SCR systems are no longer required, and/or waste heat is re-used to deliver power.

The availability of (compression ignited) dual fuel engines is expected to grow rapidly over the next few years. An overview is given in Table 6. As can be seen some dual fuel engines are already available today. Engines that can run on (e-)Diesel, E-LG, HVO, LBG are widely available, and are therefore not specifically considered here.

Table 6: Dual fuel engines (note: information is subject to changes).

Methanol	2-stroke engine available, medium-speed engines in development
Ammonia	2-stroke engine in commercial development, medium-speed in test phase
Hydrogen	Complete overview of developments given in Chapter 3

2.3 Results for ‘no design’ strategy; reducing internal space

For this exploration the reference ship and its operation remained the same.
The results are presented in Figure 2 to Figure 5, showing volume and weight ratio, CapEx, OpEx, and emissions, respectively.

Figure 2 shows relative size and weight of the resulting PPE systems is highest for the smallest ships; the ships in which the conventional engine room and bunker already takes a large part of the hull size and weight.

In addition, the smaller ships currently use compact, lightweight high-speed engines, which were assumed unavailable for alternative fuels, this on its own can have a significant impact on these smaller ships. Hydrogen takes most space due to its low energy density and contained it is also heavier than all other systems for all ships.

These results show that especially for the crew tender catamaran and the tug a significant redesign is needed to make the alternative fuel systems fit.

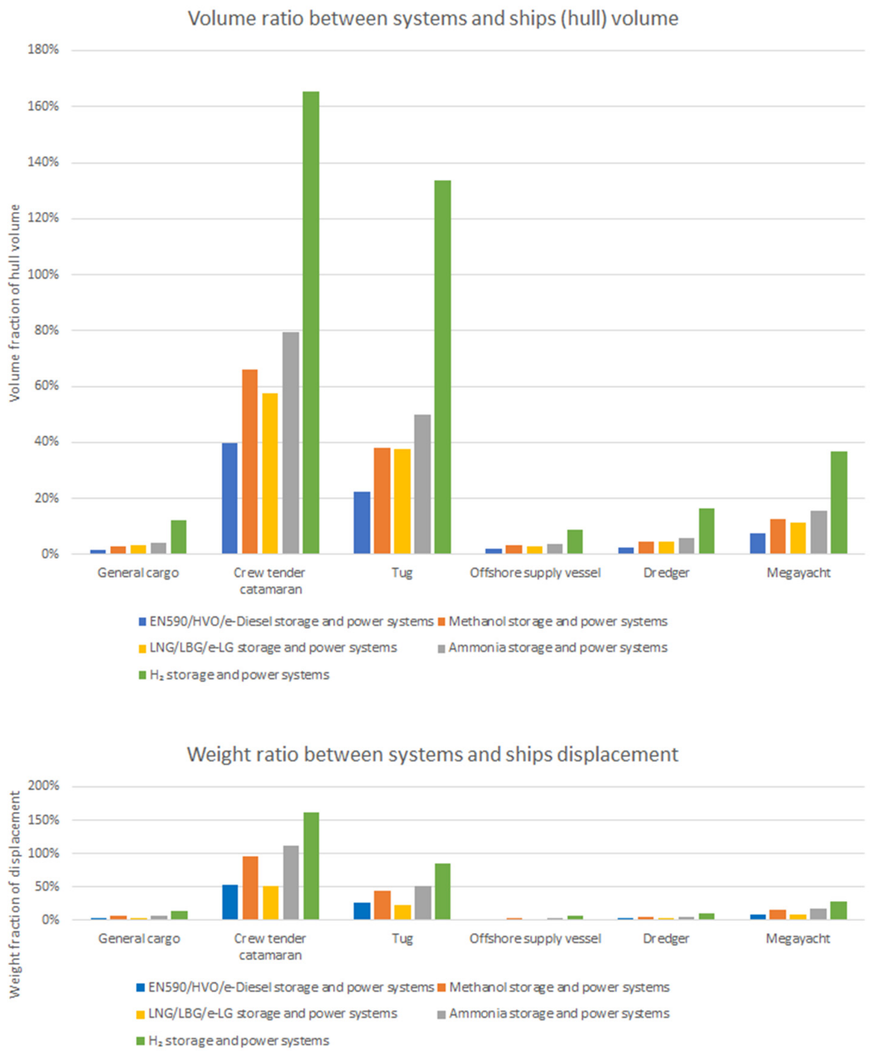

Figure 2: Volume (top) and weight (bottom) ratio (PPE-system compared to entire ship).

Figure 3 shows the hydrogen CAPEX are large; the storage costs take a considerable amount of the CapEx. For LNG this also holds, but less. For the crew tender catamaran and yacht, the CapEx of the ammonia solution is higher than LNG because of the more expensive power system.

Due to the short autonomy of the crew tender catamaran and the offshore supply vessel the storage contributions to the CapEx are much lower; in those cases the power system costs are dominant. However, for most ships the energy storage is most important for the CapEx.

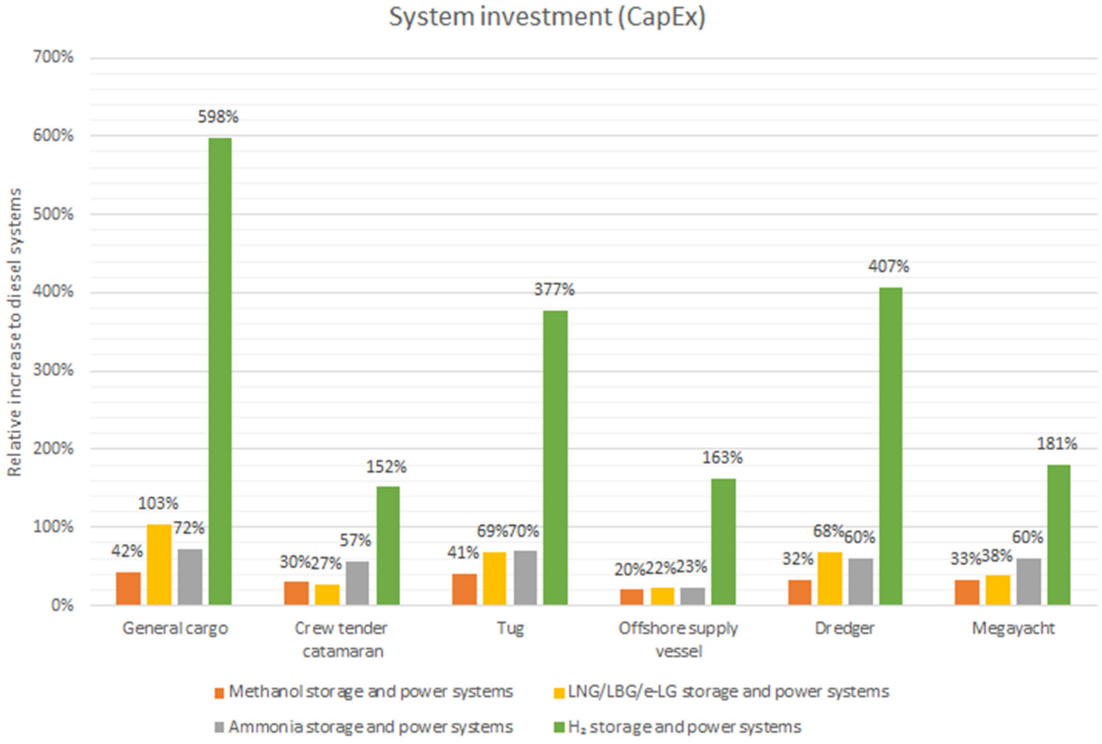

Figure 3: CapEx of the PPE system.

Figure 4 shows the fuel costs (OpEx).The error bars shown are constructed as such: For the low, medium and high scenario the price differences w.r.t. diesel are calculated. The average of those is taken as the price level w.r.t. diesel and the error bars are based on the highest and lowest differences from each one of the scenarios. This gives an indication of the spread, but one should keep in mind the error bars are relative to the diesel reference. In that sense the error bars can change from one solution to the other. Furthermore, the price levels are subject to constant change (due to market fluctuations) and the results should be considered with care. Given the uncertainties of the technological development, the costs of e-fuels show the largest variation, but are high in the low cost scenario compared to the other fuels. In biofuels, the price spread is less significant.

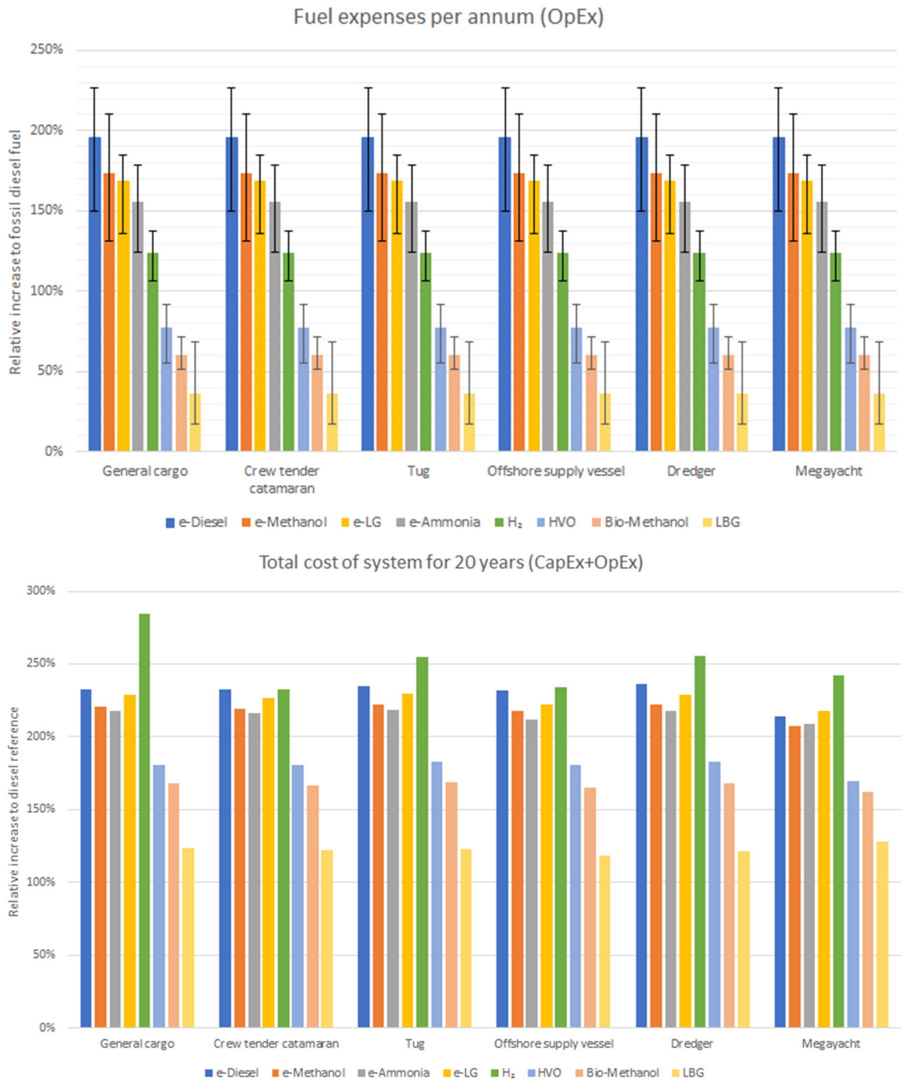

Figure 4: Annual OpEx (top) and total costs over 20 years.

The emissions are shown in Figure 5. Because the ship design was kept constant the emission reduction of the new PPE systems w.r.t. to the diesel reference is similar for all reference ships.

The LG-systems result in the highest CO_2-eq emissions; in these emissions also methane slip is accounted for 20 g/kWh (100 year). Note, the emission level used in this study is on the high end of the range found in literature. However, even the lower emission levels in the range would result in the highest emissions for LG-systems. The hydrogen is solution results in a similar emission as e-Methanol and e-Ammonia, because the synthetic fuels are 100% climate neutral in itself and the emission merely comes from the pilot fuel.

For the bioderived types of methanol waste feedstock was used, resulting in the lowest emissions because emissions further in the process are compensated by emission prevented when the waste is dumped at a landfill. When other more common feedstocks would result in similar emissions to e-methanol.

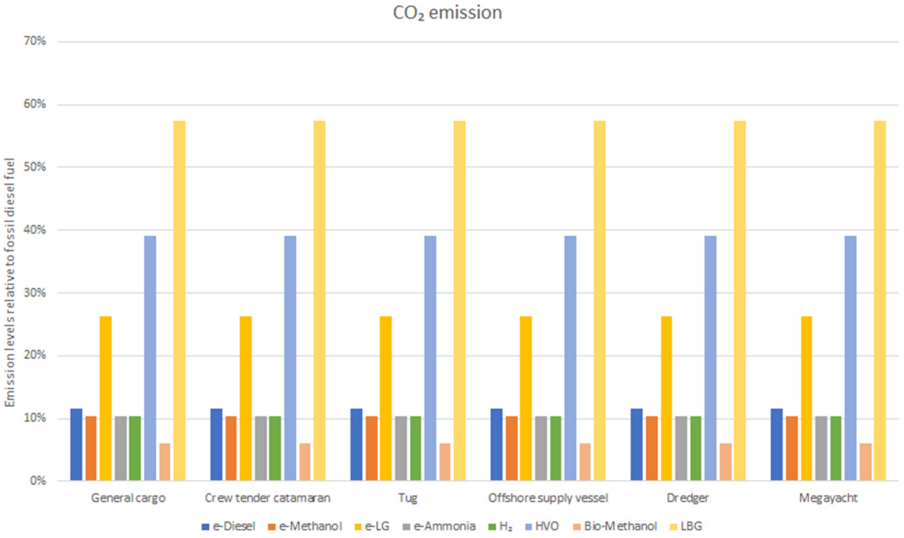

Figure 5: Emissions per PPE-system.

2.4 Results for ‘free design’ strategy; increasing ship size

For this exploration the reference ship was changed in size to fit the PPE system. This is done using an optimization loop that changes the ship size and estimates the new power requirements based on a simplified approach using Admiralty Coefficient equivalence. Without going into detail this approach holds for small changes in ship size up to about 10%. As will become clear in the results presented below some ships have to be drastically changed an do not fulfil this requirement. The results give a good indication on the possible impact on the ship design. Even for ships where small changes are indicated a dedicated design study will show how much of the ship should be redesigned in order to fit the PPE system. Previous studies showed that clever arrangements of the new PPE system components might lead to a denser system than on forehand anticipated.

The results are presented in Figure 6 to Figure 9, showing increase in ship displacement, CapEx, OpEx, and emissions, respectively.

In line with the previous section the crew tender catamaran and tug need a considerable change in ship size to fit the PPE systems (see Figure 6). Especially hydrogen, but also ammonia seems to be unrealistic for these ship types and the current operational profile. The LG systems result in the smallest ship design changes. For the high speed crew tender catamaran this may be imaginable as the hull is slender and its engines are large. For the tug this is less apparent, but based on Table 1 on reference vessels the high average power and long endurance results in 194 tonnes of diesel fuel capacity. And that is quite significant for a 32 meter tug; thus resulting in rather significant increments of the ship design. Note, this ‘design exercise’ might not take into account all measures needed to fit the PPE system. Safety measure might require extra space or different locations of parts of the system. Hence again, these results provide a good indication but detailed ship design should provide the exact consequences to fit in the new PPE systems.

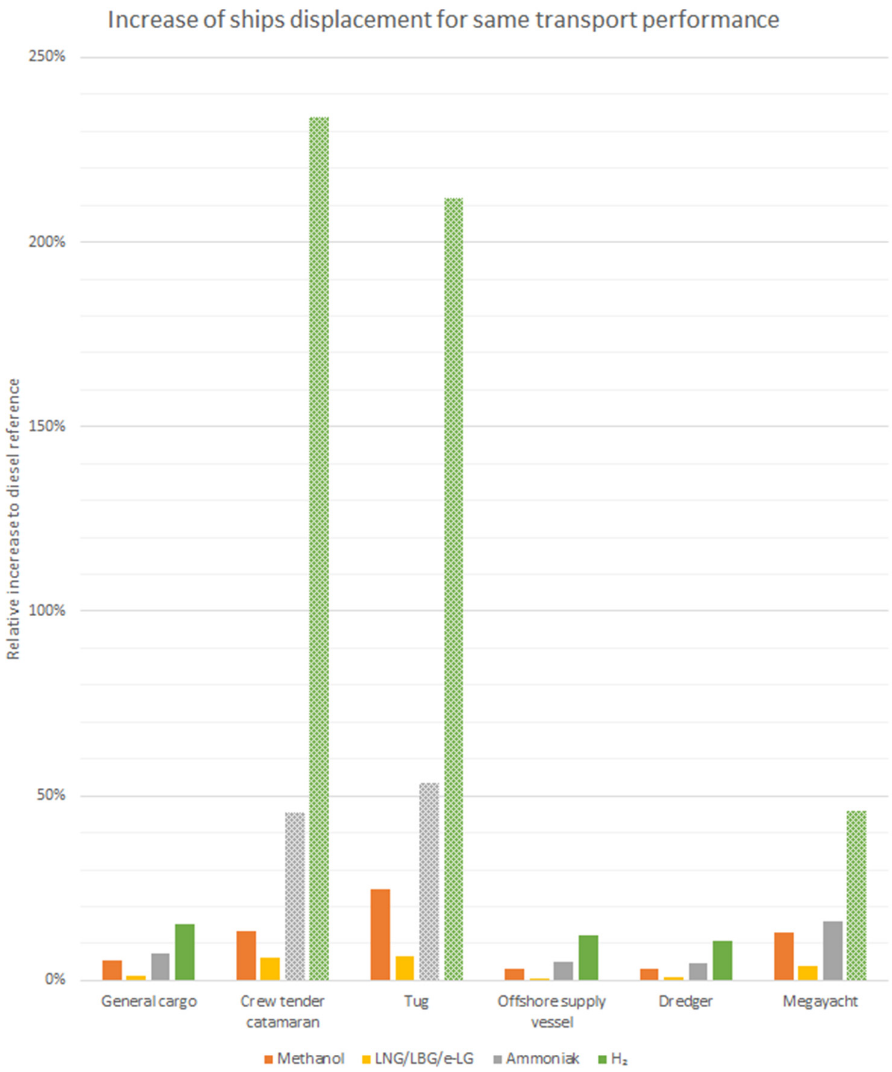

Figure 6: Increase of ship displacement in order to fit the new PPE system. Dashed bars indicate results that show a large uncertainty because of the used method to come to a new power prediction for an updated hull shape.

The resulting CapEx (see Figure 7) shows the same trends as for the fixed design strategy. However, the differences w.r.t. the diesel reference become larger because larger ships need more power and energy on board to be propelled.
Also here holds: in case much energy storage is needed LG is more expensive than Ammonia, like in case of the general cargo ship. For ships where the power system is most important ammonia is more expensive.

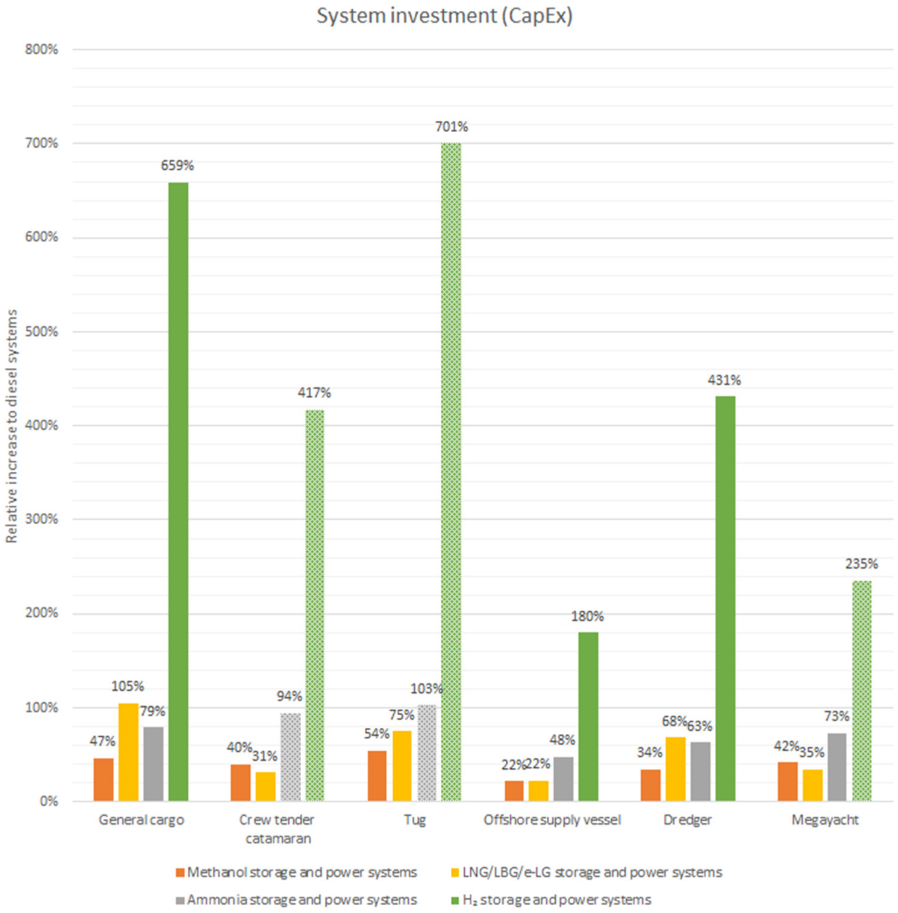

Figure 7: CapEx of the PPE system

The OpEx in Figure 8 clearly shows the effect of the larger hydrogen based crew tender and tug; consuming significantly more fuel increases OpEx.

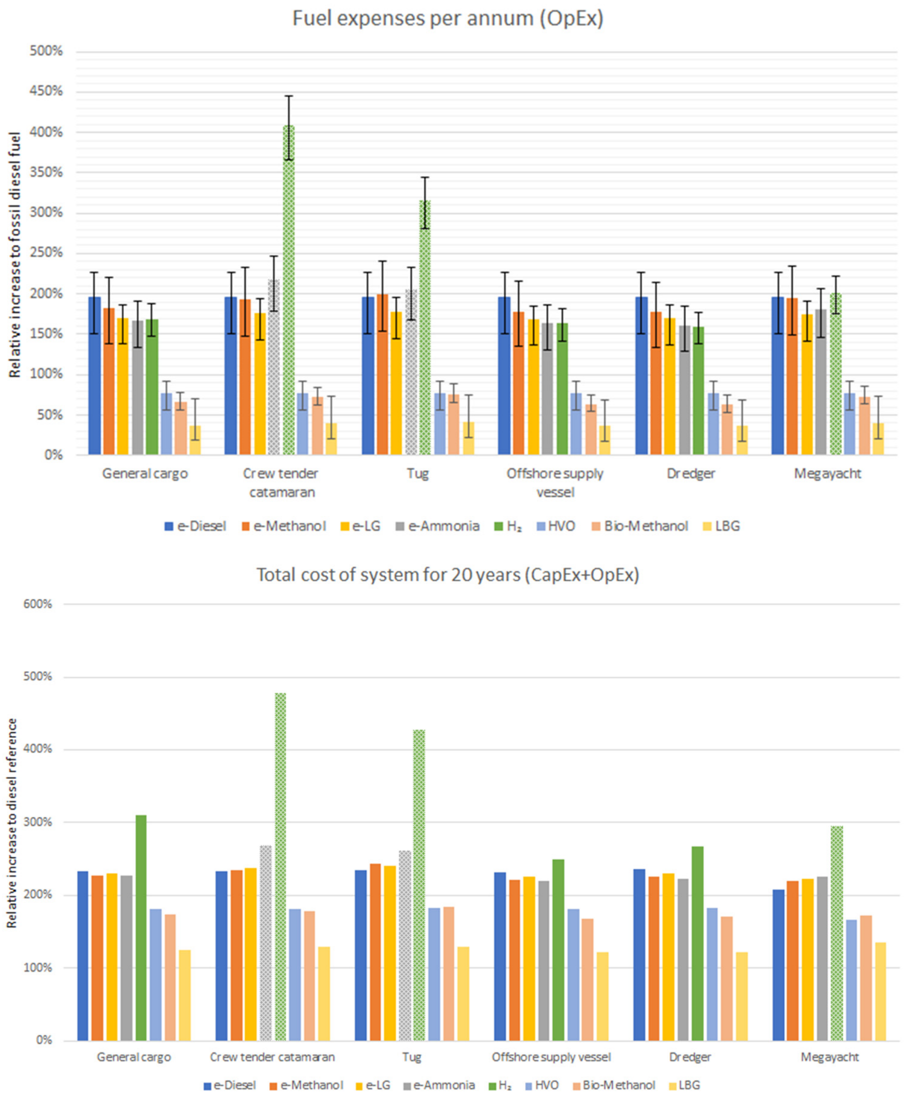

Figure 8: Annual OpEx (top) and total costs over 20 years (reference year = 2030).

The emissions (see Figure 9) are much in line with the results for the ‘no design’ in the previous section. Only for ships that become significantly large the emissions increase rapidly.

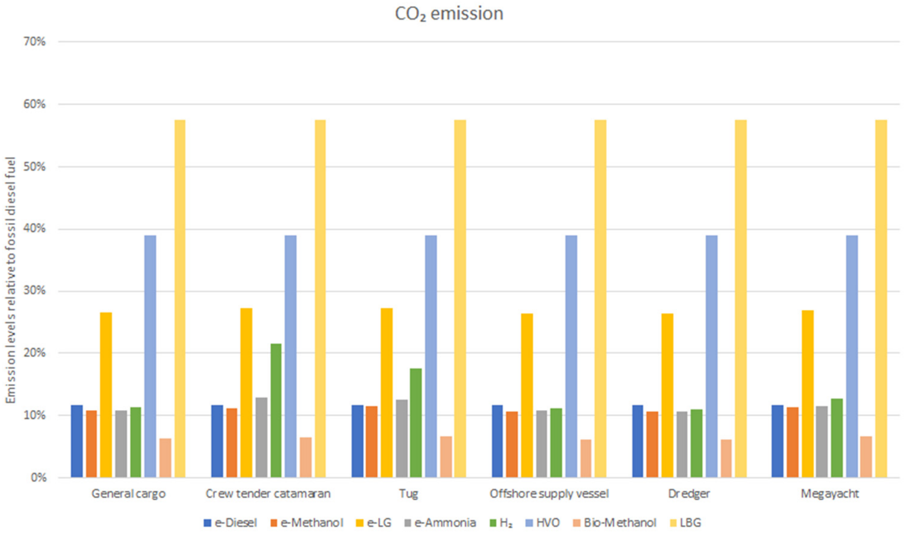

Figure 9: Emissions per PPE-system.

2.5 Results for 'fixed design' strategy; reducing autonomy

For this exploration the ship autonomy was changed in size to fit the PPE system.

The results are presented in Figure 10 to Figure 13, showing endurance, CapEx, OpEx, and emissions, respectively.

Figure 10 shows effect on endurance (autonomy). The EN590/HVO/e-Diesel autonomies are those initially defined in the ship mission profiles. Clearly the LG options result in the lowest impact, whereas hydrogen easily drops about 80% in autonomy. Methanol and ammonia show drops of about 40-60% depending on ship type and operation. Because the endurance of the systems per ship are significantly different comparing the rest of the results should be done with great care.

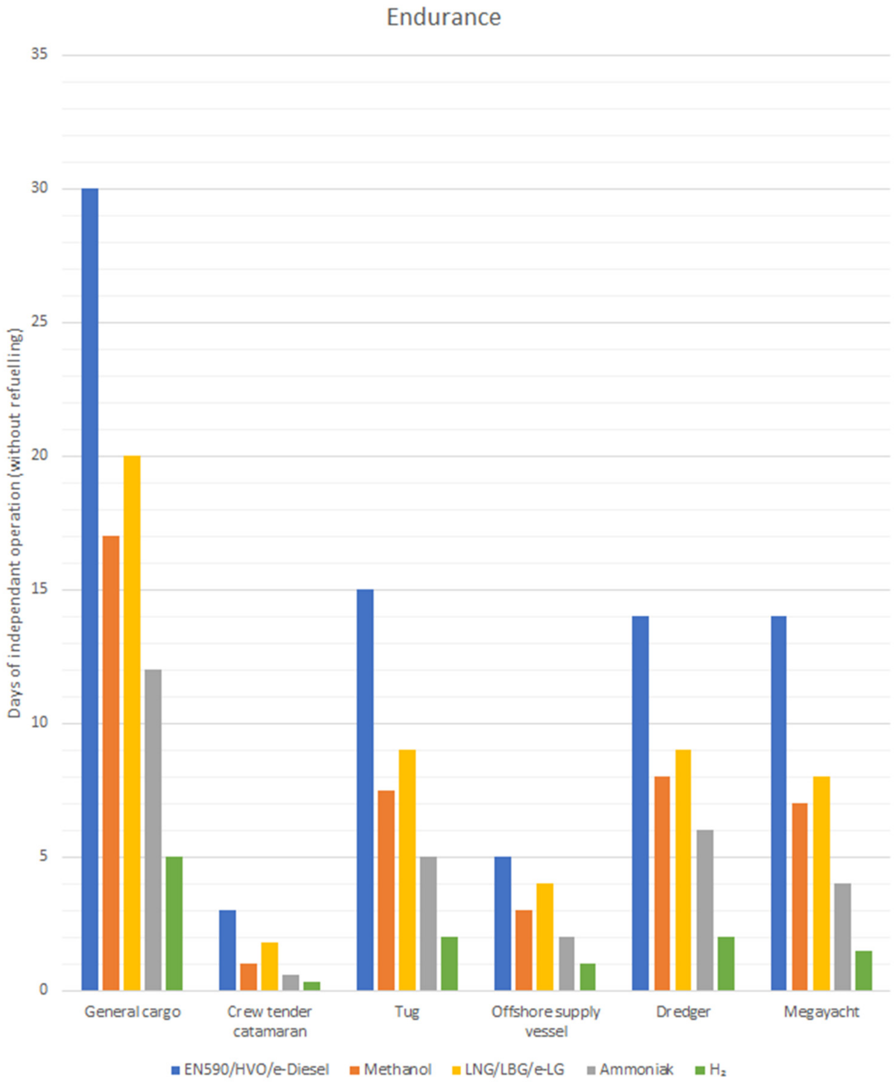

Figure 10: Reduction in autonomy in order to fit the new PPE system with fixed space for PPE system.

Figure 11 shows CapEx are largest for the hydrogen solutions, but for ships with a large drop in autonomy, e.g. for hydrogen in the crew tender catamaran, this does not hold. For the smaller ships where the power system is dominant the ammonia option is most expensive because those power systems and auxiliary system are expensive. However, much references are not yet available for these systems.

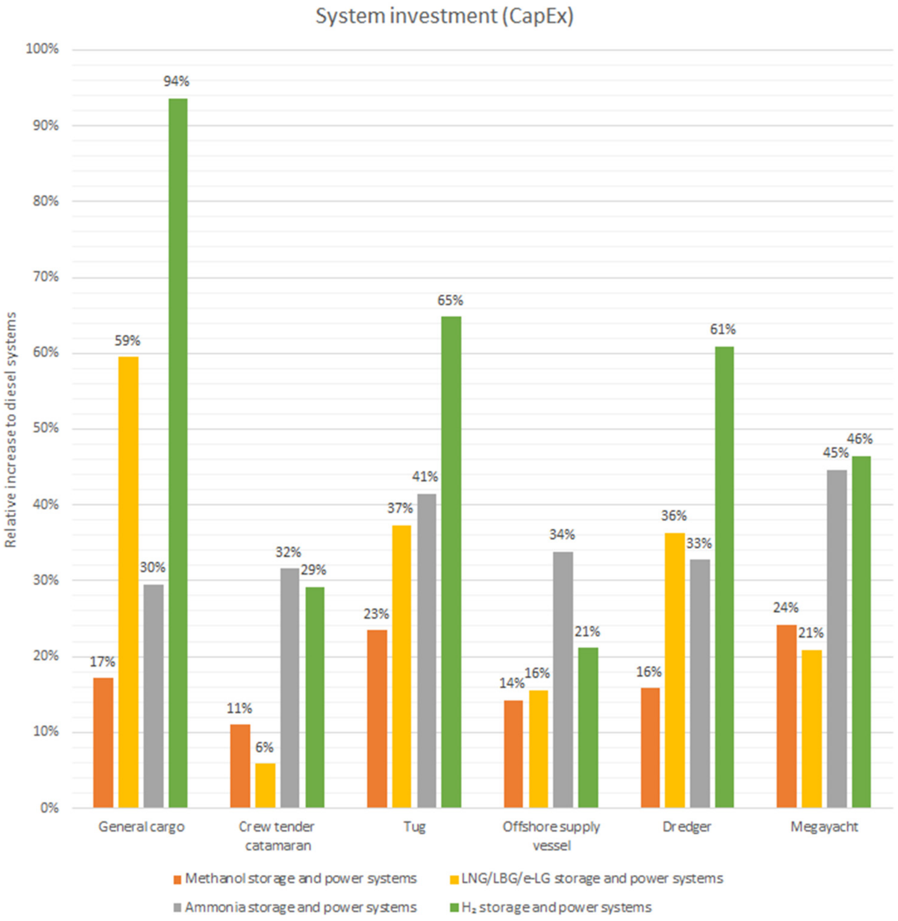

Figure 11: CapEx of the PPE system with fixed space for PPE system.

The trends in the OpEx per annum (see Figure 12) are in line with the OpEx in the ‘no design‘ case.

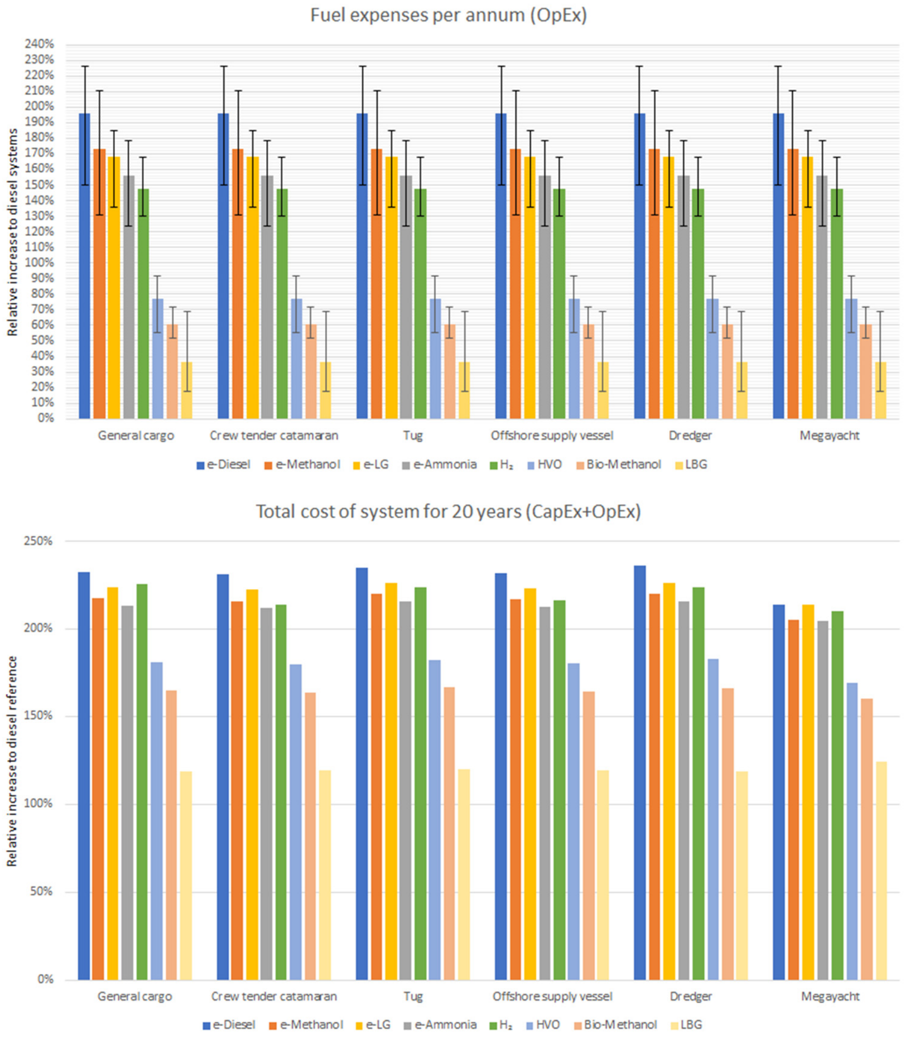

Figure 12: Annual OpEx (top) and total costs over 20 years (reference year = 2030).

Also the emissions per annum (see Figure 13) show the same trend as for the ‘no design’ case and conclusions are the same.

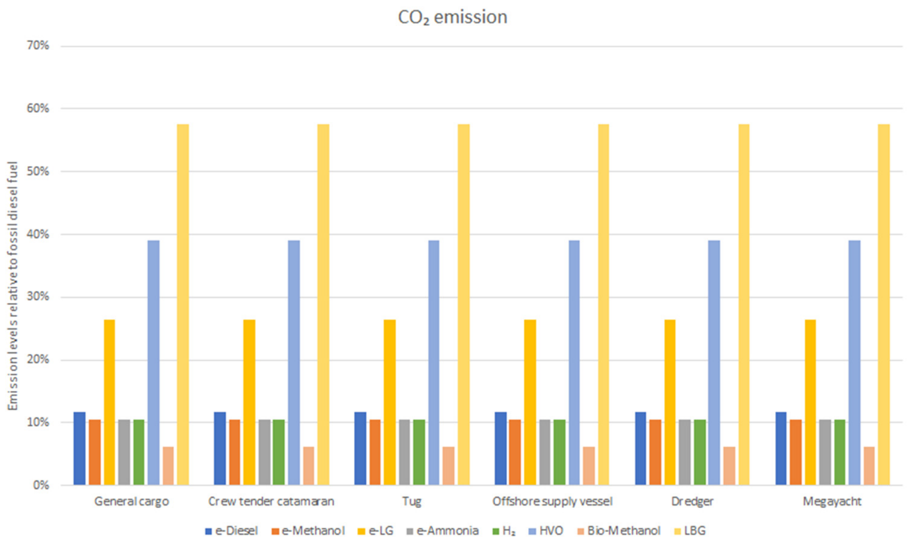

Figure 13: Emissions per PPE-system per year.

2.6 Conclusions

The evaluation of alternative fuel and ICE based PPE systems for 6 reference vessels provided many insights as discussed in the report. Some of the insights are listed here. The conclusions are based on the currently set reference operational profiles; other operational profiles lead to different conclusions.

Ship design an autonomy
The crew tender catamaran and the tug are small with a relatively large PPE system onboard. As a result, alternative fuel based PPE systems result in much larger ships (up to 50% for ammonia and 200% for hydrogen) or a much lower autonomy. To fit such system, the ship design or its operation should be changed considerably. Otherwise, high density energy carriers, like e-diesel/HVO may be required to maintain the operations. The yacht shows the same impact to a lesser extent, with an increase in ship displacement of about 50% for hydrogen. The other vessels when discarding hydrogen could be fitted with a new, alternative fuel based, PPE system with a smaller impact on ship design and operation. The hydrogen solution for e.g. the general cargo vessel results in a ship size increase of about 15% or an autonomy drop to about 85% which asks for considerable measures, this is also reflected in the total cost.

Costs
The economical choice for the energy carrier depends on the CapEx/OpEx ratio. The CapEx of hydrogen storage is high, whereas OpEx for e-fuels is lowest for hydrogen, making it an interesting candidate for future clean transport with low autonomy per mission, but large operational yearly use. In that sense also Ammonia is interesting for such ships and operations with low CapEx for storage CapEx for power in the range of hydrogen and low OpEx when synthetically made. When considering the OpEx hydrogen and ammonia are expensive fuels when made from fossil resources, and also not beneficial for future application because their emission is higher than fossil diesel fuel.

However, when considering e-fuels, hydrogen and ammonia are relative cheap to manufacture because of its simple chemical bounds. The development of the market price and availability of different e-fuels is however very uncertain and depends on both technological developments and market uptake. The same holds for bio-fuels: feedstock availability and demand in different sectors will be of great influence in price development. Furthermore his analysis does not take into account what the incremental effect is of ship hull and outfit costs when the ship needs to increase to fit new PPE systems. E-diesel/HVO can be interesting when operational hours are limited or the (CapEx) implications of alternative systems are too substantial due to the amount of energy or power needed to be taken onboard.

Emissions

The (GHG) emission reduction is lowest for the LG-solutions (~40% for LNG and ~70% for LBG) mainly because of the methane slip contribution. With HVO a reduction of about 60% could be achieved. With the other fuels (bio and synthetic) reductions of about 90-95% can be reached. Bio-methanol using tertiary waste streams shows emissions lower than e-methanol, because optimal waste streams are taken. It is questionable whether this feedstock is scalable. Using other more common feedstocks gives similar emission to e-methanol. Fully climate neutral is not reached because in all cases at least 5% pilot fuel is used and e-fuels also have emissions due to logistics, synthesis, etc...

3 Inventory and Feasibility H2-ICE for maritime applications

In recent years, much research and development has been done on the application of alternative fuels in internal combustion engines in maritime applications. Internal combustion engine research and development is carried out by many entities worldwide, including universities, research institutes, and the industry (i.e. engine OEMs). These efforts have resulted in engines running on alternative fuels such as natural gas and (to a lesser extend) methanol, proven in demonstrations, prototypes, and (in case of LNG) implementation in the market.

However, hydrogen is a less explored and certainly low maturity alternative fuel for combustion engines. At this moment, hydrogen combustion research in engines is carried out in various projects by different parties. To find knowledge gaps in the application of hydrogen as a fuel for ship engines, an overview has been created of “Who is doing What” in the field of hydrogen combustion engines research. Section 3.1 presents an overview.

In the subsequent sections, the feasibility of applying hydrogen as a fuel in internal combustion engines for the maritime sector is explored. This chapter’s focus is on the internal combustion engine, which is a component of the ship’s propulsion system. It has to be noted that also other aspects need to be accounted for to implement a hydrogen propulsion solution on a ship, for example hydrogen storage.

Hydrogen has distinctive combustion properties that can be exploited in different combustion concepts for power generation in an internal combustion engine. These combustion engine concepts all have their own pro’s and con’s regarding key performance indications, such as fuel consumption efficiency, engine-out emissions, and load range. In Section 3.2 the in this study targeted ship types and engine operating ranges are introduced, and in Section 3.3 an overview of the performance potential of these H_2-ICE concepts for maritime applications is presented.

The application of hydrogen in an engine requires special attention to some safety and reliability aspects. These are related to the flammability, corrosivity, lubricity, etc. of the hydrogen gas which are different from other combustible fuels. The impact of these gas properties on safe and reliable engine operation are presented in Section 3.4 and 3.5.

Furthermore, a brief hardware cost consideration is given in Section 3.6 from the viewpoint of the engine and the aftertreatment configuration per combustion concept. Then, different development timelines are sketched for the combustion concepts in terms of the technical readiness level in Section 3.7. Hydrogen production and availability on the market is discussed in Section 3.8. Finally, summarizing conclusions are given in Section 3.9.

3.1 Inventory of ongoing H_2-ICE developments for maritime

In this section, an overview is given about Who does What in the field of hydrogen combustion engines research. The overview is based on contacts from TNO's network in this field and by accessing public information. The search focused on existing and recently finished projects, as well as projects that will soon be started. Special attention has been paid to research that involves multi-cylinder engines running on 100% hydrogen (or in case of dual-fuel engines, a high share of hydrogen). This activity resulted in a short list of selected research with a focus on maritime size engines.

The main research and development activity regarding H_2-ICE for maritime applications is located in Europe. The activities are often clustered around collaborations in which industry seems to play an important role, either in the role as enablers for universities through supply of hardware or as prime stakeholder for using project results for product development. Japan is the only other country with substantial focus on H2-ICE for maritime and smaller applications. Interestingly, parties in the US seem to have made the decision to use hydrogen in fuel cell applications rather than ICEs, both for smaller as well as for larger applications. The geographic spread of the H2-ICE activity is depicted on a world map in Figure 14. The colours have the following meaning, Blue: H2-ICE for maritime, Yellow: H2-ICE for non-maritime, and Green: H2-ICE for maritime and non-maritime, White: no H2-ICE/no info.

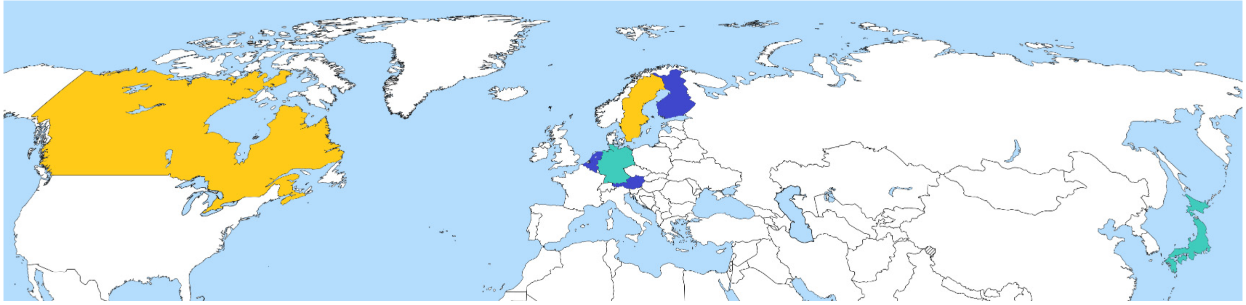

Figure 14: Countries where H2-ICE R&D is mainly present. Blue: H2-ICE for maritime. Yellow: H2-ICE for non-maritime. Green: H2-ICE for maritime and non-maritime. White: no H2-ICE/no info.

More details of the main parties that are active in H2-ICE for maritime R&D in the Netherlands and worldwide are listed in Table 7. The table is a shortlist that includes H2-ICE research for maritime or maritime size engines such as gensets. The shortlist excludes parties and projects that investigate H2-ICE for road applications and also excludes H2 fuel cell research. The type of entity, the main location, the developed technology, and other relevant details are listed for each listed party.

First of all, Table 7 starts with the Dutch entities that are active in H2-ICE research and development for maritime size engines. The only market party, engine supplier KVT, has performed field tests on a genset in 2020. They use the traditional spark ignition technology operated at stoichiometric (λ=1) conditions.

Research institute TNO investigates also other combustion technologies for hydrogen, experimentally as well as by simulations, such as the more efficient spark ignition lean concept and the dual-fuel concept that employs hydrogen as the primary fuel and a small amount of secondary fuel (for instance diesel). Currently, TNO does these studies on automotive type engines, and plans to perform tests on maritime size engines in the near future. The technical universities in Delft and Eindhoven work on lower TRL topics related to H2-ICE, namely, ammonia+hydrogen ICE and the argon power cycle, respectively.

Globally, quite a few engine OEMs are active in H2-ICE development. The engine OEMs in the shortlist make maritime engines and/or sizable gensets and are recognised parties in their sectors. This indicates that a significant impulse exists to bring H2-ICE developments towards market products.

One way or the other, the OEMs tend to collaborate with research institutes and universities which often means that research projects are run under subsidized consortia. HyMethShip is such an example of a European project in which parties from six countries collaborate. This project has a broader scope than only H2-ICE: “The HyMethShip system innovatively combines a membrane reactor, a CO_2 capture system, a storage system for CO_2 and methanol, as well as a hydrogen-fuelled combustion engine into one system.”, which in practice could only be done within a consortium existing of partners with various expertise. HyMethShip is a scarce H2-ICE example since by far the most of the hydrogen projects subsidised by the European Commission have fuel cell scope. More often the different parties find collaborative initiatives on national level, clearly seen in Table 7 for Belgium and Austria.

Furthermore, a clear observation from this inventory is the newness of the ramp-up of developments in the field of H2-ICE for maritime as well as for other sectors. Some parties have investigated H2-ICE at least a decade ago, either in form of hydrogen blend into other gas or pure hydrogen combustion on a demonstration platform. These early developments came to a standstill until a renewed interest in this topic sparked roughly around 2019 as an effective CO_2 reduction strategy. In the course of 2020, many new H2-ICE projects and development targets have been published by the industry and still more initiatives seem to be underway.

Finally, some words on the types of combustion technology being developed for H2-ICE. Both mono-fuel and dual-fuel concepts are being developed. Engine OEMs/suppliers who mainly have gas engines in their existing portfolio, often active in the genset business, have a preference for the mono-fuel path since their gas engines make use of a spark ignition system. Such a spark ignition engine can be modified to run on hydrogen only. Contrarily, engine OEMs who build diesel engines as their prime product, tend to take the route of dual-fuel hydrogen combustion. The dual-fuel concept is implemented by equipping the base diesel engine with extra injectors to introduce hydrogen to the engine. The combustion principle remains to be compression ignition for which a pilot injection of diesel(-like) fuel is required to ignite the in-cylinder charge.

Table 7: The main H2-ICE for maritime R&D parties in the Netherlands and worldwide, listed with the type of entity, location, technology, and other relevant details.

Entity	Type	Country	Technology	Other
Koninklijke van Twist (KVT)	Supplier	**NL**	Mono-fuel SI (lambda = 1), genset	Perkins distributeur First field test sucessfull in Q4 2020
TNO	Research institute	**NL**	Mono-fuel SI, Dual-fuel CI	Multi-cylinder and single-cylinder test capability with 100% H2. Combustion simulations, in cooperation with TU Eindhoven.
TU Delft	University	**NL**	SI NH3 with H2 as promotor fuel	AmmoniaDrive: ICE on Ammonia + H2 as ignition promotor (low TRL)
TU Eindhoven	University	**NL**		Hydrogen concepts, CFD, Argon Power Cycle
HyMethShip	Project	EU	Dual-fuel, DI H2, 2MW maritime/stationary	Concept with methanol on-board reforming, H2 combustion, and CO2 capture to re-use for methanol production on-site. 3 year project, end date 06-2021
ABC	OEM	BE	Dual-fuel H2-diesel (max. 85% H2). 16DZD tot 2670kW, 12DZD tot 2000kW, 8DZD tot 1335kW, 6DZD tot 1000kW (16,12,8,6 cylinders)	BeHyrdro Joint Venture together with CMB
MHIET (Mitsubishi Heavy Industries Engine & Turbocharger, Ltd.)	OEM	JP	Mono-fuel SI, target: 1 MW engine	Planning and Design Center for Greener Ships. Joint development with AIST (Japan's National Institute of Advanced Industrial Science and Technology). Achieved stable combustion of 100% hydrogen fuel with a single cylinder engine at AIST. Aims to make 1 MW-class hydrogen engine available for the introduction of hydrogen economy in the 2030s
MTU (Rolls-Royce)	OEM	DE	SI, probably lean, genset	Partner in project HyMethShip Quote: "H2-ready, which means that the engines can be converted to hydrogen operation at a later date." They have studied H2 combustion in single cylinder tests.
Wartsila	OEM	FI	Mono-fuel SI	Hydrogen mixing in SI and hydrogen-diesel dual-fuel already possible and demonstrated. Wartsila has limited believe in H2 for shipping. Rather better believe as building block for other fuels.
2G Energy AG	OEM	DE	Mono-fuel SI, Combined Heat and Power systems	Aginator SG 115 - 360kW electrical power output (129 - 371 kW thermal output)
INNIO Jenbacher	OEM	AT	Mono-fuel SI, probably lean	Flagship project using 100% hydrogen on a 1 MW J416 gas engine. Demonstrate the first J612 running on 100% hydrogen at the Large Engine Competence Center (LEC) in Graz.
CMB Tech	Supplier	BE	Dual-fuel, 2x2MW (HydroTug, expected 2021)	BeHyrdro Joint Venture together with ABC HydroBingo project together with Japanese Tsuneishi Facilities and Craft, expected in operation in 2021 in Japan.
FVTR	Supplier	DE		Partner in project HyMethShip
Large Engines Competence Center (LEC)	Research institute	AT	Dual-fuel, DI H2	Leading partner in project HyMethShip
Gent University	University	BE		FASTWATER (methanol)
TU Graz	University	AT	Dual-fuel, DI H2	Institute for Internal Combustion Engines and Thermodynamics (IVT) Partner in project HyMethShip

3.2 Maritime engines and operating range

The power and propulsion system onboard a ship can have many configurations and consists of many different components. A typical layout is shown in Figure 15 for a direct drive system. In this example, the propeller is driven by a single combustion engine, electricity for auxiliaries is generated by two generator sets, and the exhaust of all the engines are treated with aftertreatment technology before being emitted to the environment.

Six vessel types are included in the scope of this study. Each of them have their typical power installed onboard:

1. General cargo ship, 4 MW;
2. Tugboat, 5 MW;
3. Offshore supply, 6 MW;
4. Crew Tender Catamaran, 2 MW;
5. Dredger, 12 MW;
6. Yacht, 13 MW;

From engine technology perspective, they use 4-stroke medium/high speed (diesel) engines with engine bore sizes ranging from 150 to 500 mm, which is a good starting point for implementation of hydrogen combustion. At the lower size range of such engines, there is similarity with engines used in heavy-duty trucks for which more research about hydrogen application has been published which is a good knowledge source.

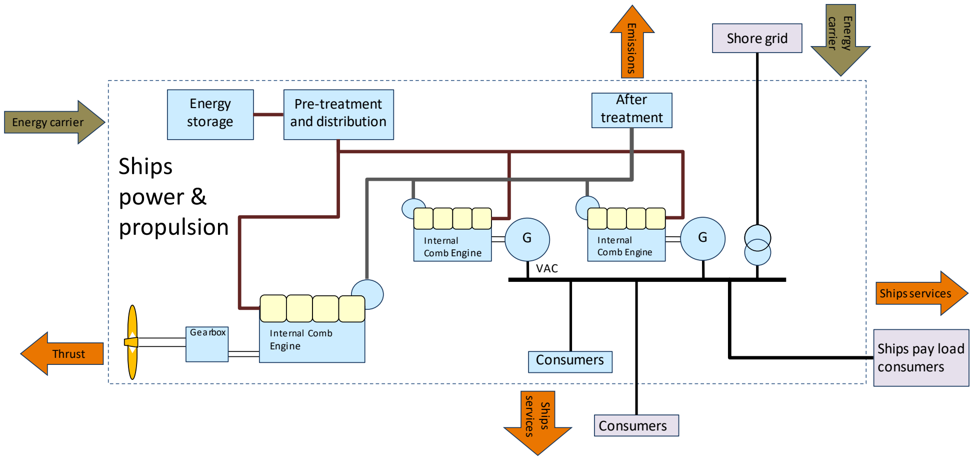

Figure 15: Example scheme of a direct drive propulsion layout with separate generator sets.

Engines for the propulsion of ships, engines for electricity generation, and engines for the propulsion of trucks are operated different from each other. The specific operating conditions and limits will impact the applicability of hydrogen for each of them differently.

Truck engines have the widest operating range regarding the load and the engine speed (units RPM) that are required to meet highly dynamic driving conditions on the road. A typical maximum load line for truck engines is sketched in Figure 16 (black line), which spans almost the entire RPM range with high torque demand values. Additionally, the dynamic driving conditions impose high requirements to the transient response of a truck engine.

Ship propulsion engines have to meet the propeller load demand curve.
The propeller load is low at low RPM and gradually increases to high load at high RPM, thereby covering only the diagonal area of the full operating map, also shown in Figure 16 (orange line). The nominal transient behaviour following the propeller curve might be relatively slow, however, more challenging transient response requirements are posed for conditions occurring at for instance manoeuvring and dynamic weather (wind and wave).

Generally speaking, the application of hydrogen could be challenging at low load and high load regions. At low load, the typical in-cylinder conditions are: low temperature, low pressure, lean fuel-air mixture. The combination of these conditions can lead to misfires or in-complete combustion with loss of engine torque as a consequence. On the contrary, at high load, the typical conditions are the opposite of that at low load, leading to increased risk of pre-ignition and knock. The magnitude of these challenges are highly dependent on the chosen combustion concept and the applied fuel injection strategy. More about these aspects are explained in Chapter 3.3.

Generator engines are restricted to a narrow operating range. The load demand for a generator engine can vary, but for current AC systems the RPM should stay constant, which is basically a fixed RPM operation along the vertical blue line in Figure 16. However, variable speed generators (DC-distribution generator engines) are not limited to a single speed operation and span a wider operating range. The application of these systems is increasing. When applying hydrogen, similar misfire and knock challenges may be faced at the low and high load ends of the operating region as for ship propulsion engines. These challenges need to be addressed properly when designing the engine.

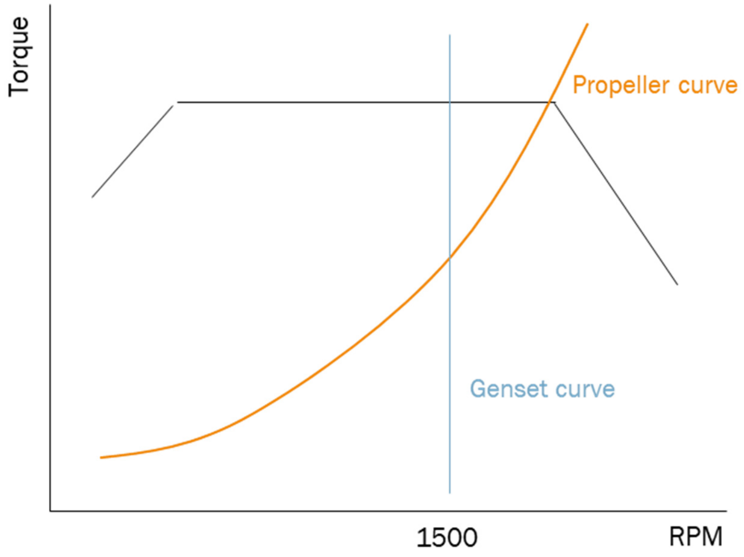

Figure 16: Engine operating map: load torque versus engine speed. Orange line: propeller curve for ship propulsion. Blue line: genset curve for electricity generation. Black line: maximum load curve for truck applications.

3.3 Hydrogen Internal Combustion Engine concepts

The application of hydrogen to drive an ICE encompasses more than to take an existing engine and to feed it with hydrogen. In this section, first, some of the relevant properties of hydrogen in the context of combustion engines are introduced. Subsequently, combustion concepts are briefly discussed that can be useful for hydrogen combustion. Finally, special attention will be paid to engine (operation) limits that one might expect. These topics are intrinsically very technical, therefore, in this report the aim is to present and discuss them briefly to sketch the technical context with the intention to support the interpretation of the remaining sections. The interested reader can find more on these subjects at (amongst others): [5], [6], [7], [8], [9], [10], [11], [12], [13], [14].

3.3.1 Hydrogen as a fuel for internal combustion engines: relevant properties

Hydrogen (H_2) is a diatomic molecule consisting of two hydrogen atoms (H). In this section, a brief overview is given in arbitrary order of the physical and chemical properties relevant for the application of hydrogen as a fuel in internal combustion engines.

Volumetric density and gravimetric energy density

Hydrogen is a gaseous fuel at standard ambient conditions with a low volumetric density of 0.0838 kg/m^3 (at 20°C, 1 atm.). This is roughly a factor of 8 lower than the density of gaseous methane (main component of natural gas) at identical conditions.

The gravimetric energy density of hydrogen is high. In other words, the energy content per unit of mass is high. The energy density, here quantified by the lower heating value, of hydrogen is 120 MJ/kg. In comparison, the lower heating value of methane is about 50 MJ/kg. For the same amount of energy, less mass of hydrogen is required. However, due to the low volumetric density, the required volume is significantly larger. For example, when storing compressed hydrogen at 350 bar the required volume is about a factor of 4.2 larger than for methane at the same pressure and same energy content. Appendix A gives an overview of the energy densities of various energy carriers in their stored condition.

Flammability limits

Flammable limits apply generally to vapors and are defined as the concentration range in which a flammable substance (fuel vapor + air) can sustain a flame or produce an explosion when an ignition source (such as a spark or open flame) is present. Outside this range of air-fuel mixtures, the mixture cannot be ignited (unless the temperature and pressure are increased). In comparison to other fuels, hydrogen has much wider flammability limits. Especially the lean flammability limit reaches to a much higher air-fuel ratio, here indicated with excess-air ratio λ. At standard conditions, a hydrogen-air mixture with an excess-air ratio λ up to ~10 can still be ignited. In comparison, for methane this limit is at λ~2.1. This means that a small concentration of hydrogen in air is reactive enough to burn. This property of hydrogen is important for H2-ICE developments for two reasons. The advantageous reason is that lean operation (high excess-air ratio λ) has the potential for low NO_x emissions and increased engine efficiency. The disadvantageous reason is that special attention is needed to ensure robust engine operation without pre-ignition and knock. Furthermore, additional safety measures may need to be addressed for safe storage and handling. See also Section 3.4.

Auto-ignition temperature

Auto-ignition is the phenomenon that an air-fuel mixture self-ignites under the ambient conditions that it is exposed to. In the literature, the ambient temperature at which auto-ignition occurs is often used to characterize fuels: the fuel is said to have a certain auto-ignition temperature. Hydrogen has a high auto-ignition temperature. It is significantly higher than other engine fuels such as diesel or gasoline, and in a similar range as methane (natural gas).

The auto-ignition temperature is a key parameter in determining the compression ratio of an engine. A high auto-ignition temperature enables the use of a high compression ratio, which is beneficial for high engine efficiency. However, a too high compression ratio will make the system prone to instable combustion in which the fuel-air mixture ignites too early during the compression stroke, i.e. so called pre-ignition.

Adiabatic flame temperature and NO_x emission formation

The temperature that results from an ideal combustion (no losses) of the fuel-air mixture is referred to as the adiabatic flame temperature. Hydrogen is characterized by a high adiabatic flame temperature. This temperature is highest for a stoichiometric fuel-air mixture (l = 1) and gradually reduces when the mixture becomes more lean (air-excess ratio l > 1) as is shown with the red line in Figure 17. Because NO_x-emission formation is strongly temperature driven, the adiabatic flame temperature is a key parameter to take into account.

The black line in Figure 17 depicts the NO_x emission concentration as a function of the (local) excess air ratio of a premixed air-hydrogen mixture. NOx emissions are highest at close-to stoichiometric conditions (air-excess ratio l = 1) where flame temperatures are highest. NO_x emissions are highest at slightly lean conditions when temperatures are high in the presence of oxygen. A temperature threshold of 1800 K is a typical lower limit for NO_x formation. From the data presented in Figure 17 it can be derived that the excess air ratio l needs to be higher than ~2.2 to realize temperatures lower than 1800 K and therefore sufficiently low engine-out NO_x levels, i.e. engine-out emissions compliant to STAGE V/EURO VI (automotive engine example). This is well within the flammability limits of hydrogen. For excess air ratio's l below ~2.2 NO_x reduction from exhaust gas aftertreatment is required in order to be compliant to current legislative levels, this "critical area" is also highlighted in the figure.

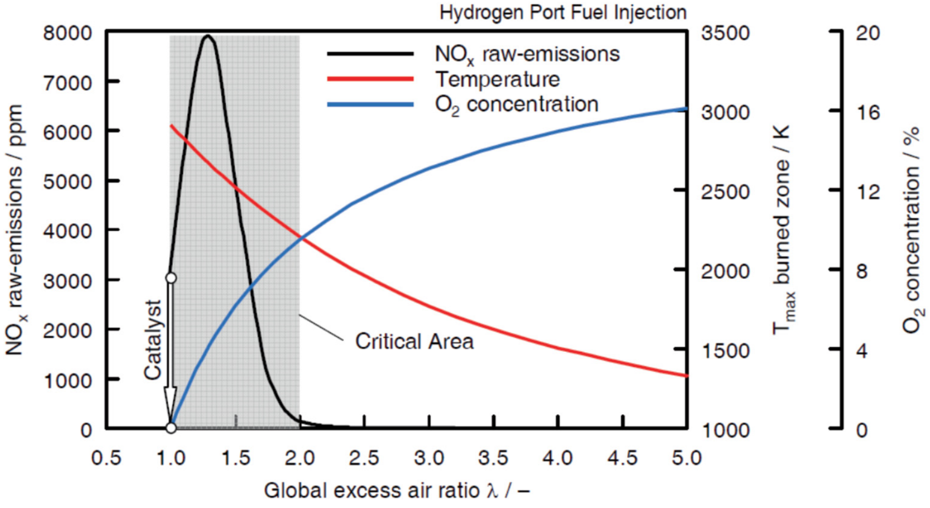

Figure 17: NO_x emissions and combustion temperature as a function of air-excess ratio λ. Taken from [7].

Flame speed

In a premixed combustion concept, the fuel-air mixture is burned by a propagating flame originating from the ignition location (for instance a spark). Hydrogen has a high flame propagation speed. High flame velocities (burn rates) result in fast heat release rates. From thermodynamics it is well-known that faster combustion is beneficial to increase engine efficiency. The high flame speed of hydrogen may be exploited to achieve high engine efficiency. However, the potential gain in thermal efficiency is limited by mechanical hardware constraints. Too fast combustion may result in too high mechanical stress on the engine components and ultimately in engine failure. Flame speeds can be reduced by lowering the combustion temperature. Here, lean operation and dilution by applying Exhaust Gas Recirculation (EGR) are known to be effective measures.

3.3.2 Combustion concepts

Various combustion concepts exist for ICEs. Some of them are well-known and highly optimized in the past century, often for a specific fuel and for a variety of application domains including the maritime sector. There are also less known combustion concepts which are developed (or still in development) with a specific target to increase the engine's thermal efficiency (lower fuel consumption and lower CO_2 emission) and/or reduce the pollutant emissions beyond the state-of-the-art of the traditional concepts. A high level overview is given as background to the results discussed in the section on the performance potential of H_2-ICE for maritime applications.

One can discriminate between three main combustion concepts (or modes) from which other concepts can be derived.

These main combustion modes are:

- Spark Ignition (SI): a premixed air-fuel mixture is consumed by a flame propagating through the combustion chamber. This propagating flame is initiated by an ignition trigger, e.g. a spark generated by a sparkplug. Spark timing is close to Top Dead Center (TDC). See Figure 18 middle drawing. This concept typically results in low thermal efficiency and high NO_x due to high peak temperatures and air-fuel ratio and knock limitation.
- Compression Ignition (CI): a highly reactive fuel is directly injected into the combustion chamber near the end of the compression stroke, close to TDC. Fuel is auto-ignited in a high temperature environment following compression, hence the name compression ignition. Fuel and air are consumed by a non-premixed flame as opposed to the premixed flame for spark ignition. See Figure 18 left drawing. This concept typically results in high thermal efficiency and high NOx and soot due to favorable air-fuel ratio, high peak temperatures, and unfavorable air-fuel mixing conditions.
- Homogeneous Charge Compression Ignition (HCCI): a perfectly premixed air-fuel mixture is auto-ignited by high temperatures following compression. This leads to multiple auto-ignition points distributed throughout the combustion chamber, leading to volumetric combustion without a clearly defined flame. See Figure 18 right drawing. This concept potentially results in very high thermal efficiency and low NO_x and soot due to favorable air-fuel ratio, short combustion duration, and low peak temperatures. However, it is demonstrated to work in a limited range of the engine operating map.

These three combustion concepts are visualized schematically in Figure 18.
The vertical cross-section of one cylinder is shown with the indication of the differences regarding fuel-air mixing and ignition process. These differences have profound consequences for the required fuel properties, the engine hardware, and the resulting engine performance.

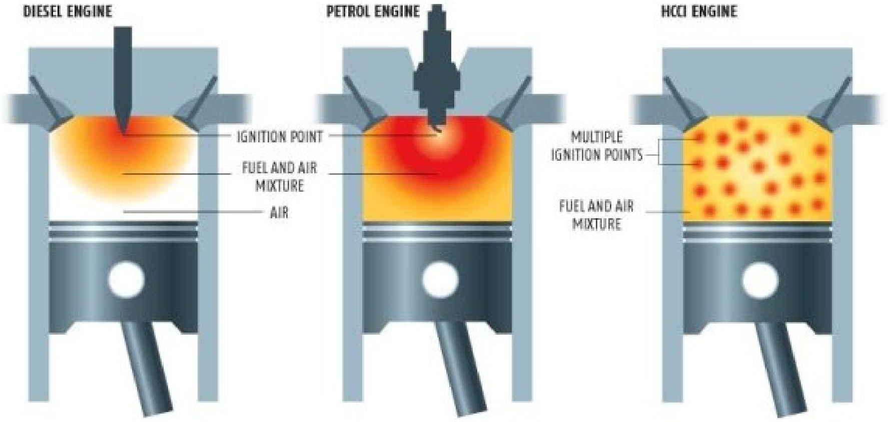

Figure 18: Three main principles of internal combustion: Compression Ignition as in a diesel engine (left), Spark Ignition as in a petrol engine (middle) and homogeneous charge compression ignition (right).

Other combustion concepts can be classified in relation to the main concepts SI, CI, and HCCI. If the three main concepts, that are fundamentally different from each other, are placed at the corner points of a triangle, then, other concepts that are relevant in this report can be positioned relative to the corner points according to their similarity as is shown in Figure 19. The mono-fuel and the dual-fuel concepts are coloured blue and red, respectively. Note that the main combustion concepts are in basis mono-fuel concepts.
The mono-fuel concepts that bear potential for H_2-ICE implementation, and therefore in the scope of this report, are all spark ignition based. The classical SI concept at stoichiometric air-fuel condition ($\lambda=1$) is a possibility for H_2 combustion. Hydrogen can also combust well at lean (air-rich, $\lambda>1$) conditions, which is an attractive alternative for higher efficiency and lower pollutant emissions. A rather more exotic variant is Spark Assisted Compression Ignition (SACI), which has the benefit of controlling the combustion by using a spark, but part of the charge will auto-ignite, leading to volumetric combustion and the typical benefit of lower NO_x emissions as with HCCI.

The dual-fuel concepts that bear potential for H_2-ICE implementation, and therefore in the scope of this report, are all compression ignition based. Conventional dual-fuel can be applied to almost any fuel, including hydrogen. It is basically a regular CI operation using diesel-like fuel injected in the cylinder, however, part of the energy input is realized by premixing another fuel with the air when it enters the engine. When the diesel-like fuel self-ignites, it will co-combust the premixed fuel.
If a high amount of diesel substitution is desired (for instance 95% or higher), the combustion process turns into a so-called micro-pilot concept.
Here, a small amount of diesel injection is sufficient to ignite the other fuel, similar to applying a spark.

The resulting combustion process includes SI-like flame propagation. Finally, the Reactivity Controlled Compression Ignition (RCCI) concept is invented to remedy the main disadvantage of HCCI, the controllability. RCCI provides improved combustion control by reactivity on demand. This is achieved by using a low and a high reactive fuel, mixed in different proportions as fits best to the engines operating conditions.

Experimental research [8],[9],[10] shows that H_2-diesel combustion using only one of the three introduced dual-fuel concepts is not feasible to span the entire engine operating range. Therefore, a flexible combination of the different dual-fuel concepts seem to be needed, which hardware-wise is possible on the same engine platform. At low load, the conditions become too fuel-lean, so substantial amounts of diesel need to be injected to get combustion started and going (like conventional dual-fuel). At mid load, small amounts of diesel become sufficient to run like micro-pilot concept with the benefit that mainly hydrogen is combusted instead of diesel. The mid load range could also be run in RCCI mode to achieve even higher thermal efficiency and lower NO_x.

To prevent knock at higher loads, either less diesel need to be injected and/or the diesel injection need to be retarded with the penalty of lower thermal efficiency.

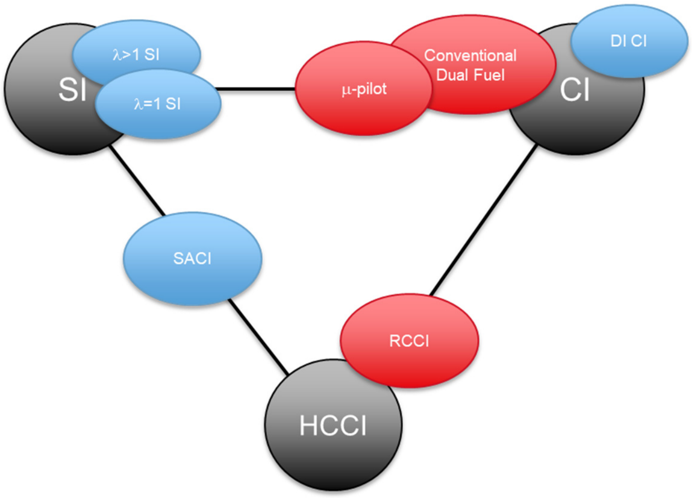

Figure 19: Overview of different combustion modes. Mono-fuel combustion concepts in blue and dual-fuel concepts in red. SI: Spark Ignition, CI: Compression Ignition, HCCI: Homogeneous Charge Compression Ignition, RCCI: Reactivity Controlled Compression Ignition, DI: Direct Injection, SACI: Spark Assisted Compression Ignition

Combustion and engine limits

Gas engines, running on natural gas, traditionally respond slower to transient load than diesel engines (nicely explained and visualised in CIMAC position paper [11]), which is seen as one of the major disadvantages for use in ships. But engine OEMs have improved the transient response of gas engines over the years to a level which is similar to the transient response as their diesel engine versions. Typical improvement measures are port or direct injection and optimized turbocharging. Mono-fuel SI examples can be found from: Rolls Royce/MTU, Caterpillar. Dual-fuel CI examples can be found from: Wartsila, MAN, Niigata.

When these engines are modified to burn hydrogen instead of natural gas, the transient response might become more challenging due to knock and other combustion limits which are different for hydrogen. Combustion limits such as knock and backfiring are discussed in Section 3.4 on operational and safety aspect.

Whenever fuel injection equipment is mentioned in the context of hydrogen fuel, one should be aware that the maturity of such devices is low and need further development. The challenges on this hardware topic relate to the physical properties of hydrogen gas which puts high requirements to sealings and lubrication. For the time being, on research and development H2-ICE platforms, typically (modified) natural gas injectors are applied. This holds true for port injectors as well as low and high pressure direct in-cylinder injectors.

3.3.3 Performance potential of H2-ICE for maritime applications

In this section, the performance potential of the combustion concepts presented in general terms in Section 3.3.2, are discussed in more detail. The focus is specifically towards the use of hydrogen as the (primary) fuel and for maritime size engines. The reference engine is the current state-of-the-art four stroke heavy duty diesel engine.

The chosen performance criteria are related to CO_2 and pollutant emissions and engine operation characteristics:

- Max. TTW CO_2 reduction;
- Brake Thermal Eff.;
- Power Density;
- Max. load;
- Engine-out NO_x;
- NO_x aftertreatment;
- Particles aftertreatment;
- Transient response;
- Risk of backfiring;

Furthermore, comparisons are made on general technical characteristics, costs, and TRL. An overview of all the concepts with their score for each criterium is given in Table 8. This table is the result of expert insights and TNO knowledge and expertise, and largely based on the findings in DKTI project “Vergelijk van verbrandingsconcepten voor waterstofmotoren” [14]. Each criterium in the table is discussed in the remainder of this section. Finally, the main observations are summarized.

Table 8: Performance potential of different combustion concepts for maritime H2-ICE compared to a diesel engine reference.

Combustion concept	**SI λ=1**	**SI λ>1 with EAS**	**SI λ>>1 w/o EAS**	**DI SI λ>>1 w/o EAS**	**SACI**	**Conventional Dual Fuel**	**Micro-Pilot Dual Fuel**	**RCCI diesel-H2**
Mono-fuel / Dual-fuel	mono	mono	mono	mono	mono	dual	dual	dual
Fallback option diesel	no	no	no	no	no	yes	yes	yes
Max. CO2 reduction	100%	100%	100%	100%	100%	40 - 60%	>90%	<60%
Brake Thermal Eff.	↓↓	0/↑	0/↑	0/↑	0	↓/0	0/↑	0/↑
Power Density	↓	↓/0	↓	↓/0	↓	↓/0	↓	↓
Max. load	↓	↓/0	↓	↓/0	↓	↓/0	↓	↓
Engine-out NOx	↑↑	↓	↓↓	↓	↓↓	0	↓↓	↓↓
NOx aftertreatment	TWC	NH3-SCR, H2-SCR	none	none	none	NH3-SCR, HC-SCR, H2-SCR	none	none
Particles aftertreatment	no	no	no	no	no	yes	yes	yes
Transient response	0	↓/0	↓	0	↓	↓/0	0	↓
Costs	↓	↓	↓↓	↑	↓↓	↑	↑	↑
Risk of backfiring	high	moderate	low	none	moderate	moderate	moderate	low
TRL for H2 (NOT in Maritime) in 2021	7	7	5	5	5	7	5	3

Fuelling, fallback option, and TTW CO_2 reduction
All the spark ignition concepts are mono-fuel concepts, which means that the entire energy input to the engine consists of hydrogen fuel only. The compression ignition concepts are dual-fuel concepts, which means that a part of the energy is supplied by hydrogen fuel and the rest by another fuel, typically diesel(-like) fuel. Whereas mono-fuel, hydrogen only, evidently leads to 100% TTW CO_2-reduction compared to the full diesel reference fuel, the dual-fuel options have a maximum CO_2-reduction potential varying from 40% up to higher than 90%. On the other hand, a dual-fuel engine can provide a fallback option to full diesel operation in whatever case it might be needed. Minor amounts of CO_2 emissions can still be caused by carbon containing engine lubricants and the use of AdBlue in a NO_x aftertreatment device (in case that is still required).

Brake thermal efficiency
How much of the fuel energy input is translated into engine output power is called the brake thermal efficiency (BTE). So, BTE is a direct measure for fuel consumption, however, it is inversely related; higher BTE means lower fuel consumption. Generally, the BTE is higher if the engine's compression ratio is higher and the air-fuel ratio (lambda) is higher. Traditionally, spark ignition engines have a much lower BTE than mono-fuel compression ignition engines because the first one has a lower compression ratio (knock limitation) and operates at stoichiometric condition (lambda=1), whereas mono-fuel compression ignition engines have no risk of knock and operate at high air-fuel ratios. When hydrogen is used, the spark ignition lambda=1 concept will show poor BTE for these reasons. Spark ignition at higher lambda (lambda >1 and >>1) bears the potential to close the BTE gap with the reference diesel engine, and even to outperform a little. SACI is a more exotic concept that has no demonstration with full hydrogen so far, but it can be expected to have at least the same thermal efficiency level as the diesel engine reference.

Dual-fuel compression ignition concepts are often based on the reference diesel engine platform and their operation is also at high lambda, so the expected BTE will be close to the reference engine, however at medium load, the micro-pilot and the RCCI concepts have the potential to outperform the reference, due to high flame speed of hydrogen and the premixed nature of the charge, respectively.

Power density and maximum load
Power density is the power (kW or MW) per unit of displacement volume of the engine, which is a measure for how much power a certain size engine can deliver. Hydrogen combustion requires relatively more air than diesel combustion and in a hydrogen-air mixture the hydrogen covers a substantial volume. In other words, it is challenging to feed the engine with sufficient amounts of hydrogen and air at the same time. Therefore, the power density of a hydrogen engine will tend to be lower than the diesel reference. As a consequence, a larger engine room space may be needed to install a hydrogen engine which delivers the same maximum power as a diesel engine. This holds more true for one concept than the other depending on the applied hardware. For instance the spark ignition lambda>1 concept will suffer minor effect since with a turbocharger one can control the combustion process and choose to run with higher or lower lambda. On the contrary, the lambda=1 concept will have a more stringent knock limitation and the very lean alternative lambda>>1 the turbocharger might come short to supply the necessary large amounts of air,

leading to a lower power density. Alternatively, the turbocharging limit might also be reached due to the allowed maximum pressure limit for the engine due to its mechanical strength. A remedy could be the application of direct injection (DI) hydrogen which makes the turbocharger to supply only the air to the cylinders.
In dual-fuel operation, the micro-pilot and RCCI also have knock limitation.
Maximum load is directly related to power density and follows the same reasoning as above.

Engine-out NO_x and NO_x aftertreatment
NO_x formation is strongly related to the (local) air-fuel ratio lambda; generally holds, the higher the lambda, the lower the NO_x formation. The premixed mono-fuel concepts follow this reasoning with the diesel reference somewhere between SI lambda=1 and SI lambda>1. The conventional dual-fuel concept will be close to the diesel reference, whereas micro-pilot and RCCI will produce less NO_x due to low amount of diesel used, and the hydrogen-air mixture being well premixed and at high lambda. So far the NO_x formation, thus the expected engine-out levels have been discussed. To meet low tail-pipe emission limits related to IMO tier III, the SI lambda=1, SI lambda>1, and the conventional dual-fuel concepts need a NO_x aftertreatment system. Proven NO_x aftertreatment technologies that are also possible with H2-ICE are the three-way catalyst (TWC) for SI lambda=1,
the NH_3-SCR for SI lambda>1, and NH3-SCR and HC-SCR for conventional dual-fuel. A less matured aftertreatment technology is the H2-SCR which can also be applied in conjunction with the aforementioned $\lambda>1$ concepts. H2-SCR has the advantage that mono-fuel H2 ICE concepts will remain a mono-fuel concept, thus without the need for an additional substance to inject in the aftertreatment system. The necessity for an aftertreatment system makes the powertrain more complex and expensive.

Particles aftertreatment
When diesel is used in dual-fuel engines, Particulate Matter (PM) or soot will be produced. These particles can be removed using a particle filter (DPF). Unless low-sulphur diesel is being used, the sulphur content of diesel fuel will additionally result in SO_x formation, which can be reduced using SO_x aftertreatment. Furthermore, current IMO emission limits do not impose a limitation on Particle Number (PN) emissions. If in the future a PN limit would be introduced for ships, like already enforced for automotive, then particle filter technology will become unavoidable. Perhaps even for mono-fuel H2-ICE concepts, because of for instance the particles originating from the combustion of engine lubricants.

Transient response
Transient response of an engine is the ability to go from one load point to another within a certain time window. The transient response is good if the engine can go fast through this transition. Two main hardware aspects affect this behaviour the most: the fuel injection and the turbocharger technology. The combustion concepts that operate with fuel injected in the intake manifold (single point injection) are less responsive than fuel injected in each cylinder port (multi point injection), and even better transient response can be expected from direct in-cylinder injection. Furthermore, the combustion concepts that operate at high air-fuel ratio (high lambda) will probably have inferior transient response due to relatively slow adaptation of the airflow through the turbocharger.

Costs

The cost criterium in the table only includes engine and aftertreatment hardware costs. Main cost components are direct injection technology, aftertreatment technology, and all extras needed for the second fuel for dual-fuel concepts.
As a result, the lowest costs are foreseen for the port fuel injected mono-fuel spark ignition concepts that do not require aftertreatment. More details are presented in Section 3.6.

Risk of backfiring

Backfiring refers to the combustion of fresh hydrogen-air mixture inside the engine combustion chamber and/or the intake manifold during the intake stroke (intake valves are open). This is obviously an unwanted process that needs to be prevented at all times. The risk of backfire directly relates to the air to fuel ratio employed; the λ value. Around λ=1 conditions, the fuel air mixture is most reactive and prone to early ignition in the presence of hot spots in the combustion chamber. The higher λ becomes, the lower the reactivity of the mixture, and therefore, the lower the risk of backfire. Although this theoretical relation between λ and risk of backfire is generally applicable to different fuels, the risk of backfire in the case of hydrogen deserves extra attention in practice. On one hand, the reactivity of hydrogen-air mixtures remain high for a wide range of λs, and on the other hand, the local λ variation can give rise to an increased risk of backfire, even for high λ concepts. In case the fuel is directly injected in the cylinder after the intake valves are closed, there is no risk of backfire.

TRL

The technology readiness level (TRL) is used to indicate the maturity of the concepts for H2 application as of today. Here the TRL is based on the readiness level of the concept for H2 regardless of the application domain. For instance some combustion concepts are studied so far on truck engines which are at the small side of the maritime engines spectrum. One can observe that the concepts that supposed to have a higher thermal efficiency and can do without aftertreatment have the lowest TRL. Least mature is RCCI using H_2, which is at the stage of experimental proof of concept (TRL 3). Already more matured are the TRL 5 concepts for which a validation at application relevant conditions is accomplished. The most matured concepts are at TRL 7, the engine prototypes are demonstrated in operational environment.

Main observations from the table

- The use of hydrogen results in lower power density when using port fuel injection (current state of technology). Engine swept volume will increase for diesel-like power densities or the power demand will be realized by using multiple engines in parallel. Both options will result in an increased space claim.
  Means to reduce the loss in power density are:
  - Application of DI injection technology: By directly injecting hydrogen into the combustion chamber no air is replaced by low density hydrogen. This allows higher power output for fixed swept volume.
  - Application of EGR: Exhaust Gas Recirculation is effective in reducing the combustion temperatures. This allows extension of the knock limit. Furthermore, the replacement of air by exhaust gas reduces the mass flow rate through the compressor and hence the required boost pressure.

The increase in NO_x resulting from the reduction in excess-air ratio can be balanced by the reduction in combustion temperatures as a result of EGR.

- The lean burn SI hydrogen engine with air-excess ratios in range of 2.2 – 2.4 has the potential to realize engine-out NO_x emissions compatible to Tier III legislative limits, i.e. without the need for NO_x exhaust gas aftertreatment.
- The Conventional Dual Fuel hydrogen/diesel concept allows close-to-diesel like performance with hydrogen shares up to 60%. Diesel aftertreatment (DPF and SCR) is required to fulfil legislative Tier III requirements.
  Increasing the hydrogen share to above 90% results in the micro-pilot (Otto-like) combustion concept which has the potential to operate without NO_x aftertreatment system.

3.4 Hydrogen ICE operational and safety aspects

In this section an overview will be presented of important aspects related to safe engine operation when using hydrogen as a fuel. Hydrogen is a colourless, odourless, tasteless fuel which has a wide range of flammable concentrations in air and that may ignite more easily than other engine fuels like gasoline or natural gas. On the other hand, hydrogen fuel is characterized by a low density and high diffusivity. This means that hydrogen gas rises quickly and hydrogen fires are typically vertical and highly localized at the source of hydrogen leakage. The fire burns away from the source with less risk of the fire propagating into the source of leakage (e.g. the fuel storage tank). For safe engine operation it is however crucial to eliminate the risk of hydrogen accumulation and mixing with ambient air that may result in a combustible/explosive mixtures. This forms the core aspect of the safety regulations addressed in this section.

Dedicated regulations for hydrogen powered ships are not present. For ships fuelled with hydrogen the IMO IGF-Code [18] provides the requirements regarding safe ship design and operation. The current version of the IMO IGF Code includes regulations to meet the functional requirements for natural gas fuel (CNG/LNG). Regulations for other low-flashpoint fuels, like hydrogen, may be added to this Code as, and when, they are developed by IMO. In the meantime for hydrogen, as a low-flashpoint fuel, compliance with the functional requirements of this Code must be demonstrated through “alternative design”: risk-based design method. In general, safety regulation implications for hydrogen on ship design are therefore similar to the requirements for LNG/CNG fuels.

This section first briefly discusses important safety design implications on ship level. Thereafter, main focus is on the important safety implications on engine level (balance-of-plant).

Ship level

On ship level, the IMO IGF-Code mentions various design regulations.

To mention a few typical design implications:

- The space directly above the energy storage has to be explosion-safe. Alternatively storage tanks need to be located on deck;
- Energy storage tanks must be protected from collision impact;
- Application of double-walled piping for hydrogen fuel;
- Capability of nitrogen blanketing to reduce explosion risk;

- Gas detection needs to be in place in all areas involved with hydrogen;
- Areas around hydrogen exhausts (such as ship exhaust system, venting systems, storage tank outlets) are marked as ATEX zones (spark free).

From the above list it becomes apparent that the use of hydrogen fuel has significant implications for the ship's design. Therefore, a more detailed review of the design implications on ship level is highly recommended as future work.

Balance-of-Plant Engine level

The IMO IGF Code lists dedicated regulations for "internal combustion engines of piston type". Several important aspects from these regulations are highlighted in this section.

The basis of these safety design regulations is formed by following functional requirements:

- the exhaust systems shall be configured to prevent any accumulation of unburnt gaseous fuel;
- Engine components that (are likely to) contain an ignitable hydrogen/air mixture shall be fitted with a suitable pressure relief system or should be designed in such a way that they can withstand the worst case over pressure due to ignited hydrogen leaks
- the explosion venting shall be led away from where personnel may normally be present; and
- all hydrogen consumers shall have a separate exhaust system.

These functional requirements are generic for the application of hydrogen in an internal combustion engine and not dependent on the used engine combustion concept.

For the hydrogen internal combustion engine these functional requirements are translated into dedicated regulations accounting for:

- Occurrence of misfires and securing correct functioning of the ignition system
- Hydrogen slip into the engine's crankcase
- Prevention of gas dispersion into the auxiliary system medium, i.e. oil or cooling water

The regulation regarding misfiring and correct functioning of the ignition system is valid for spark ignited combustion concepts. The other regulations are generic and not dependent on the combustion concept.

Occurrence of misfires and securing correct functioning of the ignition system

Misfiring is the phenomenon that the in-cylinder hydrogen-air mixture is not ignited as intended and exits the combustion chamber as an unburned mixture misfiring has occurred Misfiring can be a significant source of hydrogen leakage to the engine's environment resulting in hazardous situations. . Misfires result in unburnt hydrogen/air mixture entering the exhaust system where it may ignite and damage exhaust components, such as the turbocharger or catalysts. It is a main source of undesired hydrogen accumulation with a high risk of uncontrolled combustion / explosion because of the high chance for the unburned hydrogen exiting the combustion chamber to get into contact with hot surfaces in the exhaust system.

Oxidation of (small concentrations of) unburned hydrogen over platinum containing aftertreatment components may also result in excessive and damaging thermal stresses. Misfiring is often the result of a too lean hydrogen-air mixture. Lowering the excess-air ratio of the fresh charge by throttling reduces the risk of misfiring. A failing ignition system can also be a source of misfiring. One of the regulations in the IMO IGF Code also explicitly states that engines fitted with ignition systems, should have the capability to verify the correct operation of the ignition system on each unit prior to the admission of the hydrogen fuel. Furthermore, a means shall be provided to monitor and detect poor combustion or misfiring. Engine operation can only continue when the fuel supply to the misfiring cylinder is shut-off and provided that the torsional vibrations (resulting from one cylinder not firing) are acceptable. The ignition system and spark plugs in particular are components that should be part of periodic inspection and replacement. Consequently, the spark ignition concepts must be ranked lower than the compression ignition concepts from a durability/robustness point of view.

Hydrogen slip into the crankcase
The combustion chamber of a reciprocating engine is not perfectly closed. In between the moving piston and the combustion chamber wall, a small crevice is present which forms a small passage way between the combustion chamber and the oil-filled crankcase. During operation, a small portion of the in-cylinder charge “leaks” from the combustion chamber to the crankcase, so-called “blow-by”. Especially during the compression stroke the in-cylinder charge contains significant amounts of unburned hydrogen. Accumulation of hydrogen in the crank case as a result of this blow-by may result in a spontaneous undesired combustion potentially damaging engine internal components and/or uncontrolled hydrogen leakage to the ambient. In order to reduce the risk, the crankcase needs to be actively vented. This can be done by applying positive crank-case ventilation preventing the accumulation of a combustible mixture in the crankcase.

Misfiring is explicitly accounted for in the IMO IGF Code. There are, however, other combustion irregularities associated to the hydrogen internal combustion engine that may indirectly impact safe and reliable engine operation:

- Backfiring: backfiring refers to the combustion of fresh hydrogen-air charge during the intake stroke in the engine combustion chamber and/or the intake manifold.
- Pre-ignition: pre-ignition is the phenomenon that auto-ignition occurs during the compression stroke <u>before</u> the combustion is initiated as intended, e.g. by a spark.
- Knock: knock is the phenomenon that uncontrolled auto-ignition occurs <u>after</u> the combustion is initiated as intended, e.g. by a spark.

The occurrence of backfiring may result in excessive damage with the risk of fire when engine components fail. The application of flame retarders in the intake manifold may prevent damage to the system. Furthermore, the risk of backfiring can be reduced by adjustment of the port fuel injection timing relative to the valve timing. This can be accounted for during engine calibration. The application of direct hydrogen injection completely eliminates the risk of backfiring.

Pre-ignition may occur when in-cylinder temperatures locally exceed the ignition temperature of the local air-fuel mixture. An oil droplet, a (soot) particle or a hot surface (combustion chamber wall or spark plug) can act as a local hot spot triggering pre-ignition. In-cylinder temperatures may also exceed the ignition threshold temperature as a result of a too high compression ratio. Specifying the correct compression ratio – with reduced risk of pre-ignition – is a fundamental engine design choice.

Both backfiring and pre-ignition are impacted by local hot spots in the combustion chamber. Oil droplets in the unburned mixture can act as a local hotspot.
All locations where oil can come into contact with fresh air or combustion gasses (e.g. lubrication of turbocharger, oil filter system of crankcase ventilation) must be carefully designed (in agreement with the regulation on hydrogen leakage to the auxiliary system medium). For dual fuel combustion concepts in which hydrogen fuel is combined with a carbon containing fuel, soot particulates present in residual combustion gases can act like a hot spot and trigger undesired ignition. For spark-ignited concepts, the ignition system must be properly designed to prevent an unintended “spark” triggering backfiring or pre-ignition.

The occurrence of severe knock can be damaging to the internal engine components and may result in engine failure followed by hydrogen leakage and fire/explosion hazard. Knock can be prevented by ensuring that local temperatures in the unburned hydrogen-air mixture remain below the auto-ignition temperature before the mixture is actually consumed by the propagating flame. Similar to pre-ignition the selection of the correct compression ratio (piston shape) is essential to reduce the risk of knock. Furthermore, engine calibration should minimize the risk of knock occurrence by specifying proper engine operating conditions.

Dealing with combustion irregularities already starts at the base engine design with a proper selection of the compression ratio and piston shape. In service, unstable combustion can be circumvented by operating at a safe distance from the combustion limits. This typically is accompanied by a reduction in engine performance (load range, power density, emissions, etc.). In some cases, the occurrence of unstable combustion may not be avoided completely and/or operation close to the combustion limit is targeted to achieve targeted performance. This includes also (unexpected) dynamic operation in which in-cylinder conditions become less defined. In this case, robust detection and mitigation (control) of the combustion irregularities is essential. Here, the use of an in-cylinder pressure sensor may be effective, but not desired from cost or durability point of view.

Furthermore, the nature of hydrogen combustion and varying ways in which uncontrolled hydrogen combustion phenomena can manifest themselves pose great challenges to robust detection and mitigation. This aspect forms an important research and development topic for the H2-ICE.

3.5 Safeguarding reliable engine operation: design challenges and maintenance

In this section several properties of hydrogen will be discussed that impact the engine's durability:

- Hydrogen corrosion;
- Poor lubricating properties of hydrogen;
- High exhaust gas water content.

These properties already have to be accounted for in the engine design phase to ensure safe and reliable engine operation. Furthermore, the impact of these properties on engine component durability impact the required effort on maintenance.

<u>Hydrogen corrosion</u>
Hydrogen corrosion is the phenomenon in which the small hydrogen atoms penetrate metals to adversely affect its strength and ductility. Hydrogen corrosion weakens metals internally negatively affecting the engine component durability. It can manifest itself in form of a gradual wear, but can also lead to sudden component failure with little or no prior sign of material weakness. The latter can occur as a result of so-called high temperature hydrogen attack (HTHA). This type of hydrogen corrosion occurs when metal is into contact with high concentrations of hydrogen in combination with high temperatures ($T > \sim 200^oC$) and pressures ($p >> 1$ bar) as for example occur in the engine's combustion chamber. Intake and exhaust valves and valve seats are critical components in this light.

Another form of hydrogen corrosion is hydrogen embrittlement. Hydrogen embrittlement, unlike HTHA, occurs already at low hydrogen concentrations (hydrogen partial pressures) even as low as few parts per million. Furthermore, hydrogen embrittlement can already occur at room temperature when hydrogen exposure for longer periods of time occur. Most vulnerable are high-strength steels, titanium alloys and aluminum alloys. Hydrogen storage and fueling components (rail, ducts, valves, etc.) are subjected to hydrogen embrittlement. For applications where there will be hydrogen absorption while a component is in service, the use of lower strength steels and reduction of residual and applied stress are ways to avoid fracture due to hydrogen embrittlement.

In general, the risk of component failure by hydrogen corrosion can be limited by proper material selection and component design. Periodic inspection and maintenance of engine components is recommended. Here, fuel injection system components and intake/exhaust valves and valve seats are important parts to include. The possibility of hydrogen corrosion makes the hydrogen combustion engine more reliant on frequent service and maintenance than their diesel or natural gas counterparts.

<u>Poor lubricating properties of hydrogen</u>
Hydrogen is a very clean fuel with high purity. As such hydrogen has no lubricating properties. During combustion, no deposition on internal engine components like e.g. the valve seats occur that would prevent metal-to-metal contact.

Without countermeasures, wear of valves and valve seats will be increased with respect to e.g. diesel fuel. Hardened valve seats are recommended together with for example stellite faced valves.

Fuel injection system components such as valves, pump components, injectors, are typically lubricated by the fuel flow. Hydrogen fueling systems however cannot rely on the lubricating properties of hydrogen as this will result in excessive wear due to the poor lubrication quality of hydrogen.

The low lubricating properties of hydrogen make sufficient maintenance and service very important. The effort related to the maintenance and service is expected to increase w.r.t. that of the diesel reference and more in line with natural gas engines.

High exhaust gas water content
Hydrogen ICE exhaust gas contains roughly 3 times as much water than diesel exhaust gas.

The high water content can cause increased wear due to corrosion for components that are in contact with the exhaust gasses. The increased water content may result in high water condensation rates in the EGR cooler.
For hydrogen exhaust gas, condensation will already start at higher temperatures. The condensed water in the EGR flow can result in increased corrosion rates, i.e. wear, of internal engine components, especially in the presence of sulfur. Sulfur may originate from diesel fuel (in dual fuel combustion concepts), lubrication oil or as an impurity in the used hydrogen fuel.

In the exhaust system, condensation of the water on cold catalysts can result in high thermal stresses within the catalyst substrates that may be damaging. This is especially true for zeolite containing catalysts, like many NOx reducing Selective Catalytic Reduction (SCR) catalysts.

The blow-by gasses in the engine crankcase also contain high water concentrations. These gasses are in contact with the lubrication oil and condensed water may form an emulsion with the lubrication oil. As a result the lubricating properties of the oil are reduced with increased risk of engine component wear and failure. Lubrication oil that is compatible with the increased water concentration in the crankcase should therefore be used.

Summarizing overview
The table below presents a summarizing overview of important engine component selection and design considerations that need to be taken into account to ensure safe and reliable engine operation.

Engine component	Safety issue	Risk reducing measure
Intake manifold	Backfiring	• Optimize port fuel hydrogen injection timing relative to intake valve • Direct Injection of hydrogen
Combustion chamber, piston shape	Pre-ignition	• Prevent local hot spots • Lower compression ratio

Engine component	**Safety issue**	**Risk reducing measure**
		• Lower intake charge temperature • Robust Pre-ignition control • Use ash-less oil to prevent deposits formation (hot spots) in the combustion chamber
Combustion chamber, piston shape	Knock	• Lower compression ratio • Optimize combustion parameters (EGR, turbulence, charge temperature, etc.) • Robust knock control
Exhaust system, turbine, catalysts	Misfiring	• Intake throttling • Robust misfire control
Crankcase	Combustion in crankcase resulting from accumulation of hydrogen containing blow-by gasses	• Positive crankcase ventilation
Spark plug	Backfiring, pre-ignition, misfiring	• Use cold rated spark plugs • Do not use platinum electrodes. • Properly ground the ignition system • Avoid induction ignition in an adjacent cable. Here a coil-on-plug system can be used. • Optimize the spark plug air gap.
Valves and valve seats	High Temperature Hydrogen Attack	• Use cooled exhaust valves/additional cooling passages. • Use multi-valve engine heads to lower the exhaust valve temperature. • Application of variable valve timing can also help to decrease residual gas temperatures.
Valve seats	High wear due to poor lubrication	• Use suitable valve seat materials.
Lubricating oil	Oil dilution by water	• Positive crankcase ventilation • Use lubrication oil that is compatible with increased water concentration in the crankcase should be used.
Lubricating oil	Pre-ignition	• Use ashless oil to prevent deposits formation (hot spots) in the combustion chamber
Aftertreatment system components	High thermal loading / stress due to H2 oxidation and water adsorption on catalyst	• Limit use of platinum containing washcoats • Optimize use of zeolites in SCR catalysts

3.6 Cost indication – Relative cost based on required subtechnologies

Each hydrogen combustion concept requires its specific hardware that results in a cost associated with the engine in question. Here, the engines are compared based on the required costly sub-technologies, such as fuel injection equipment, aftertreatment system, and turbocharger. This is done relative to a diesel engine reference. Table 9 shows an overview of the required sub-technologies with the combustion concepts listed in the first column and the cost components in the first row.

The CAPEX of a medium speed maritime engine running on diesel is about 350 €/kW and (SCR) aftertreatment for ships is about 236 €/kW. A medium speed maritime engine running on an alternative fuel such as hydrogen increases the CAPEX to 462 €/kW, whereas the SCR aftertreatment system cost will stay roughly unchanged. To put these into perspective of the total engine and bunker system costs, for the ship types defined in Chapter 2, the engine is responsible for 13% up to 50% of the total. These figures have been used in Chapter 2 and listed among others in Appendix A.

Some observations based on these cost values and Table 9 are as follows:
- The hydrogen ICE currently has a higher level of required technology costs compared to the diesel engine.
- The engine cost increase due to the switch to hydrogen is lower than the cost of an aftertreatment system.
- The need for aftertreatment technology is a key factor for the required costs. Hydrogen combustion concepts that do not need aftertreatment technology are expected to have lower costs than the current diesel engine.
- All spark ignition technologies have lower costs, even the ones with an aftertreatment system, since the required EAS has lower costs than a diesel aftertreatment system.
- Hydrogen Direct Injection (DI) technology may be used to increase the power density, and is an expensive sub-technology. However, low pressure DI technology is more expensive than manifold injection technology. High pressure DI technology is even more expensive than the low pressure DI alternative.

Table 9: List of essential sub-technology hardware of the different H2 combustion concepts compared to a diesel engine reference.

	HP FIE	MPI/SPI	Spark plug	EAS	EGR	Turbocharger	LP H2 DI	HP H2 DI	VVA
Diesel reference	√			√	√	√			
SI $\lambda=1$		√	√	√	√	√			
SI $\lambda>1$ with EAS		√	√	√	√	√			
SI $\lambda>>1$ w/o EAS		√	√		√	√			
DI SI $\lambda>>1$ w/o EAS			√		√	√	√		
SACI		√	√		√	√			
Conventional Dual-Fuel	√	√		√	√	√			
Micro-Pilot Dual-Fuel	√	√		√	√	√			
RCCI diesel-H2	√	√			√	√			√

3.7 Technical Readiness Levels and development timelines

In the following paragraphs, different development timelines will be sketched for the combustion concepts.

The timelines are quantified by defining the technical readiness level of the different concepts. The reference and starting point is a current diesel engine platform.

3.7.1 *Mono-fuel spark ignition (SI) concepts*

Figure 20 shows the TRL level of the mono-fuel hydrogen SI ICE concepts. Two feasible SI concepts have been identified in this study: the stoichiometric SI engine with TWC and the lean burn SI engine. The stoichiometric SI engine with proven TWC aftertreatment technology is at a relatively high TRL of 6-7. Base technology is available and proven. Prototypes demonstrating the concept in a relevant environment are in development, but mostly limited to stationary power generation. For the lean burn SI engine a system without aftertreatment is ideally targeted as a low-cost solution. As an intermediate step an engine with aftertreatment can be targeted. The use of aftertreatment provides more relaxed requirements regarding the required excess air ratio to meet the targeted engine-out NOx level. Selective Catalytic reduction with use of NH_3 (from AdBlue®) can be used to further reduce the engine-out NOx to below the legislative levels. This requires an additional AdBlue storage tank. The lean burn SI engine without aftertreatment requires more development and is currently at a TRL of 5-6.
It has to be noted that also SCR with use of hydrogen (H_2-SCR) might be used to relax the constraints on engine-out NOx level, especially in transient operation. Because this aftertreatment technology is not mature, this lean burn concept with H_2-SCR is also considered to be on TRL 5-6. The Spark Assisted Compression Ignition (SACI) engine is in production by Mazda with use of gasoline fuel. Of the CI concepts it is the technology with the highest TRL although the feasibility of the transition of the concept from gasoline to hydrogen still has to be demonstrated.

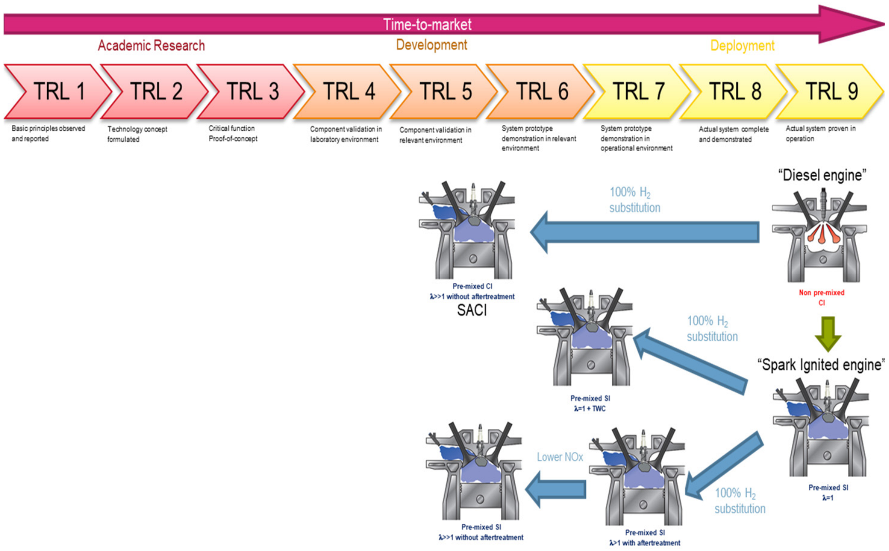

Figure 20: Overview of Technical Readiness Level (TRL) of the identified mono fuel SI hydrogen ICE concepts.

3.7.2 *Dual-fuel compression ignition (CI) concepts*

For the dual-fuel concepts the TRL is mostly dependent on the hydrogen share as shown in Figure 21.

Substitution of max. 40%- 60% of the diesel fuel by hydrogen (on energy basis) is relatively straightforward and can be considered as a minimum change solution using the current diesel platform as a reference (see also Chapter 4). Increasing the hydrogen share to levels above 90% results in the concept of “micro pilot combustion” also referred to as “liquid spark”.

The Reactivity Controlled Compression Ignition (RCCI) concept has already been investigated quite extensively in the Natural Gas/Diesel fuel combination. The concept shows good potential for high efficiency and low NOx emissions. The reduction of engine-out methane is an ongoing research topic. Substitution of part of the methane with hydrogen is a means to reduce methane slip emissions while (at least) maintaining the level of efficiency and low engine-out NOx emissions. Hydrogen substitution ratios (energy based) are relatively low and in the order of max. 15%. Proof-of-concepts are available in research laboratory, mainly using single-cylinder research setups. Significant research and development is required to increase the H2 share and current TRL is low: TRL 3 – 4.

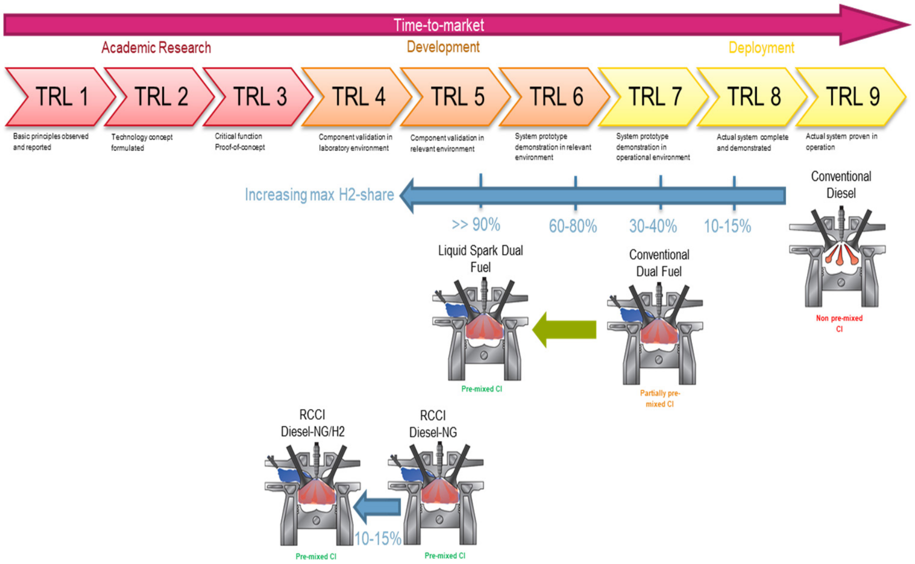

Figure 21: Overview of Technical Readiness Level (TRL) of the identified dual fuel CI hydrogen ICE concepts.

3.8 Hydrogen availability

Hydrogen can be produced from various feedstock routes. Currently, hydrogen is mainly produced via Steam Methane Reforming (SMR) using gas as a basis. The total annual production of hydrogen in Europe is in the range of 9.8 Mt. Main consumption of hydrogen in Europe, consists in the use of oil refineries (30%), ammonia production (50%), methanol production (5%) and other applications (approx. 13%) (Kakoulaki, 2021). Production in the Netherlands is around 0.9 Mt, which uses 4 billion m^3 gas as input and leads to 12.5 Mt CO_2-emissions. As mentioned in Chapter 2, an important possible feedstock route for hydrogen is via electrolysis of renewable energy. Several initiatives are currently being developed as initial production locations. The energy efficiency of hydrogen production by PEM electrolysis can be assumed to be 64%. The production potential of e-hydrogen largely depends on the availability of electricity from renewable sources.

In 2019 the Netherlands produced 21,8 million MWh (78,5 PJ) of electricity from renewable energy sources from wind, biomass and solar energy, according to CBS. The Netherlands has a large potential for production of electricity from offshore wind, compared to other countries. The total potential for the Dutch continental shelf is estimated at 900 PJ per year. By combining technical developments (increasing the energy density of windmills in MW/km through better design of rotor blades and higher towers) and use of a larger share of the Dutch continental shelf the potential of offshore wind may grow to more than 2000 PJ per year. A likely scenario however is that renewable hydrogen will be produced at specific regions in the world and imported to the Netherlands [**3**].

The hydrogen internal combustion engine has a high tolerance towards hydrogen purity. The degree of purity specifies the quality of hydrogen and is represented by the number of “nines”. For example, the indication 4.0 means 99.99% pure hydrogen. Usual industrial hydrogen grades are 3.0 or 4.0. Fuel cells require hydrogen of purity 5.0. Here, especially the presence of contaminants of CO and sulphur compounds have to be limited to an absolute minimum, because these poison the fuel cell catalyst causing degradation of fuel cell performance. The hydrogen internal combustion engine shows relatively high tolerance towards hydrogen quality. Hydrogen with purity 3.0 (99.9% purity) can be safely used. As such, the hydrogen ICE can use the same quality as used in industry, which is currently mainly produced via SMR.

3.9 Conclusions

H2-ICE research and engine concepts

- A clear renewed ramp-up of developments in the field of H2-ICE for maritime as well as for other sectors can be observed from 2020 onwards.
  - The main research and development activity regarding H2-ICE for maritime applications is located in Europe and to a lesser extent in Japan.
  - Globally, many of the recognised maritime engine manufacturers are active in H2-ICE development highlighting that a significant impulse exists to bring H2-ICE developments towards market products.
  - These OEMs tend to collaborate with research institutes and universities which often means that research projects are run under subsidized consortia.
  - Developments on both dual fuel H2-ICE concepts as well as mono fuel concepts have been identified. The chosen development direction for the different engine OEMs/suppliers is most often in line with their current expertise. Engine OEMs/suppliers that currently have gas engines in their portfolio have a preference for mono-fuel spark ignited hydrogen engine concepts. Contrarily, engine OEMs who build diesel engines as their prime product, tend to take the route of dual-fuel hydrogen compression ignition combustion.
- The presented H2-ICE concepts are all feasible for application as ICE for maritime applications. However, not all concepts can currently be applied over the full engine operating envelope, therefore, a combination of concepts – using the same hardware – may be required to cover the complete targeted operating range.
  - Currently, the conventional dual fuel combustion concept has the highest Technical Readiness Level for maritime application.

  On basis of a “minimum change philosophy” moderate CO_2 reductions in the order of 40 – 60% are viable without compromising engine-out pollutant emissions. Standard diesel aftertreatment is applicable. The option to fall back to conventional diesel combustion is considered as a key advantage of this concept for maritime application. Development of the micro-pilot combustion concept (currently at a TRL of ~5) can enable further CO_2 reductions in excess of 90% over (part of) the engine operating window. Further development and in-use demonstration of these dual fuel concepts with increasing hydrogen shares is highly recommended.
  - Mono fuel H2-ICE concepts are feasible from technology point-of-view. They have the potential to realize a climate neutral solution. The potential to eliminate costly deNO$_x$ aftertreatment systems is highest for these concepts. The mono fuel DI SI concept has been identified as future concept with highest potential regarding efficiency, emissions and power density. Lack of a diesel fall back is considered as a main disadvantage of this concept for application as a direct drive.

Engine performance and costs

- When hydrogen is injected into the engine’s intake manifold (port fuel injection) the maximal achievable power density is reduced. Application of direct injection hydrogen technology can eliminate this loss and has been identified as an important enabling technology that needs development.
- From performance point-of-view, transient response and load range are important. Development of advanced charging technologies and direct injection of hydrogen technology are enablers for increasing H2-ICE performance.
  - The use of hydrogen as a fuel for internal combustion engines does not necessarily result in a loss of transient response with respect to the base diesel engine. For similar transient response, the engine’s charging system may need to be adjusted. This may be more challenging for the engine concepts applying port fuel injection in combination with lean burn operation. Here, the application of direct hydrogen injection is of great added value.
  - Current feasibility study compares the different hydrogen combustion concepts without explicitly considering the dynamics (i.e. transient performance requirements) of the different mission profiles. This dynamic data was currently not available. In order to examine the feasibility of a combustion concept for a dedicated application regarding transient response, data regarding the anticipated mission profiles quantifying the targeted engine dynamics need to become available and used as input.
- The selected engine concept mainly affects CaPex through the necessity of aftertreatment technology. Other component costs are considered to be marginal w.r.t. base engine costs and do not differ greatly between the different engine concepts. Aftertreatment systems on the other hand do impact CAPEX greatly. For implementation of the hydrogen internal combustion engine, the costs associated with hydrogen storage are expected to be dominant, similar to the application of hydrogen fuel cell technology.

Safety and reliability

- Reliable and safe H2-ICE operation already needs to be addressed in the engine design phase.

The interaction of hydrogen with metals requires proper material selection. Furthermore, hydrogen has poor lubricating properties which impacts key engine components like valve and valves seat and the fuel injection system.

- Dedicated safety regulations for H2-ICE are not present at the moment. Currently, requirements listed in IMO IGF Code for gas engines (CNG/LNG) and low-flashpoint fuels need to be considered. Ship design implications for hydrogen are therefore of similar complexity as the regulations for CNG/LNG ships:
  - Regulations on ship level provide ship design implications including, amongst others, the design and integration of hydrogen storage systems, ventilation systems, gas detection systems and areas marked as ATEX zones. These requirements may be challenging to comply to when a modification of an existing ship is targeted.
  - Dedicated regulations on engine level mainly focus on preventing accumulation of hydrogen in exhaust system, auxiliary system media (oil, coolant water) or engine crankcase that may result in combustible/explosive hydrogen/air mixture. This can be accounted for during engine design by use of dedicated hardware like e.g. positive crank-case ventilation. During engine operation a monitoring should be in place to detect the occurrence of poor combustion or misfires.
- Hydrogen can be produced from various feedstock routes. The hydrogen internal combustion engine shows relatively high tolerance towards hydrogen quality. Hydrogen with purity 3.0 (99.9% purity) can be safely used. As such, the hydrogen ICE is not very selective regarding the hydrogen feedstock source.

4 Validation tests for H_2 in Internal Combustion Motors – Tests

This chapter describes a diesel-hydrogen dual fuel concept that was built and tested within TNO Powertrain Test Centre in order to analyse the potential for application of this technology in the maritime sector. A naturally aspirated (NA), direct injection (DI) diesel base engine was modified to dual fuel hydrogen, following a minimum-change philosophy, thus demonstrating a low-cost and relatively straightforward solution of an existing diesel engine. The applied hydrogen combustion concept is the conventional dual fuel hydrogen-diesel concept as is also discussed in Chapter 3.

The modification of diesel engine to a hydrogen dual fuel engine has a significant TTW CO_2-reduction potential since this reduction will be approximately proportional to the hydrogen blend ratio (on energy basis). A second advantage is that the fall back to conventional diesel operation may still be available for robustness and availability reasons.

The technical challenges with respect to engine performance are the power density that can be achieved with a significant blend ratio and the pollutant emission levels that can be achieved in dual fuel mode.

4.1 Test setup

4.1.1 Test platform

The test platform is a NA four-cylinder Volkswagen DI diesel engine. Specifications for this engine can be found in Table 10. This engine was chosen for its simplicity and robust design that lies in line with maritime engines. The engine has a conventional distribution pump and has no EGR or inlet pressurization. The engine size was chosen on the basis of availability of hydrogen fuel injection equipment. The fuel injection equipment was based on a fuel injection system from PRINS Alternative Fuel Systems, using four CNG injectors.

Table 10: Engine specifications.

Engine code	ASY	-
Engine configuration	In-line	-
Number of cylinders	4	-
Compression ratio	1:19.5	-
Injection system	Bosch distribution injection pump	-
Number of valves	8	-
Engine displacement	1896	cm³
Bore x stroke	79.5 x 95.5	mm
Maximum torque output	125	Nm
Maximum power output Automotive rating	47	kW

Diesel is directly injected into the combustion chamber while hydrogen is injected into the intake manifold for each cylinder individually.

The hydrogen gas is supplied at a pressure of 30-200 Bars, then reduced to approximately 2.5 Bars before being injected near the intake ports via a PRINS sequential injection system.

Diesel injection timing was adjusted by manipulating the coolant temperature sensor's resistance. Using a needle lift sensor on cylinder 3, diesel injection was monitored.

The intake manifold was customized to facilitate a pressure relief valve and flame retarder to mitigate any backfire effects. In order to prevent hydrogen gas building up in the crankcase ventilation system, active gas extraction was implemented. Furthermore, a throttle valve was mounted in order to control manifold air flow.
In a later stadium a cooled EGR system was fitted.

4.1.2 *Test setup*

The tests have been performed at TNO Powertrains Test Centre in Helmond in test cell P6. Figure 22 shows the installation of the engine in the test cell.

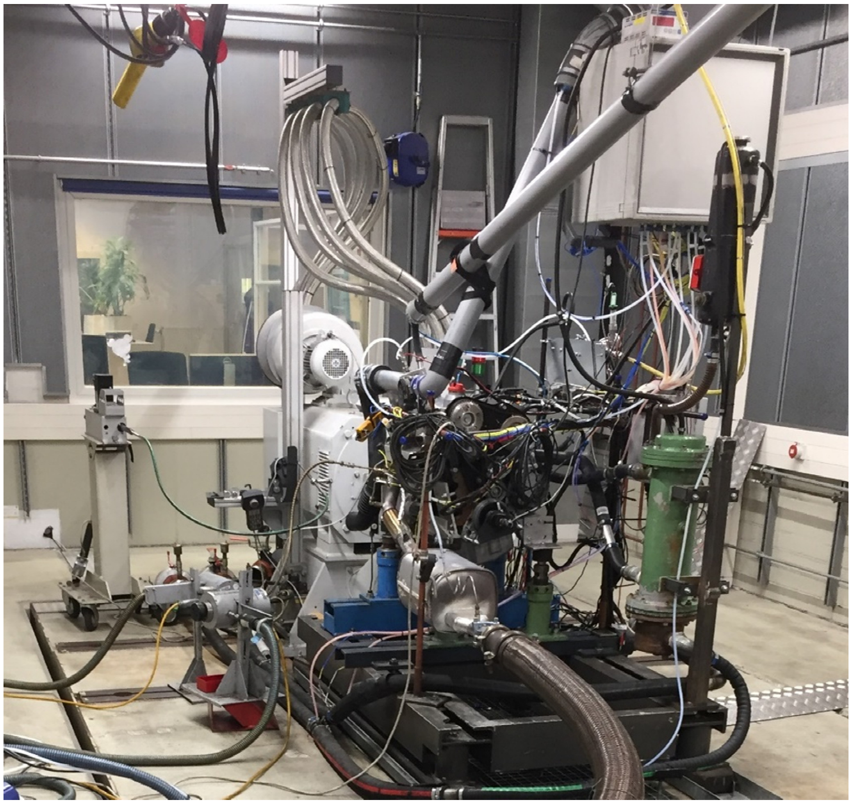

Figure 22: Installation in TNO PTC, cell P6.

The setup is schematically illustrated in Figure 23. A four-quadrant transient dynamometer was used as an external load for the engine. The test cell allows conditioning of inlet air temperature and humidity.

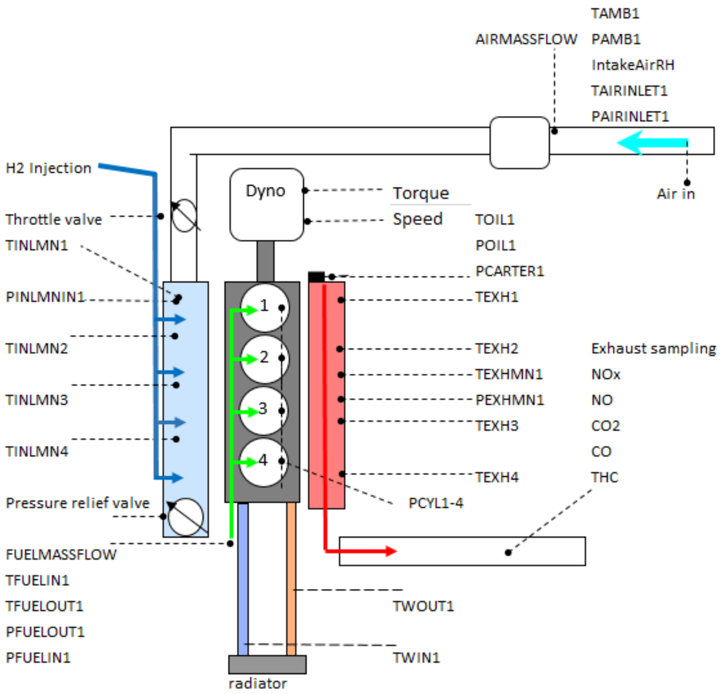

Figure 23: Test setup and measurement locations.

For testing EN590 diesel and Hydrogen 3.0 (purity of 99.9%) were used. Note that the level of hydrogen purity is significantly lower than the purity level required for fuel cells (see also section 3.7.2).

Measurement equipment
Exhaust emission concentration for NO, NO_X, CO_2, CO and total hydrocarbon emissions (THC) were measured as well as Filter Smoke Number (FSN) using a Horiba MEXA one and AVL 415 respectively.

Cylinder pressure was measured for all cylinders and monitored using a AVL 617 crank angle measurement system. Furthermore, temperatures and pressures were measured for both gas and fluid flows in the engine as illustrated in Figure 23.

4.1.3 *Test program*

Figure 24 illustrates the measurement program in a flow chart.

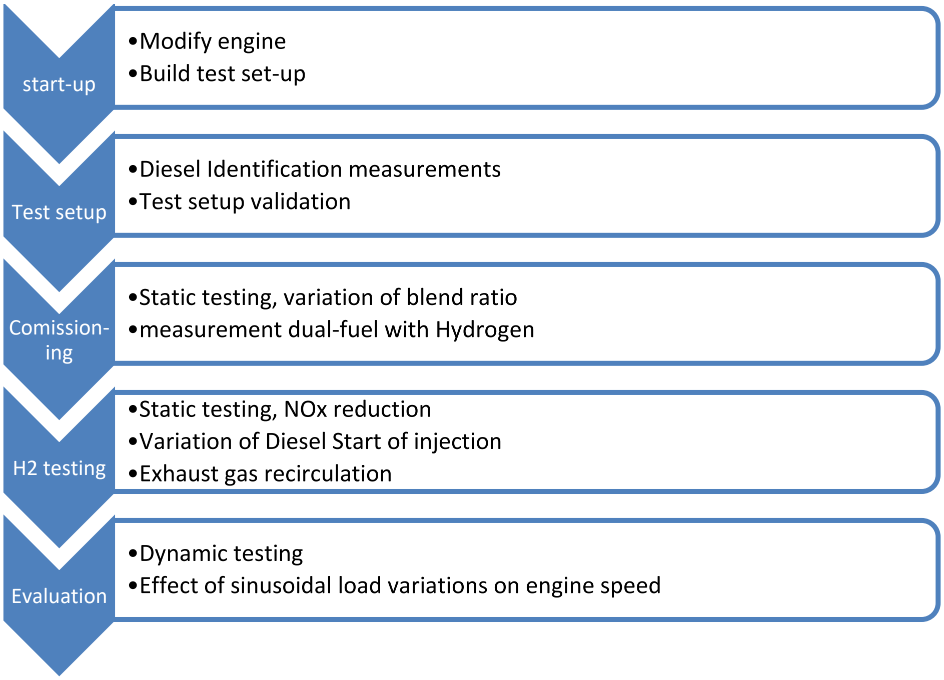

Figure 24: Measurement program.

4.2 Results

In this chapter, an overview is presented of the dual fuel diesel-hydrogen engine measurements. First, the steady state measurements are described. These measurements target the exploration of the available operating range with respect to hydrogen share and load range. For this purpose, several engine parameters have been evaluated. The second part of this chapter describes the dynamic measurements in which a disturbance is added to the engine brake torque.

4.2.1 Increasing the hydrogen share: Blend Ratio variation

The hydrogen blend ratio (BR) describes the ratio between the lower heating value of the hydrogen's (LHV) energy share and that of the combined fuel energy flow and is defined below:

$$BR = \frac{\dot{m}h2 * LHV_{H2}}{\dot{\mathrm{m}}_{\mathrm{Diesel}} * LHV_{diesel} + \dot{m}h2 * LHV_{H2}} * 100\%$$

Various tests were done to determine the effect of the blend ratio on the engine's combustion. The engine operating point is described in the table below.

Table 11: Engine operating point.

Engine speed	2200 rpm
BMEP	4.3 Bar
Diesel inj. timing	3.5°BTDC
Lambda	2.4

The blend ratio was increased by increasing hydrogen fuelling and reducing diesel fuelling, while keeping the engine’s load constant. In this test, a blend ratio of 85% (energy based as indicated by the equation above) was achieved before the combustion’s cycle to cycle variation became instable. The ignition timing of the diesel fuel was not adjusted.

The goal of increasing the hydrogen share is to reduce TTW CO_2-emissions. Figure 25 shows the TTW CO_2 emissions for varying Blend Ratio. In the figure, the values for the diesel reference are indicated by the red line. As Blend ratio is increased, TTW CO_2 emissions drop drastically. However, a trade-off is present with the engine-out NOx emissions.

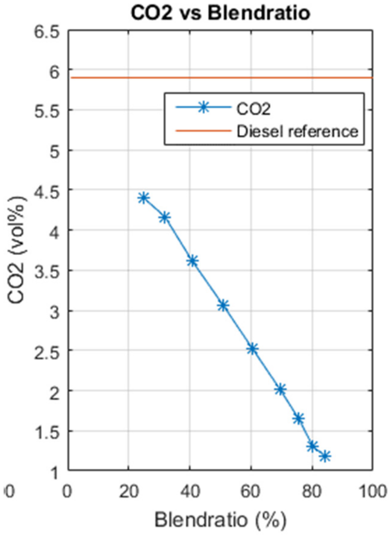

Figure 25: Engine-out NO_x and CO_2 emissions as a function of blend ratio. Red lines indicate the diesel reference.

Hydrogen is known for its high combustion velocity. The energy stored in the hydrogen fuel is released quickly which results in a rapid increase in in-cylinder pressure and high maximum in-cylinder pressure. Both the pressure rise rate as well as the maximum in-cylinder pressure are constrained by mechanical engine component limitations. This limits the maximum achievable hydrogen share. In this case, the maximum hydrogen share was limited to a blend ratio of 50% in order to achieve 75% of the diesel reference power in Automotive rating of 47 kW.

During the blend ratio tests, the diesel ignition timing was kept at is original diesel setting. With this setting, the NO_x emissions rise with increasing blend ratio and NO_x emissions are exceeding the diesel reference. In section 4.2.2 and 4.2.3 it will be shown how the engine-out NO_x emissions can be reduced to a level similar to the base diesel engine by changing diesel injection timing and EGR respectively.

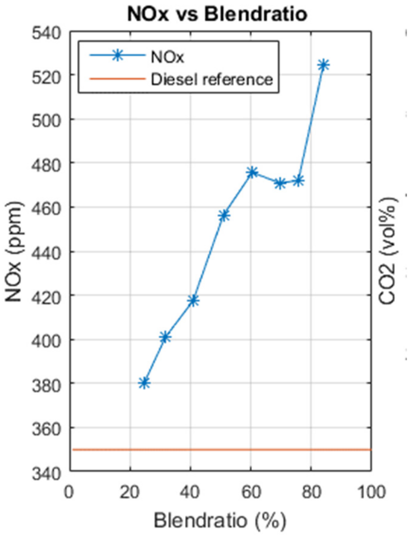

Figure 26: NOx vs. blend ratio with original diesel injection timing.

4.2.2 *NO_x reduction: DI Diesel NO_x reduction: DI Diesel timing sweeps*

In this section, the timing of the diesel injection is evaluated as a means to reduce NO_x emissions. Diesel injection timing has a direct influence on peak cylinder pressure and compression end temperature. In a diesel timing sweep, SOI (start of injection) was varied at a constant operating point. Table 12 shows the engine's operating conditions.

Table 12: Engine operating conditions for Diesel Injection timing variation.

Engine speed	2200 rpm
BMEP	4.3 Bar
Blend ratio	50%
Lambda	2.4
DI diesel injection timing	[-1 -2 -3 -4 -5 -6 -7 -8] ca aTDC

By delaying the SOI for diesel injection, NO_x emissions can be greatly reduced without significant decrease of brake thermal efficiency of the engine. Figure 27 shows the NO_x emissions and engine torque for a SOI range of 8 to 1 °BTDC, bringing down engine out NO_x emissions to diesel-like numbers without compromising torque output significantly (Figure 27 bottom plot). Further delay of Diesel injection was not possible in this test due to the limitations of the Volkswagen Engine Control Unit (ECU).

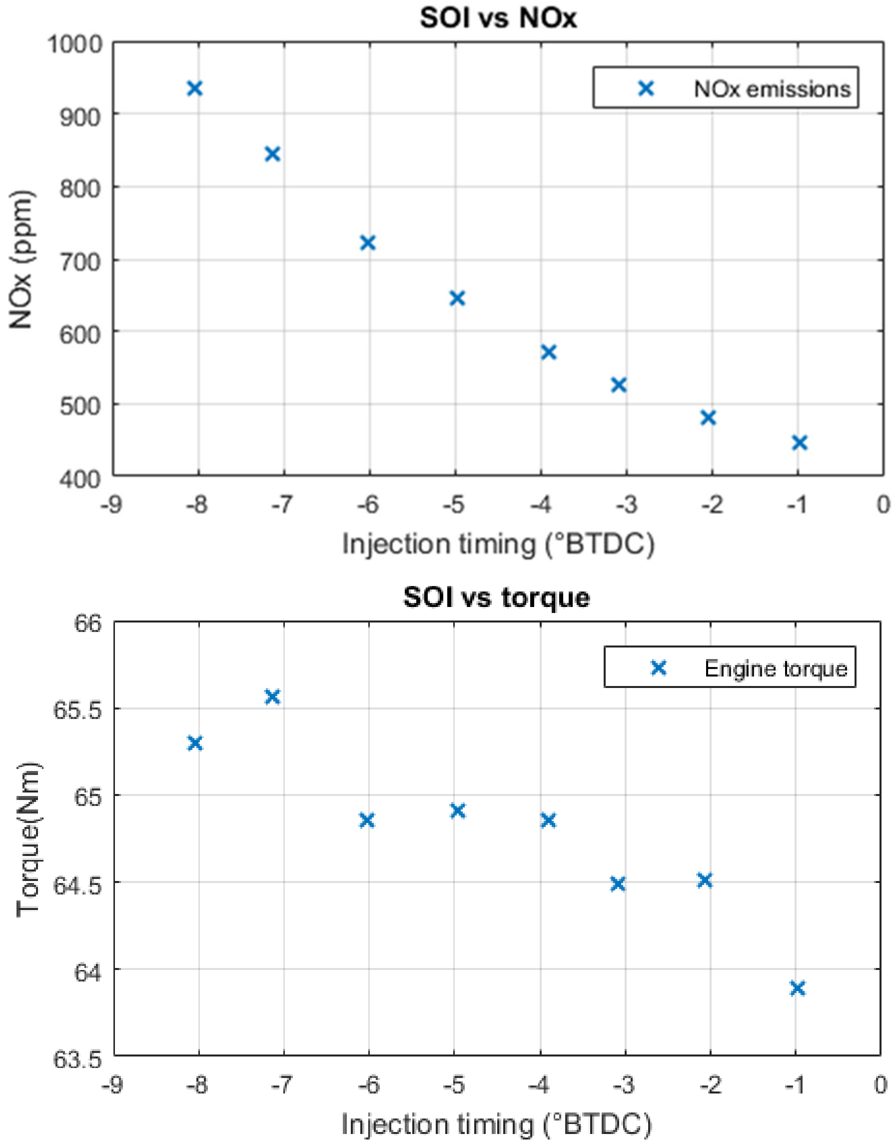

Figure 27: Engine-out NO_x emissions as a function of Diesel injection timing (top) and Brake Torque as a function of Diesel injection timing (bottom).

4.2.3 *NO_x reduction: Exhaust gas recirculation*

A second NO_x reduction measure is the application of Exhaust Gas Recirculation (EGR). In order to mitigate the increase in NO_x formation as result of hydrogen blending, the engine was retrofitted with a cooled EGR system. Figure 28 shows the system mounted on the engine. CO_2 concentration was measured at the inlet manifold to determine the EGR ratio.

Table 13: Engine operating conditions

Engine speed	2200 rpm
BMEP	4.3 Bar
Diesel inj. timing	8°BTDC
Blend Ratio	50%
EGR percentage	Varied 0 to ~30 %

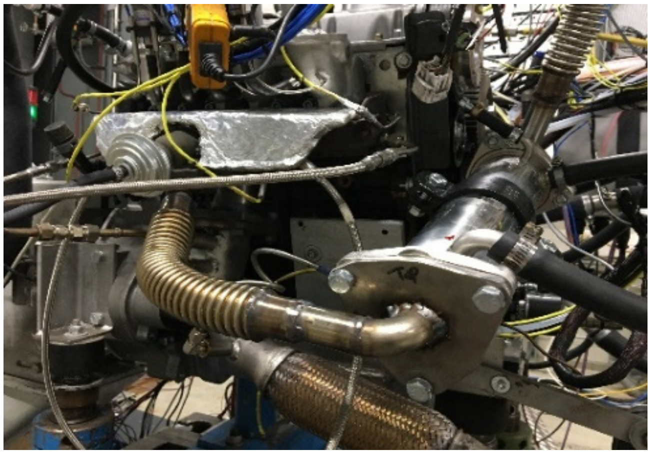

Figure 28: Cooled EGR system added to the base engine.

Using the EGR valve and throttle valve, EGR ratio was varied. Table 13 shows the engine's operating conditions.

Figure 29 shows the trade-off between smoke, NOx and EGR (CO_2 emission). As becomes clear from the figure, it proved feasible to reduce engine-out NO_x emissions to diesel-like values before exceeding the smoke levels (as measure for particulate emissions) from the diesel reference measurement. The figure shows that the NO_x emission is strongly reduced proportional to the EGR percentage. At about 19% EGR, the NO_x level is very similar as with 100% diesel operation. Up to about 19% EGR also has little impact on the particulate emissions. Above 19% PM emissions rises significantly.

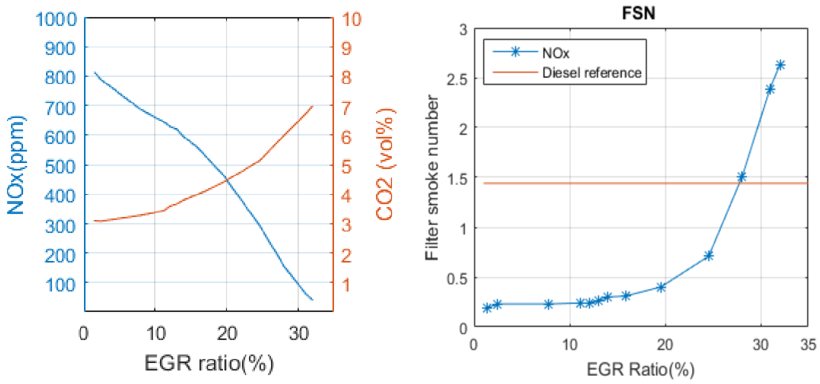

Figure 29: NO_x-EGR trade-off (left) and Filter Smoke Number as a function of EGR percentage (right). Operating point: 2200 rpm, 4,3 bar BMEP en 50% H2 blend.

As a summary, Table 14 shows a comparison between emission results for diesel, dual fuel and dual fuel + EGR operation.

Table 14: Results for various operations at the same load point: 2200 rpm, 4.3 bar BMEP

	Diesel	**Dual Fuel** original diesel injection timing	**Dual Fuel** Optimised diesel injection timing	**Dual Fuel +EGR**
NOx (g/kWh)	**4.60**	**12.54**	**5.90**	**4.74**
CO_2 (TTW g/kWh)	**750**	**369**	**381**	**372**
Efficiency (%)	**35.4**	**34.1**	**34.0**	**34.5**
EGR ratio (%)	**0.0**	**0.0**	**0.0**	**19.1**

These results show that a TTW CO_2-reduction of >45% can be realized without compromising engine-out NO_x emissions with respect to the diesel reference when ~20% of EGR is used and an H_2 substitution ratio of 50%.

The IMO Tier 3 regulation states a NO_x emissions limit of 3.4 g/kWh for engines that run slower than 130 rpm and up to 1.96 g/kWh for engines that run at speeds over 2000 rpm. Because engine-out NOx emissions are the same as the base diesel engine a similar NO_x reduction from exhaust gas aftertreatment would be required.

The results from section 4.2.2 respectively 4.2.3 show that changing diesel injection timing and EGR are effective measures for NO_x reduction. Engine-out NO_x emissions can be reduced to similar levels as the base diesel engine while at the same time realizing CO_2 reductions in excess of 45%. It has to be noted that the presented results show the impact of the individual changes of diesel injection timing and EGR. It can be expected that further NO_x reduction potential and CO_2 reduction potential is available through a combination of both timing and EGR. This optimization is recommended as future work.

4.2.4 *Transient response*

After the assessment of the diesel/H_2 concept as described in Table 14, a safe operating condition was determined in which some transient engine response was determined. For this study, MARIN provided several load profiles. These load profiles have been translated to viable load conditions for the test engine platform. The load profiles provided are sinusoidal variations around a stationary operating point.

The torque variations are derived from tests performed with several ship models in the basins of MARIN. Tests on sailing in waves, manoeuvring and propeller ventilation were investigated. From the time series of the propeller torque measured during the tests a selection is taken to determine torque variation figures: (sine ware) amplitude and frequency. The found data are scaled down to the scale of the engine under test. As the scaling factor, what will be applied for the various situations, is not fixed depending on the intended drive train modelling and ship scaling, the scaling is performed over a range of values. Froude scaling is applied. This is for torque [Nm]: λ^4, for frequency [Hz]: $\lambda^{-0.5}$. In Figure 30 the individual curves for torque sine wave amplitude against frequency of these sine waves are shown in one chart. Each coloured line in the chart is one derived set of torque variation figures (amplitude and frequency) scaled down over the relevant scaling factor range. As propeller torque variations requirement, the envelope of the curves is taken (black dashed line): a sine wave shape torque with an amplitude Ma = 200 Nm (~30% of nominal torque) under 1.2 Hz. Above 1.2 Hz a sine wave shape torque with an amplitude Ma = 200 / (f / 1.2)^{8}.

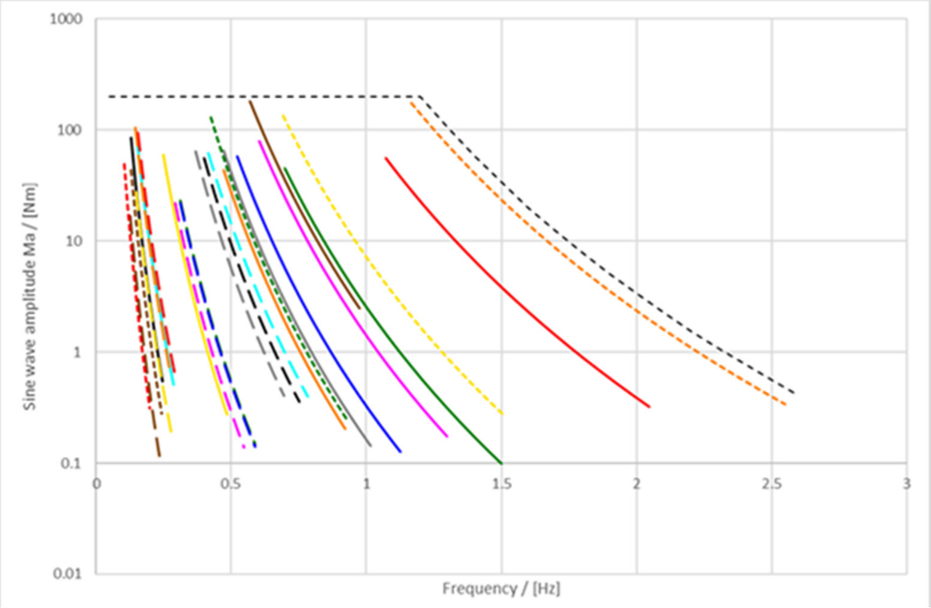

Figure 30: Torque sine wave amplitude against frequency of these sine waves

The envelope described by the black dashed line in the figure is used to create the test points for a study of the transient response of the engine. The testing points are based on a grid created between 0.25-2 Hz and 0-30% rated torque which are the limits for the envelope described above.

These torque variations as stated by MARIN are variations on the propeller and not on the fly wheel of the combustion engine. The propeller – shaft – gearbox will affect as a low pass filter towards the torque variations at the fly wheel of the engine. MARIN however lacks information at this moment to incorporate that effect into the disturbances, this will be addressed in research in 2021.

For the given application, load variations of 10, 20 and 30% are considered at a frequency of 0.25Hz, 0.5Hz, 1Hz, 1.5Hz and 2Hz.
During these tests, the engine control unit was modified such that the pedal map was modified to a speed-governor characteristic (alike for a ship engine that operates along a propeller curve). The testbed was switched to an operating mode where the engine dyno subjects the engine to a torque variation whereas the pedal/governor is used to keep the speed constant. This was done for 100% diesel operation and for a -nominal- blend of 50% H_2 on energy basis.

For 100% diesel operation the response to a sinusoidal load variation with a frequency of 0.25 Hz is shown in Figure 31. The engine speed variation is less than 40 rpm for a 30% load variation. Figure 32 shows the same test in dual fuel mode. Here, the engine speed variation is also around 60 rpm. The speed variation in dual fuel mode is therefore larger than in diesel only operation.

However, this is not necessarily due to the dual fuel operation but could also be caused by the fact that the combination of and the communication to the two ECU’s (the original Volkswagen diesel ECU and the Prins ECU for the hydrogen injection) leads to more control delay. This should be investigated in more detail.

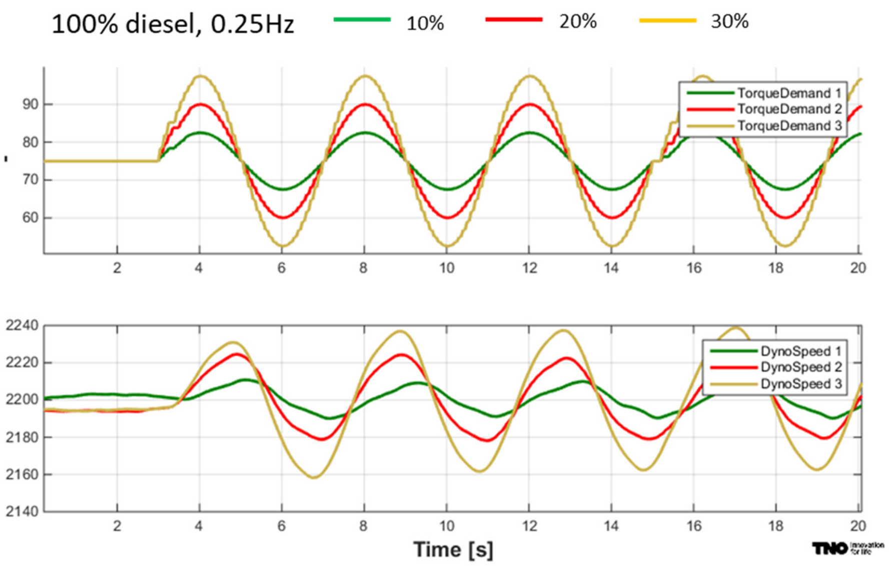

Figure 31: Engine speed response to load variation, 0.25 Hz, Diesel only.

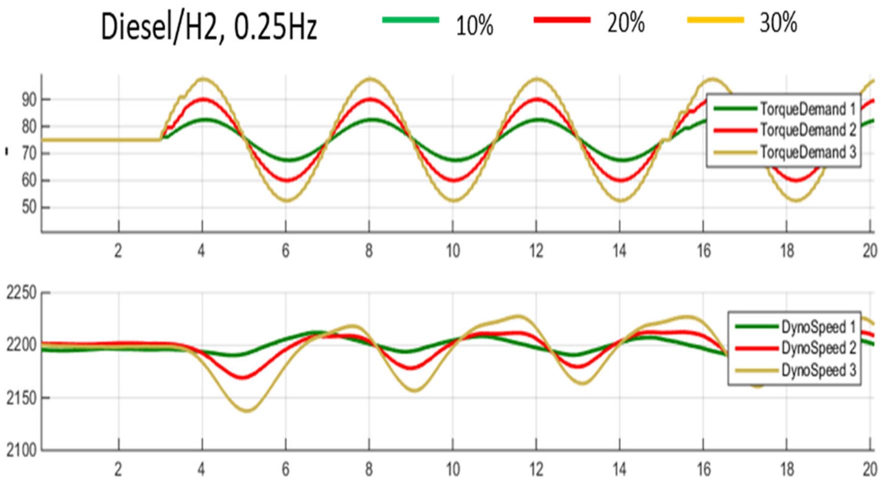

Figure 32: Engine speed response to load variation, 0.25 Hz, Dual fuel.

The engine speed variation is lower for higher disturbance frequencies.
For a 30% load variation at 1 Hz, the engine speed varies ±15rpm in diesel only mode (see Figure 33) and max. 20 rpm in dual fuel mode (Figure 34).

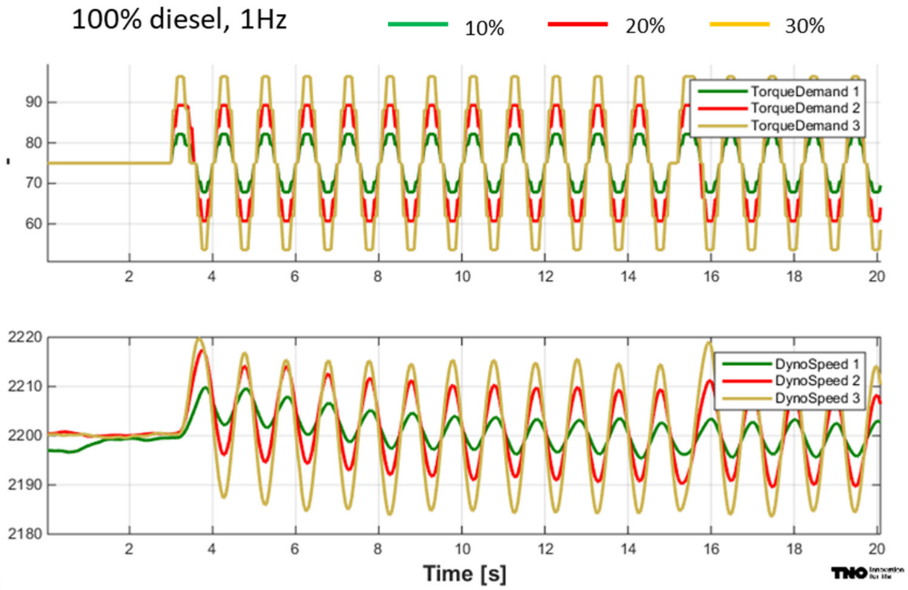

Figure 33: Engine speed response to load variation, 1 Hz, Diesel only.

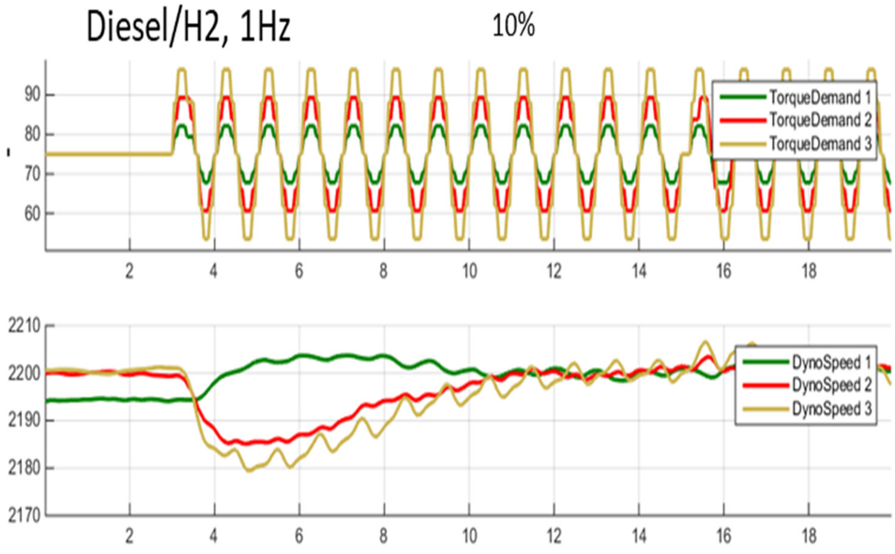

Figure 34: Engine speed response to load variation, 1 Hz, Dual fuel.

4.3 Conclusions

- The engine testing showed that for this type of engine, about 50% of diesel fuel can be replaced by H2 within the mechanical design limits of the engine. This also leads to a 50% (TTP) CO_2 reduction.
- Without engine adaptations, H2 blend leads to a rise in NO_x emissions due to the very fast H2 combustion.

- Injection timing retard and EGR are for this engine type, very suitable measures to keep the NO_x emissions on the same level as with 100% diesel operation.

Retrofitting diesel engines to operate on a dual fuel hydrogen mixture leads to a significant reduction in TTW CO_2 emissions. Special care should be taken to prevent NO_x emissions to increase to unacceptable limits. It is shown that NO_x emissions can be kept to a level, comparable to the original diesel engine by delaying the diesel injection timing. The delay of the diesel injection timing in this case does not lead to a significant drop in engine performance or efficiency. A second way of decreasing engine out NO_x is to use Exhaust Gas Recirculation (EGR). The initial tests with an EGR system showed a decrease of NO_x emissions to the diesel reference values for blend ratio’s up to 50%.

Using hydrogen as an alternative fuel, TTW CO_2-emissions can be greatly reduced, allowing for a very low ‘cost/CO_2 reduction’ ratio.
However NO_x emission limits need to be respected in order to comply with current and future regulations. Thus, further engine modifications as EGR or modification to aftertreatment systems such as SCR are a necessary part of the implementation.

5 Conclusions and recommendations

5.1 Conclusions

The following conclusions summarise the findings of the present project:

Section 2, Exploration study for alternative fuel based combustion engine PPE (Propulsion, Power & Energy) systems:

- The results in this work package are based on the currently set reference operational profiles; other operational profiles lead to different conclusions.
- The size and weight of the PPE components, the costs and the emissions are based on the current knowledge the sector. Detailed studies in which e.g. OEM's are consulted to provide designs and information for specific PPE system components might lead to different results.
- Fitting alternative fuel (lower energy density) based PPE systems in small ships with a relatively large PPE system compared to the ship size results in larger ships (up to twice the size in case of hydrogen) to fit the new PPE system or a large reduction in ship autonomy. For the larger ships like the general cargo the consequence of an alternative fuel based PPE is limited to about 15% of the ship size in case the autonomy is unchanged.
- The costs of these new systems depend on the balance CapEx and OpEx. The report provides guidance on price levels but it is stressed that these levels depend much on the feedstock in case of the fuels (OpEx), the energy storage size and type and the development of the ICE techniques and necessity of e.g. after treatment to reach TIER III. Therefore these price levels should be considered with care. Furthermore, this analysis does not take into account what the incremental effect is of ship hull and outfit costs when the ship needs to increase to fit energy and power systems.
- The GHG emission reduction potential is lowest for the LG (liquid methane gas)-solutions mainly because of the methane slip contribution. With HVO a reduction of about 60% could be achieved. With the other fuels (bio and synthetic) reductions of about 90-95% could be reached in theory, but the technical readiness level varies per fuel type.
- As also shown in work package 2.1 (section 3) high emission reduction levels still need some development (at least in case of hydrogen). Bio-methanol using tertiary waste streams show lower emission than e-methanol, because optimal waste streams are considered.

Section 3, literature study on the feasibility of a H2-ICE solution:

- The H2-ICE developments go fast with the main research and development activity for maritime applications in Europe and to a lesser extent in Japan. Many of the recognised maritime engine manufacturers are active in H2-ICE development with developments on both dual fuel H2-ICE concepts as well as mono fuel concepts.
- The presented H2-ICE concepts are all feasible for application as ICE for maritime applications, but not all concepts can currently be applied over the full engine operating envelope.

- Currently, the conventional dual fuel combustion concept has the highest Technical Readiness Level for maritime application. Moderate CO_2 reductions in the order of 40 – 60% are viable without compromising engine-out pollutant emissions. Standard SCR diesel after treatment is applicable. The option to fall back to conventional diesel combustion is considered as a key advantage of this concept for maritime application. Development of other combustion concepts can enable further CO_2 reductions in excess of 90%
- Mono fuel H2-ICE concepts are feasible from technology point-of-view with the potential to realize a climate neutral solution. The potential to eliminate costly after treatment systems is highest for these concepts.
- The application of direct injection hydrogen technology has been identified as an important enabler for increasing the engine's load range and elimination of the risk of backfiring. Currently this technology is not mature and further technology development is desired.
- The use of hydrogen as a fuel for internal combustion engines does not necessarily result in a loss of transient response with respect to the base diesel engine. For similar transient response, the engine's charging system probably needs to be adjusted.
- In order to examine the feasibility of a combustion concept for a dedicated application regarding transient response, data regarding the targeted engine dynamics need to become available.
- On engine level the selected engine concept mainly affects CapEx through the necessity of after treatment technology. Other component costs are considered to be marginal w.r.t. base engine costs and do not differ greatly between the different engine concepts. For implementation of the hydrogen internal combustion engine, the costs associated with hydrogen storage are expected to be dominant, similar to the application of hydrogen fuel cell technology. Results from WP1 show the engine CapEx ranges between 10 and 50% of the total costs of engines and storage, depending on ship type and mission profile.
- Reliable and safe H2-ICE operation already needs to be addressed in the engine design phase. The interaction of hydrogen with metals requires proper material selection. Furthermore, hydrogen has poor lubricating properties that need to be accounted for when designing or selecting engine components like valves, valves seats and fuel injection system components.
- Dedicated safety regulations for H2-ICE are not present at the moment. Currently, requirements listed in IMO IGF Code for gas engines (CNG/LNG) and low-flashpoint fuels need to be considered. Ship design implications for hydrogen are therefore of similar complexity as the regulations for CNG/LNG regarding hydrogen storage, venting systems, gas detection and areas marked as ATEX zones. Dedicated regulations on engine level mainly focus on preventing accumulation of hydrogen in exhaust system, auxiliary system media (oil, coolant water) or engine crankcase that may result in combustible/explosive hydrogen/air mixture. These risks may be higher than for CNG/LNG. This can be accounted for during engine design by use of dedicated hardware like e.g. positive crank-case ventilation. During engine operation a monitoring should be in place to detect the occurrence of poor combustion or misfires.

- Hydrogen can be produced from various feedstock routes. The hydrogen internal combustion engine shows relatively high tolerance towards hydrogen quality. Hydrogen with purity 3.0 (99.9% purity) can be safely used. As such, the hydrogen ICE is not very selective regarding the hydrogen feedstock source.

Section 4 tests on a dual fuels H2-ICE concept:

- Retrofitting diesel engines to operate on a dual fuel hydrogen mixture leads to a significant reduction in TTW CO_2 emissions.
- Special care should be taken to prevent NO_x emissions to increase to unacceptable limits. It is shown that NO_x emissions of a dual-fuel engine, can be kept to a level, comparable to the original diesel engine by delaying the diesel injection timing. The delay of the diesel injection timing does not lead to a significant drop in engine performance or efficiency.
- A second way of decreasing engine out NO_x is to use Exhaust Gas Recirculation (EGR). The initial tests with an EGR system showed a decrease of NO_x emissions to the diesel reference values for blend ratio's up to 50%.
- NO_x emission limits need to be respected in order to comply with current and future regulations. EGR or SCR aftertreatment are necessary to comply with Tier III NO_x level for dual-fuel engines. Otto or RCCI technology engines may be able to meet Tier III emissions without aftertreatment. ((or
  Thus, further engine modifications as EGR or modification to aftertreatment systems such as SCR are a necessary part of the implementation))

The above conclusions and recommendations do not supersede the statements made in the previous chapters and in the tables and figures with results.

5.2 Recommendations

The following recommendations for future developments originate from this study:

Ship technology: Propulsion, Power & Energy system

- For a more in depth analysis of the consequences of incorporating an alternative fuel based PPE system in a ship a dedicated design study should be conducted incorporating the specific design requirements of the (sub-)systems. The current study made use of generalized averaged parameters for size, weight and costs. In a dedicated design study the engine room and bunker layout should be fitted in a specific ship to show the actual feasibility and the impact of regulations (or the lack thereof).
- To be able to perform ship specific validation tests detailed power time charts should be constructed. These charts provide the typical power variations in time (in the order of ~seconds) for important operational tasks. Such charts can be derived from existing full scale data and/or a dedicated monitoring campaign. For the current study this was out of scope.

- The engine tests performed as part of this study show good potential of the dual fuel hydrogen-diesel engine to realize significant CO_2 reductions while simultaneously realizing acceptable engine-out NO_x and particulate emissions. Even without any optimization these pollutant emissions did not exceed the emission levels of the base diesel engine. Especially for high H_2 shares in excess of 90% (micro-pilot dual fuel combustion concept) the potential is there for the elimination of costly NOx aftertreatment. Furthermore, the concept can be designed to enable a liquid fuel fall back. Therefore, further development and demonstration of a practical dual fuel H2-ICE concept with increasing H_2 shares (> 90%) is highly recommended.
- The mono fuel lean burn SI hydrogen ICE has the highest potential as a fully climate neutral solution, i.e. near 100% TTW CO_2 reduction in combination with near zero engine-out pollutant emissions. The possibility to eliminate the use of costly aftertreatment systems is also highest for this engine concept. Especially for application in near coast/harbour shipping further experimental development and demonstration of this engine concept is recommended.
- Current hydrogen ICE applications use port fuel injection of hydrogen in which low density hydrogen displaces part of the fresh intake air. This reduces the maximum possible power output, i.e. power density. Next to this, the presence of hydrogen in the intake manifold makes the system more prone to backfiring (safety risk). Further development of Direct Injection hydrogen technology is recommended as an important enabler for increasing the engine's power density. Furthermore, the application of DI H_2 injection will eliminate the risk of backfiring completely and is considered beneficial for improved transient response.

Fuel supply chain

Account for availability of fuels; which fuels will be available for the maritime sector?

- Particularly lower grades of biodiesel (compared to automotive), such as upgraded pyrolysis oil, bio-methanol and LBG using waste streams of agriculture and forestry. Also a road map should be developed to find out which feedstocks and production processes can support the necessary volumes for maritime transport. This should include combined processes (including with E-H2) to make better use of the carbon in the bio-feedstock and increase the fuel output.
- E-fuels that should be investigated include H2, E-NH3, E-methanol, E-methane.

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7 Signature

The Hague, 27 May 2021

Ann Delahaye
Projectleader

TNO

Xander Seykens
Author

A Specification of the fuels used in this study

All characteristics in this Appendix are structured according to the systematic approach described in paragraph 2.1. The specific metrics listed here for the PPE system are a snapshot taken on 15-02-2021 from MARIN's Sustainable Power website (https://sustainablepower.application.marin.nl/). The engine data is based on medium speed engines ranging from 900 to 5500 kW. In the 'Data table' tab under *information* on this site all references are (being) documented. It must be said that the data is preliminary, and in continuous development. Some metrics, in particular those relating to physical properties (size, weight) are quite reliable and are usually based on multiple references, whilst others are only educated guesses. Most references in the database are for the energy carriers, followed by the energy converters. Pre-treatment, after-treatment and distribution and drives consist of far less references, but the major differences are also in the energy carriers and energy converters.

Energy carrier physical properties

	Storage condition	Uncontained Energy density		Contained Energy density		Energy CapEx
		MJ/l	MJ/kg	l/kW	kg/kW	€/kWh
Diesel / HVO / e-Diesel	Liquid / ambient conditions	34.0	30.1	34.0	30.1	0.6
MGO	Liquid / ambient conditions	33.2	29.6	33.2	29.6	0.6
Methanol	Liquid / ambient conditions	15.6	19.7	14.6	15.3	0.9
LNG / LBG / e-LG	Liquefied at -162°C	20.3	48.0	13.6	30.4	2
Ammonia	Liquefied at -35°C	12.7	18.6	10.4	12.6	1.1
Hydrogen	Compressed at 700 bar	5.6	120	3.3	7.1	9.4

Bandwidth energy carrier prices

€/GJ	Fossil			Biofuel / carbon recycled			E-fuel		
	Low	Middle	High	Low	Middle	High	Low	Middle	High
EN590 / HVO / e-Diesel	9	12	19	14	23	35	28	30	62
LNG / LBG / e-LG	8	9	11	12	15	35	28	31	59
Methanol	14	16	18	16	23	32	28	31	66
H2	21	25	30	-	-	-	27	31	51
Ammonia	14	25	30	-	-	-	28	30	56

Specific CO_2 emissions energy carriers

g/MJ	Fossil	Biofuel / carbon recycled	E-fuel
EN590 / HVO / e-Diesel	85.8	33.54	10
LNG / LBG / e-LG	93.5	55	25.5
Methanol	84.2	4.4	10
H2	115.2	-	10
Ammonia	96.8	-	10

Pre-treatment and distribution

	Power density		Capex power	Efficiency
	l/kW	kg/kW	€/kW	%
Evaporation	1.005	1.3	200	100%
Expansion	0.05	0.4	100	98%

Energy conversion

	Power density		Capex power	Efficiency
	l/kW	kg/kW	€/kW	%
ICE CI med-speed	10.87	7.03	350	46%
ICE CI hi-speed	5.69	3.46	263	39%
ICE CI DF med-speed	16.84	13.62	462	50%
ICE CI DF med-speed (LNG/e-LG/LBG)	10.87	7.03	350	48%

Exhaust after-treatment

	Power density		Capex power	Max Efficiency
	l/kW	kg/kW	€/kW	%
SCR after treatment	5.12	1.25	236	98%

Power distribution and drives

	Power density		Capex power	Efficiency
	l/kW	kg/kW	€/kW	%
ICE-direct	9.0	1.2	300	97%

The metrics in the tables above are combined as per the configuration provided in Table 2. Efficiencies are multiplied to a chain efficiency and Capex and power densities are added together. With respect to power distribution and drives: only “ICE-direct” is considered: direct mechanical coupling of main engine to propeller shaft and gearbox. Auxiliaries are assumed to be powered via a PTO.