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CIMAC Guideline

Alternative fuels emission control for large combustion engines

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Content

Abbreviations

ASC	ammonia slip catalyst
BC	black carbon
CCU/S	carbon capture and utilisation/storage
CH_4	methane
CI	compression ignition
CO	carbon monoxide
CO_2	carbon dioxide
comp.	compressed
DAC	direct air capture
DF	dual fuel
DPF	diesel particulate filter
EATS	exhaust aftertreatment system
ECA	emission control areas
EN	European norm
ESP	electrostatic precipitator
EtOH	ethanol
EU	European Union
GHG	greenhouse gas
GWP	global warming potential
HAP	hazardous air pollutant
H_2	hydrogen
H_2O	water/steam
HC	hydrocarbon
HCCI	homogeneous charge compression ignition
HCHO	formaldehyde
HFO	heavy fuel oil
HVO	hydrotreated vegetable oil
IMO	International Maritime Organisation
ISO	International Organisation for Standardisation
liq.	liquefied
LCA	life cycle assessment
LNG	liquefied natural gas

MeOH	methanol
MGO	marine gas oil
MJ	megajoule
MOC	methane oxidation catalyst
MW	megawatt
N_2O	laughing gas / nitrous oxide
NH_3	ammonia
nm	nanometre
NO_2	nitrogen dioxide
NO_X	nitrogen oxides
NMHC	non-methane hydrocarbons
NRMM	non-road mobile machinery
PM	particle mass
PN	particle number
RWGS	reverse water gas shift
SCR	selective catalytic reduction
SMR	steam methane reforming
SO_X	sulphur oxides
UCO	used cooking oil
ULEV	ultra-low emission vessel
ULSD	ultra-low sulphur diesel
US EPA	United States Environmental Protection Agency
VOC	volatile organic compound

Executive summary

Considering the variety of large engine applications in marine, stationary power generation and rail, it is improbable there is a single fuel as solution for all use cases. Thus, from an emission control perspective, a large variety of specific gaseous pollutant challenges exist in parallel. Additionally, particulate emissions including ultrafine particles will persist for many of the alternative fuels, albeit with different compositions and in lower quantities. The respective pollutant emissions from alternative fuels are presented and their abatement technology options outlined, supporting a transition to alternative fuels which would not only ensure reduced climate impact but also improved air quality.

1 Introduction

Efforts to transition the large engine industry away from fossil fuels are accelerating, with various future zero or low greenhouse gas (GHG) impact alternative fuel options being favoured depending on the applications. There is no “clear winner” among the potential alternative fuels: hydrogen (H_2), ammonia (NH_3), methanol (MeOH), methane (CH_4) or other non-fossil liquid diesel fuel substitutes are all under consideration – it is likely they will all find their applications and will all be required to meet the global targets. The origin of the fuel carbon molecules should be either biological or synthesized from biosphere sources (e.g. atmospheric CO_2) using renewable energy to avoid a shift from consuming direct fossil energy to their indirect use. However, carbon capturing technology must be mentioned as an exception to enable the continued use of fossil primary energy sources, provided the fossil carbon balance can be closed. Cost-benefit comparisons of the different carbon source options should also be part of the overall selection process. Please refer to the previously published WG5 guideline on carbon capture utilisation/storage (CCU/S) for further details. [1]

In terms of specific pollutant emissions, each of the above fuels comes with intrinsic challenges and potentials. The injection and ignition technologies utilized for their combustion largely determine the emission profile, becoming the starting point for any exhaust emission control technology. Other main factors are the future emission limits on global, transnational, national or regional levels that define the goal to be reached. Moving from start to finish line, there are specific obstacles for the various fuels in discussion and, hence, different paths one can take, each with peculiarities along the way.

In this contribution, the characteristics of different alternative fuels and combustion concepts in terms of emission control possibilities and restrictions are introduced. Many of the statements remain general in their nature, as exhaust gas conditions and compositions are not yet fully understood for all scenarios. However, considering today’s technology and where significant challenges remain, some conclusions of available solutions can already be made. This is due to the experience in niche applications in which emission control technology has already been combined with alternative fuels because ambitions for outperforming legal clean air requirements exist. There are also many ongoing research activities exploring various future engine setups far from today’s fuel system solutions which also disclose exhaust gas composition. The optimum arrangement of dedicated engine and exhaust gas aftertreatment components dealing with all potential pollutants is also an important topic due to the possible interactions.

Most likely, one will continue to see no single fuel being the solution for all large engine applications and the application use cases, thus, from an emission control technology view a large variety of specific gaseous pollutant challenges exist in parallel. Additionally, particulate emissions including ultrafine particles will persist for many alternative fuels, even if different in composition and concentrations.

Exhaust emission control as well as engine development will see more varieties than in past decades. Interaction and collaboration between all large engine industry members and other technology providers will become even more crucial and CIMAC can play a key role in this process.

2 Alternative fuels

2.1 Fuel properties

Until a few years ago the wide application range for large engines was clearly dominated by a few fuel types, even on a global level: while residual fuel oil, such as heavy fuel oil (HFO) or diesel distillate fuel, such as marine gas oil (MGO) was covering the majority of mobile applications, stationary power generation also worked with natural gas. The uptake of liquefied natural gas (LNG) in mobile large engine applications in recent years only marked the starting point of a much larger fuel diversity likely to be experienced still within this decade after half a century of stability. This fuel variety is driven mainly by the ambition to cause less climate impact and pollutant emissions rather than cost optimisation. The fuels currently considered to be most promising for this purpose are hydrogen (H_2), ammonia (NH_3), methanol (MeOH), methane (CH_4) or non-fossil paraffinic liquid direct substitutes for diesel fuel (“drop-in diesel”). Being essentially chemically stored chemical energy to be utilized by an energy converter such as a large internal combustion engine, one of the most important parameters for these fuels are the energy storage density (gravimetric and volumetric) and any special storage requirements. Table 1 lists these key properties of the mentioned alternative fuels and the fossil fuels.

Table 1. Energy densities as lower heating values of alternative and fossil fuels with respective storage conditions. [2]

	Energy density [MJ/kg]	**Energy density [MJ/l]**	**Storage pressure [bar] @ temperature [°C]**
Residual fuel oil [liq.]	~38	~35	ambient @ ambient
Diesel distillate [liq.]	~43	~38	ambient @ ambient
LNG [liq.]	~50	~21	ambient @ -163°C
Hydrogen [comp.]	120.0	4.5	700 bar @ ambient
Hydrogen [liq.]	120.0	8.5	ambient @ -253°C
Ammonia [liq.]	18.6	11.5	9 bar @ ambient ambient @ -33°C
Methanol [liq.]	19.9	15.6	ambient @ ambient
Methane [liq.]	50.0	21.1	ambient @ -163°C
Drop-in diesel fuel [liq.]	~44	~34	ambient @ ambient

As expected, the drop-in replacement for distillate diesel and methane for LNG are very similar in energy density and require identical storage conditions. The major difference in the table exists between the gaseous and liquid fuels, with the gaseous ones requiring elevated pressure or sub-ambient temperatures for dense storage as a liquid. NH_3 as a polar molecule already starts to liquefy under moderate pressure or cooling in comparison to both H_2 and CH_4. Consequently, the observed energy density considering the tank volume of the pressure vessel or insulation in addition to the contained fuel will be increasingly affected for the latter two fuels. Moreover, the impact of the tank insulation and pressure vessel containment on the effective total energy density is dependent on the tank size and shape, increasing with higher surface to volume ratio, so the fuel’s tank will have a strong impact on the total effective energy density, particularly for applications requiring small quantities of stored energy. In contrast, independent of fuel type and energy amount, tanks for fuels that are liquid under ambient conditions have only a minor impact on the observed total energy density for typical large engine applications.

The choice of alternative fuel will depend on several factors, including fuel properties, cost, availability and engine application. Therefore, no single fuel is currently seen as the solution for all large engine applications and all their use cases.

2.2 Fuel production

In terms of how the fuels are produced today and how they might be produced in the future, the chemical relationship of the candidate fuels becomes apparent. As a detailed discussion of the production pathways for alternative fuels is beyond the scope of this paper, only a brief summary is provided below due to the more extensive documents published by the CIMAC GHG strategy group. [3]

Today, H_2 is mainly produced by steam methane reforming (SMR) of natural gas, the other significant processes being reforming of naphtha or using coal – these three methods represent in total >96% of global H_2 production. [4] In the SMR process, CH_4 reacts with steam (H_2O) to yield H_2 and CO_2 as a coupled product after the reverse water gas shift (RWGS) reaction. One option is to deploy the Haber-Bosch process continuing the reaction of H_2 with N_2 in order to yield NH_3, which is one of the most applied chemical processes in the world. Alternatively, H_2 can be combined with CO or CO_2 creating MeOH, CH_4 or even longer hydrocarbon chains yielding drop-in diesel fuel via the Fischer-Tropsch process. Figure 1 provides an overview of the different produced fuels and pathways. The production of synthetic CH_4 is not industrially applied today due to natural gas being frequently utilized as H_2 feedstock. Instead, MeOH is largely produced by the described route, though its use today is mostly as a chemical rather than as a fuel. [5] Synthetic paraffinic Fischer-Tropsch diesel from CO and H_2 already has a long history, though it is only produced in large amounts during special political and economic circumstances and so far without the motivation to reduce net climate impact. [6] However, there are also biomass or waste derived paraffinic drop-in diesel fuels like HVO (hydrotreated vegetable oil) produced today. For their production, H_2 is also required during the upgrading of the low value feedstock. Furthermore, fatty acid methyl ester (FAME) biofuel is produced today globally as well. Ethanol (EtOH) is also directly produced as bioalcohol from certain biomass like sugar cane, corn or other starch-containing crops, bypassing the synthetic route involving biogenic CO_2 mentioned below. In general, sustainability of biofuels must be considered.

In a lower CO_2 footprint fuel production future, needing H_2 as a core feedstock, such would either be produced by SMR from natural gas coupled with carbon capture and storage (CCS) to avoid release of CO_2 to the atmosphere ("blue H_2"), or by electrolysis of water using zero CO_2 footprint electricity ("green H_2"). H_2 and NH_3, would not only be locally CO_2 emission free, as they don't contain any carbon atoms, but would also be over the full production chain without significant direct CO_2 footprint. Production of synthetic MeOH and CH_4 would require CO_2 for their synthesis in addition to H_2. In the case of an incompletely closed cycle for CO_2, this could be maintained via carbon capture during fuel combustion and returning it for a new fuel synthesis (carbon capture and utilisation = CCU). Alternatively, the CO_2 could be previously captured from the atmosphere via biomass or direct air capture (DAC). However, CO_2 captured from point sources which are not using synthetic- or biofuels, but using fossil fuels instead, ultimately add CO_2 to the atmosphere. Drop-in paraffinic diesel fuel could be produced with low CO_2 footprint already today in significant shares using biomass or used cooking oil (UCO), but these global feedstocks will be limited. Thus, like for synthetic CH_4 or MeOH, one could follow the path of combining green or blue H_2 with CO_2 derived from biomass or DAC to theoretically produce feedstock unlimited amounts of fuels which would work in existing fuel storage, supply infrastructure and combustion engines without any significant need for modifications or CCU/S retrofitting.

2.3 Fuel safety

Considering all these different synthetic fuels being produced like specific chemicals rather than as refined fossil hydrocarbon mixtures, one could also conduct the safety assessment, as is normally done with other chemicals. Again, the drop-in replacements paraffinic diesel and CH_4 for diesel and LNG are very similar to their templates, being respectively a flammable and toxic liquid and a highly flammable but non-toxic gas. H_2, like CH_4, is also a highly flammable but non-toxic gas, while NH_3 is considered flammable but also corrosive and toxic. Methanol is a flammable liquid with low flashpoint and toxic vapour. [7]

It should be noted that flammability is not just dependent on one parameter but several, why the above description should be read as general note. The discussion of adequate safety provisions for handling and use in engines is mandatory when introducing any of the mentioned alternative fuels but outside the scope of this publication. Reference is made to (planned) publications from other CIMAC working groups. Also, marine classification societies have published guidance documents and rules about the handling of these alternative fuels. [8][9][10][11] The international maritime organisation (IMO) has published reference documents for MeOH and NH_3, while for H_2, this documentation is still under development. [12][13]

3 Alternative fuel emissions

3.1 Engine impact on emissions

Moving from the stored energy in fuels to power which can be used for propulsion or electricity production, large internal combustion engines are efficient energy convertors with high reliability and high power density, even under adverse operating conditions and comparably little need for maintenance – all at a competitive price up to several tens of megawatts. However, to achieve all these advantages, the engines must be adapted to the fuels they are supposed to convert. Due to the wide range of fuel properties, an engine being able to burn all kinds of alternative fuels would likely come with too many concessions. When instead the operation is optimized for a certain kind of fuel some others might not be converted with equally high efficiency, if they could be used at all. The production, transport and storage of alternative fuels will be more expensive than for fossil fuels today. Further, several sectors have introduced regulatory measures to improve the energy efficiency of engines. Thus, engine efficiency will be a key objective. Engines are generally limited to run on a single or at least very similar fuels to achieve their best efficiency. A safer fall-back option might still be desired similar to today's liquid fuel oil mode for marine dual fuel (DF) engines.

Typically, when an engine is optimized for a certain fuel, there are several hardware modifications involved besides the altered engine control parameter settings. Apart from the engine architecture itself, the hardware components having the biggest leverage on efficient fuel conversion are the fuel injection, the ignition and the turbocharging systems.

For the fuel injection system one can generally distinguish between the direct fuel injection into the required compressed air for Diesel like combustion or an air and fuel premix formed due to earlier fuel admission in an Otto like process. In terms of ignition system, air-fuel mixtures may be ignited by a spark from an electric spark plug or other device, by a pilot fuel flame from specifically injected fuel or the fuel will self-ignite. The spark ignition may be direct and for the full amount of air-fuel mix or indirect by igniting only a part of the fuel or a dedicated air-fuel mixture with a spark in a prechamber and consequential full ignition of the main air-fuel mix. The latter principle is also to a certain degree employed in pilot fuel ignition systems, in which a small amount of self-igniting fuel initiates the combustion of the main air-fuel mix. While forced ignition concepts for premixed air-fuel combinations can be summarized as Otto principles, the ignition of the injected fuel in compressed air is denoted as Diesel principle. For self-ignition, it relies on the spontaneous reaction of part of the injected fuel with the compressed and hot air in the combustion space at pressures and temperatures beyond the specific fuel autoignition parameters. [14] The different engine, injection and ignition concepts and principles all have their specific advantages and drawbacks; in terms of emission parameters, they can be very different even for the same fuel. Special combustion concepts currently not utilized for large engines, e.g. homogeneous charge compression ignition (HCCI) are not considered in this publication even though they could possibly be more relevant for alternative fuels.

In general, different engine applications and operating profiles will favour different alternative fuels, as already observed today and in the past. For instance, stationary power generation for electric grid balancing with MW-sized engines may run exclusively on a gaseous fuel when supplied by pipeline as opposed to a large commercial vessel, which must maintain manoeuvrability even in case of gaseous fuel supply system issues. As fuel flexibility is conceivably compromising efficiency with a single well-defined fuel to some degree, even if the flexibility is limited to a back-up mode, engines will only be as fuel agnostic as economically acceptable. Moving towards defined molecule type fuels which are describable by a chemical formula – rather than mixes of hydrocarbon compounds only similar in a physical property such as boiling point like today's fuels – one can also expect much less fuel quality variations and, hence, more refined engine optimisations to push for maximum efficiency on these higher cost fuels.

Where and which fuel will finally be the fuel of choice depends on many factors, possibly only the minor ones being technicalities related to the engine or even the emissions or aftertreatment systems. However, these are part of the picture as well and when considering all the possibilities of fuel choices, combustion processes and ignition concepts, already some general statements about the typical emission compounds and their relative severity can be made.

In Figure 1 an overview of the expected exhaust emissions, splitting the different fuels by their production pathways and distinguishing between their combustion in different engine types and ignition concepts, is provided. Besides merely listing the typically expected exhaust components, an indication about the anticipated relative level of emissions is provided.

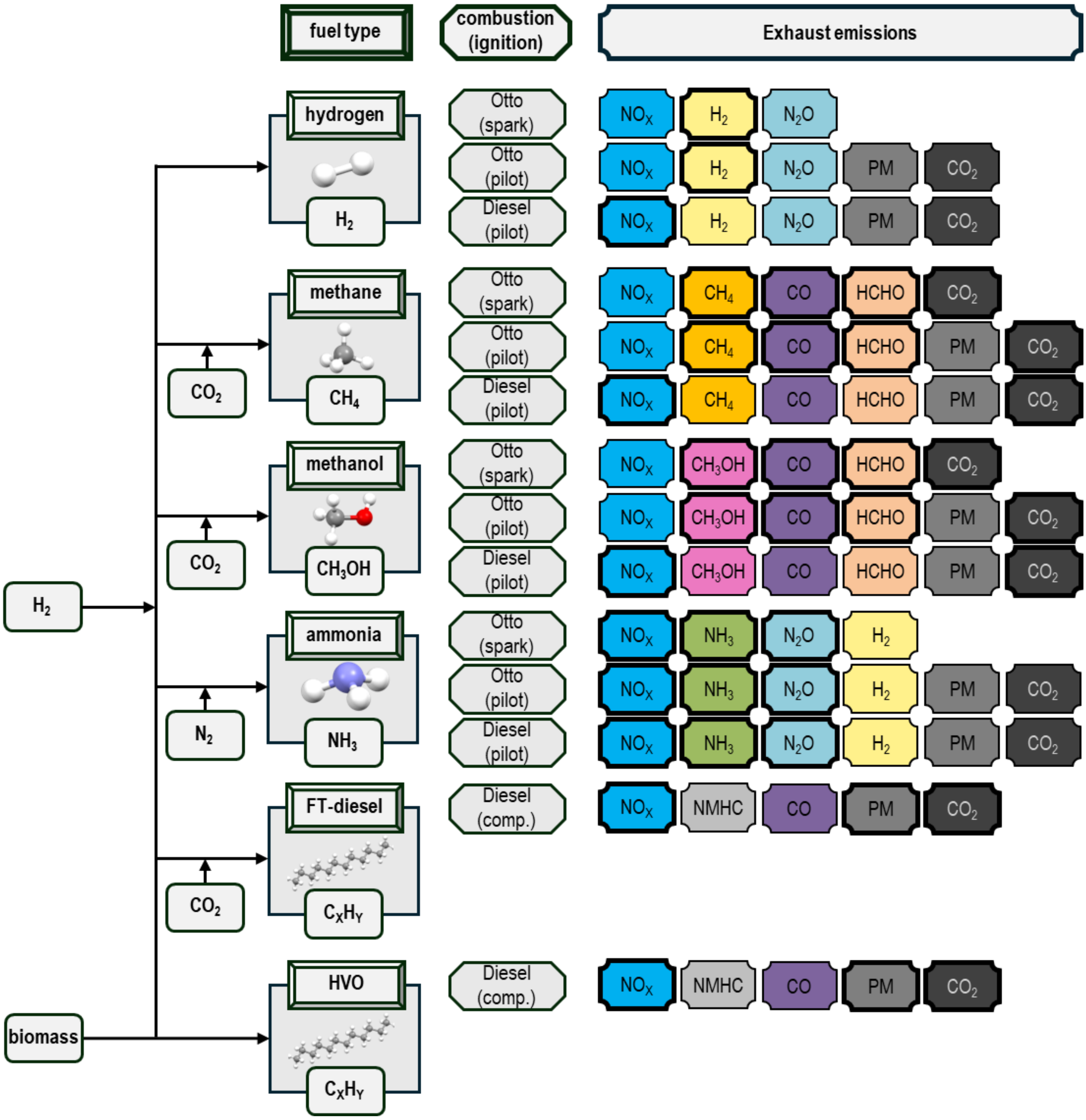


Figure 1. Overview of alternative fuels originating from hydrogen and their expected exhaust emissions, distinguishing between different engine types and ignition concepts. The emissions which are commonly considered to be in focus for each fuel and technology are highlighted (thick line frame). Carbon-containing fuels, also considering the pilot fuel for ignition of carbon-free fuels, produce CO_2 as an emission. All presented fuels also yield H_2O as combustion product, which is not listed.

- NO_X

While NO_X is formed for every single combination presented in Figure 1, independent of the fuel, combustion process or ignition concept, the order of magnitude will strongly vary. The explanation is that in all above cases a fuel is combusted at relatively high temperatures and pressures with excess air containing nitrogen (N_2) and oxygen (O_2), enabling the two gases to combine to form NO_X. [15] Even though this process cannot be prevented completely, certain combustion concept choices as well as additional engine-based measures can significantly reduce NO_X formation in relation to today's reference situation. Generally, reduced flame front temperatures during the combustion, as experienced in premix combustion, reduces NO_X formation. Both, fuel and combustion choice already have the potential to further decrease engine-out NO_X emissions. NO_X reduction by modifying the combustion process typically presents a trade-off with energy efficiency as reduced combustion temperature leads to higher fuel consumption.

However, in addition, environmental ambitions have strengthened over the past years and future ambitions to further cut the emission of NO_X are likely to remain, as NO_2 (the atmospheric oxidation product of all exhaust NO_X) is a strong factor in reducing local air quality, directly as an irritating gas or indirectly by being a key reactant in the photochemical smog chemistry, as well as eutrophication, which could lead to loss of biodiversity. To that end, NO_X is one of the sources for acid rain and secondary nitrate particulate formation. [16]

- N_2O

Nitrous oxide (N_2O) or more commonly known as laughing gas does not pose a safety risk or health issue for the anticipated concentrations, but as it constitutes a strong climate gas with a greenhouse gas warming potential of 265 times (as assumed in IMO's LCA Guidelines) [25] the one of CO_2 when considered over 100 years, already low concentrations are critical. [26] Concentrations at ppm levels can seriously endanger the idea of moving away from climate impacting fossil fuels to a climate friendly alternative. N_2O is considered the third most important GHG, after CO_2 and CH_4. N_2O has an atmospheric lifetime of 116 years and absorbs infrared radiation, trapping heat in the atmosphere.[17] It also plays an important role in stratospheric O_3 depletion through reaction with excited atomic oxygen. [18]

- Unburnt fuel – general

For every fuel there are also unavoidable emissions of unburnt fuel, again, depending on the combustion type there are variations in terms of severity. While a reduced flame front temperature is beneficial for reducing NO_X emissions, for complete combustion of the respective fuel it has the opposite trend. The different fuel gases also have different laminar flame speeds varying by almost two orders of magnitude from the slow burning NH_3 (~7 cm/s) all the way to the fastest burning H_2 (~290 cm/s). [19] Across the different fuels, traces of unburnt fuel will have very different impacts due to the very different chemical nature. For the gaseous fuels which are also flammable or even highly flammable substances, there could be safety risks at high concentrations. At lower concentrations, there can be local impacts like toxicity for NH_3, or global climate impact as for CH_4 or for H_2.

- Unburnt fuel – CH_4

CH_4 is the second most important anthropogenic GHG apart from CO_2 and according to sources accounts for around 20% of the man-made radiative warming effects since the preindustrial period. [17] It is also a chemical precursor to tropospheric ozone (O_3) formation, consequently depleting air quality. [18]

- Unburnt fuel – H_2

In the current scientific literature, H_2 is considered an indirect GHG. It reacts with hydroxyl radicals in the air, which in turn extends atmospheric lifetimes of primary GHGs like CH_4, resulting in a higher global warming potential for them. Furthermore, H_2 increases tropospheric O_3 production, hence hydrogen emissions must also be considered when trying to minimize air pollution. Last, in the stratosphere it supports the depletion of the O_3 layer and increases water vapour leading to stratospheric warming. [20]

- Unburnt fuel – NH_3

NH_3, apart from its toxicity is considered a secondary source for PM formation. NH_3 can react with sulphuric and nitric acids and form ammonium sulphates and nitrates, respectively. [21] Further, similar to NO_X emissions, atmospheric deposition of NH_3 leads to eutrophication and loss of biodiversity. Regarding toxicity, NH_3 is readily detectable by the human olfactory system and concentrations as low as 5 ppm are detectable by its characteristic odour. The human respiratory system can tolerate approx. 100 ppm NH_3 for several hours, but at a concentration of approx. 1700 ppm, the respiratory system is strongly affected and at concentrations above 5000 ppm, immediate death by respiratory arrest can occur. [22][23] Under the authority of the United States Federal Advisory Committee Act (P.L. 92-463) of 1972, the National Advisory Committee for Acute Exposure Guideline Levels (AEGL) after reviewing relevant toxicological and scientific data determined that 110 ppm exposure for 4 – 8 hours by an individual, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape. Also, a person exposed to 2700 ppm for 10 minutes or 1600 ppm for 30 minutes could experience life-threatening health effects or death. [24]

- Partially burnt fuel – CO, HCHO, NMHC, PM

The emissions of CO, formaldehyde (HCHO), non-methane hydrocarbons (NMHC) and particulate matter (PM) constitute different types of partially burnt carbon-containing fuel which was not fully oxidized to CO_2 and H_2O. Further, lubrication oil can contribute to the formation of PM, independent of the combustion concept. The emission impact is in particular a local issue, as CO is a toxic gas and both, HCHO and PM are carcinogenic compounds. NMHC is an important precursor for tropospheric ozone formation and secondary organic aerosols.

PM is in addition a strong factor for reduced local air quality, [16] impacting general health due to ultrafine particles (<100 nm particles) which have the potential to enter the alveoli in the lung and can also cross cell membranes and into the blood stream. [27]

The climate impact of black carbon – a fraction of PM as defined by Bond et al. [28] targeted to represent fuel independent soot emissions – should be considered. Within the arctic zone, local black carbon (BC) emissions decrease surface albedo causing ice melting and thereby up to 900 times more climate forcing than the fossil fuel CO_2 emissions from the respective sources at GWP100 conditions. [26] In United Nations bodies such as the IMO, black carbon emission regulation is consequently discussed for large engine applications, yielding so far only non-binding recommendations for voluntary actions.

- Ash

Depending on the fuel and lubrication oil type as well as their consumption, the PM emitted will also contain ash. The elemental composition of the ash depends on the initial composition of the consumed engine fluids. Besides general eutrophication concerns there can also be specific toxicity topics regarding specific metals the ash may contain, such as heavy metals.

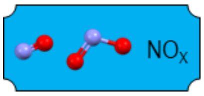
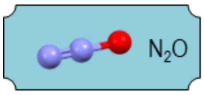
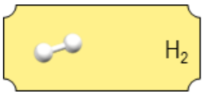
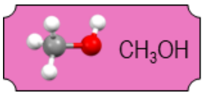
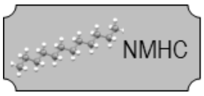
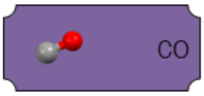
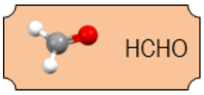
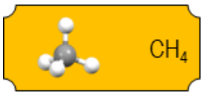
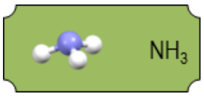
- General note

Providing detailed numbers – emission concentrations or normalized to g/kWh – for all the above emission components in combination with the different fuels, combustion principles and ignition concepts is far beyond the scope of this document. The emission values would vary depending on factors such as the detailed engine design by the manufacturer or the engine speed (low, medium or high). Additionally, engines are not commercially available for some fuel types yet. Instead, in the next section in a similar general approach it’s discussed how the abovementioned emission components can be reduced by exhaust emission control technology.

3.2 Emission control technologies

As mentioned above, the wide variety of engine types, engine operation strategies and ignition concepts make it impossible to discuss all possibilities in detail – even if engines were already available for all the listed fuels and possible combinations, which is not the case. Instead, Table 2 provides an overview of the key environmental aspects on pollutants, potential existing emission abatement technologies in case the fuel switch itself and advanced engine internal measures are not providing the required emission reduction for those pollutants, and potential issues for present and future emission control systems. While the ambition of alternative fuels is to have a lower environmental impact and they are typically chemically more defined than traditional fuels, they can produce specific emission components which are further discussed in the following table and section.

Table 2. Overview of all anticipated pollutants originating from alternative fuels, their key environmental issues, known existing emission abatement system technology and its corresponding present and future limitations/issues.

	Key issues environment	**Technology**	**Potential issues of emission abatement system**	
 NO_X	toxic eutrophication ground level O_3	SCR	activity: selectivity:	limited conversion at low temperatures lower SCR selectivity at high temperatures
		EGR	applicability:	engine internal measure with altered combustion
 N_2O	GHG	N_2O catalyst	activity:	no conversion at low temperature
			availability:	no catalysts for engine exhaust commercially available
 H_2	indirect GHG	OXI	activity:	exothermicity by conversion of H_2 slip SO_X poisoning from pilot fuel and lube oil
 CH_3OH	toxic	OXI	activity:	exothermicity by conversion of slip SO_X poisoning from pilot fuel and lube oil
			selectivity:	potential formation of other pollutants
 NMHC	toxic ground level O_3 odour	OXI	activity:	low activity for short-chain saturated hydrocarbons SO_X poisoning from pilot fuel and lube oil
 CO	toxic	OXI	activity:	SO_X poisoning from pilot fuel and lube oil
 HCHO	toxic	OXI	selectivity:	potential formation of other pollutants SO_X poisoning from pilot fuel and lube oil
 CH_4	GHG	CH_4 OXI	activity:	no conversion at low temperatures & catalyst ageing SO_X poisoning from pilot fuel and lube oil
			availability:	no catalyst for typical engine exhaust gas composition & temperature commercially available
		non thermal plasma	activity: availability:	high electric power consumption for removal no commercial system available
		recuperative oxidizer	activity:	large size required
			efficiency:	long start up time and slow response to load changes, high parasitic power consumption
		EGR	applicability:	engine internal measure with altered combustion
 NH_3	toxic eutrophication odour	SCR/OXI	activity:	limited conversion at low temperatures SO_X poisoning from pilot fuel and lube oil
			selectivity:	catalyst can form N_2O and NO_X
 PM	toxic GWP	DPF	availability: efficiency:	limited today to <10 MW power range engines need to handle higher backpressure
		ESP	efficiency:	reduced PM removal efficiency for engine ESP in comparison to boiler ESP applications
		W-ESP	applicability:	to be combined with upstream wet scrubber
		bag filters	activity: efficiency: durability:	requires cooling of exhaust for bag filter materials requires additional power for exhaust fans reduced availability if used without protection agent

- NO_X

As established in Figure 1, NO_X are formed by all combustion processes, which is why their removal is established for various combustion processes, including internal combustion engines running on various fuels ranging from crude oil or residual fuels to high purity gases such as CH_4 or H_2. Even though the NO_X concentrations can vary by an order of magnitude for the different applications, the same catalytic NO_X reduction process called selective catalytic reduction (SCR) can be used to enhance the emission abatement reached by primary methods. Of course, the process parameters and installed catalyst type and size must be adapted depending on the exhaust conditions, but SCR based NO_X reduction is successfully utilized globally to meet specific emission requirements. The most important operating parameter is the catalyst temperature, which should generally be on a certain minimum level exceeding 250-300°C to ensure sufficient activity, but also not exceeding temperatures of 500-550°C due to loss of SCR reaction selectivity or even destruction (e.g. sintering) of the catalyst. As there are different types of SCR catalysts, the exact temperature ranges must always be defined individually. In addition, other parameters such as the fuel sulphur content can be relevant for specifying the operating temperature range. The SCR process requires a chemical reducing agent for NO_X abatement. Today, aqueous urea solution according to ISO 18611 or ISO 22241 is most widely used as it is a very convenient and an abundant commodity. Aqueous ammonia solution is also used in some stationary installations as reducing agent. When dosed into the hot exhaust according to the amount of NO_X which should be reduced, urea decomposes and releases the active reducing agent NH_3. Hence, for NH_3 combustion engine applications there's the possibility to change the utilized reducing agent, thereby eliminating the need for a separate reactant fluid. For H_2 combustion engines one could imagine moving away from urea solution as a reducing agent and replace it with H_2 instead, since it is already available in large quantities where such engines are operated.

For some engine types and applications, exhaust gas recirculation (EGR) or water injection can be applied to reduce NO_X. Other engine internal NO_X reduction methods of modern large diesel engines are low NO_X combustion concepts (e.g. “Miller concept”). [29] In the EGR system, after a cooling and cleaning process, part of the exhaust gas is recirculated to the intake air. In this way, part of the oxygen in the intake air is replaced by CO_2 from the combustion process. This replacement decreases the O_2 content and increases the heat capacity of the combustion air, thus reducing the peak temperature of combustion and consequently slowing the formation of NO_X. EGR and water injection should be considered as an engine-internal measure rather than an exhaust gas aftertreatment system technology, due to the altered combustion concept and its impact on engine performance. Further discussion of these technologies is outside the scope of this publication.

- N_2O

For the potential N_2O emissions from NH_3 combustion engines, there currently exists no proper exhaust gas aftertreatment catalysts. N_2O is not a completely unknown pollutant, it has already been observed in engine exhaust as a side reaction product in poorly designed exhaust aftertreatment systems or during unusual operating conditions. Instead of actively decomposing N_2O, the emission could be mitigated by improved catalyst designs. Outside the engine combustion world there are N_2O aftertreatment catalysts, but the operating conditions of these are very different from typical engine exhaust which contains also residual oxygen and large amounts of water vapour. As there have been limited focussed activities on reducing N_2O in engine exhaust, the catalyst industry cannot yet assess how much of a development task it will be to find a satisfactory solution, but activities are ramping up and first results are being reported. [35]

- Unburnt & partially burnt fuel

For unburnt or partially burnt fuel components in the exhaust, an oxidation catalyst can complete the oxidation process to CO_2 and H_2O. Oxidation catalysts are widely applied for exhaust gas aftertreatment today. However, today's fossil marine distillate fuels contain typically up to 0.1% sulphur. These "traditional marine distillate fuels" have impeded the use of oxidation catalysts for such applications. For the above-mentioned alternative fuels, this restriction no longer applies for the marine applications, as these fuels do not contain significant amounts of sulphur. For dual fuel engines utilizing significant energy shares of traditional marine distillate fuel the topic must still be reviewed specifically. In general, the sulphur poisoning of oxidation catalysts strongly depends on the operation temperature. Typically, oxidation catalysts are affected by sulphur. Depending on the species which should be oxidized, the degree of sensitivity will vary. [30]

Another issue that should be highlighted is the magnitude of temperature increase while using the oxidation catalyst. When there is a significant amount of unburnt or partially burnt fuel in the exhaust, the oxidation in the aftertreatment system releases the chemical energy which can lead to high exhaust temperatures. The increased exhaust temperature and potential for the exhaust temperature to rise rapidly could damage the oxidation catalyst and any components downstream of the catalyst. While the catalyst will require a temperature above the minimum activation temperature (i.e. the light-off temperature), the catalyst could be physically damaged by excessively high exhaust gas temperatures. The exothermicity can be estimated by the concentrations of oxidizable material and core exhaust parameters, requiring basic knowledge of the engine exhaust raw emissions. These restrictions aside, the oxidation catalyst will not require any additional chemical compounds for operation as it consumes only residual oxygen still available in the exhaust after lean combustion. Thus, emission control technology, with the abovementioned restrictions, would be available for H_2, NH_3, MeOH, volatile organic compounds (VOC)/NMHC, CO, HCHO, and other hazardous air pollutants (HAPs) converting all of them to N_2, CO_2 and H_2O.

One should note that even if emission reduction data is available for an emission abatement system technology, it typically refers to very stable engine operation only and does not reflect the potentially elevated emissions during dynamic operation.

As a consequence of the abovementioned varieties of exhaust emissions, no further details can be provided in general, but as the effects are well-understood there is ample experience to provide specific guidance for individual setups.

- CH_4

For CH_4, an oxidation catalyst will struggle with the high chemical stability of the symmetric CH_4 molecule, which needs high temperatures for CH_4 oxidation light-off. A CH_4 oxidation catalyst, sometimes abbreviated MOC (methane oxidation catalyst), which would work under typical engine exhaust gas temperature conditions (including also traces of catalyst-deactivating SO_X in the exhaust), remains an unresolved challenge for emission control so far. Feasible solutions would require longer catalyst lifetime or catalyst regeneration solutions to restore the activity. Unfortunately, the last decades of work in this field have not resulted in fundamental breakthroughs or major advancements, so expectations are not too high to find a very convenient solution without requiring impacts on engine design & flexibility (impact on engine dynamic capabilities and performance).

Non-thermal plasma is proposed as an alternative method to reduce CH_4 slip emissions, utilizing electric power to convert methane to CO and H_2O. The non-thermal plasma generates hydroxyl radicals which react with methane, breaking it down via a series of transient species mainly to CO and H_2O. Small scale laboratory tests with plasma systems confirmed methane reductions at a temperature of 190°C for model exhaust gas. The model exhaust gas did not contain any SO_X, but the technology is claimed not to be impacted by the traces of SO_X in engine exhaust gas. [31] The electrical power consumption of the plasma system is estimated at around 4% of the engine power, but the technology is still under development, as this technology is still pending validation and scaling to large engine exhaust conditions and size. [32]

Recuperative oxidizers have been demonstrated in few land-based applications to be another alternative for reducing CH_4 emissions. However, their thermal after-burning of CH_4 in the exhaust requires large reactor systems. The functional principle of recuperative oxidizers is based on an internal bed (typically sand or ceramic material) that is heated up to 800 ºC, [33] enabling the ignition of CH_4. Thus, start-up of a cold reactor is associated with a high additional power consumption and these systems have a long start-up period (up to several days depending on reactor size). Therefore, the system is preferably kept hot in standby conditions resulting in additional power consumption. Finally, if the hydrocarbon emission is too low to keep up the sufficient temperature during operation, additional fuel will have to be added.

Exhaust gas recirculation (EGR) has proven to be a viable method for some engine types to reduce CH_4 emissions in combination with engine internal combustion measures. [34] Reduction is dependent on the recirculated fraction, while clogging due to soot particles and corrosion where sulphuric acid is present are potential issues.

- NH_3

Even though NH_3 has not been used as an engine fuel in traditional engine technologies, the oxidation of NH_3 in engine exhaust has been frequently applied. Instead of NH_3 originating from the engine as unburned fuel, it has its origin in unreacted reducing agent downstream of the SCR process. Even though the root might be different, the method for abatement would be identical, an ammonia slip catalyst (ASC) or sometimes even referred to as clean-up catalyst oxidizing NH_3, preferably to N_2. Unburned fuel from ammonia combustion may be primarily used as SCR reagent, and if an excess of ammonia is left after NO_X reduction reactions, basic catalyst concepts for unburned fuel in NH_3 combustion engine emissions are therefore already available. For NH_3 combustion engines, further refinement of the catalysts may be needed due to higher concentrations of NH_3 emitted by the engine.

- PM

PM emission characteristics and concentrations may change for all combinations in which liquid hydrocarbon fuels are still used, whether as a main fuel or only for lighting up another air-fuel mix in the combustion chamber as a pilot injection. In addition, lubrication oil also creates particle emissions, independent of the combustion concept. Compared to residual fossil fuel oils currently used in large engine applications, alternative ash and sulphur-free low- or zero-carbon fuel candidates are expected to yield lower PM emissions. Thus, in most cases, meeting PM requirements for alternative fuels may be achievable using only engine internal measures. Aftertreatment PM reduction methods might be considered if there is a need or desire for further reduction.

Solutions to remove PM from engine exhaust are already well-established in the on-road and non-road mobile-machinery sectors. Due to their typical application, they are called wall-flow diesel particulate filters (DPF). Exhaust particles mainly composed of soot are filtered from the exhaust gas by physical interaction with the DPF ceramic. Typical filtration rates for liquid fuel operation are >97% for PN (particle number) and black carbon for EN590 fuel. [36] For PM, the filtration was determined on average around 90% (EN590) and 80% (MGO) due to the effect of condensable PM when using alternate PM sampling methods to hot-gas filtration sampling during certification of a 2 MW marine engine. [36] For PM emission reductions, the measurement result is highly dependent on the measurement method and the fuel. [37] Today DPFs are optional equipment for engine applications using only distillate or gaseous fuels, as the high ash content of other traditional fuel operations would fill up the filtration structure too quickly. However, this limitation in the future is non-existent for all alternative fuel candidates, and if needed the use of DPF to meet lowest PM emissions would therefore no longer be impeded by the fuel quality. It should be mentioned though, that in a reference, [30] a catalytic coated DPFs has been demonstrated for 100 h on an engine testbed to function efficiently on a 2 MW engine operated on residual fuels.

DPF systems on seagoing vessels for < 3 MW marine engines running on traditional marine distillate fuels were first launched in 2005. [38] Consequently, at least one emission control technology for removing black carbon and soot emissions from alternative fuels already exists if required. It is noted that for double digit MW power range engines the DPF technology has so far not been applied. Instead, DPFs have been installed voluntarily on 100's of ocean going yachts with a focus on auxiliary high-speed engines from below 200 kW of up to about 3-5 MW size as well as on ferries, work vessels and government vessels also additionally for propulsion engines. DPF installations on commercial ocean going vessels are so far rare on medium-speed and non-existent on low-speed engines. Limited reports exist, to validate successful long term DPF operation on commercial ocean going vessels. Further, systems where a DPF is operated on traditional marine distillate fuels and corresponding lubrication oils requires regular DPF filter cleaning for ash removal. This requirement will remain for dual fuel engines utilizing significant energy shares of such fuel. The main impact of mounting a wall-flow DPF on an alternative fuel engine is the increase in backpressure, because the exhaust gas flow is forced to migrate through a finely structured wall. Large medium speed and low speed engines are particularly sensitive to increased exhaust gas backpressure compared to high-speed engines. However, they could consider using also particle removal methods like bag filters and dry ESP as used in some stationary plants. [28][36][39][40] It is to be noted that dry ESPs and bag filters are today used in applications mostly burning high ash and sulphur fossil fuels. Their expected PM reduction impact on alternative fuels with low particulate emissions may therefore be decreased and tests are needed before reduction efficiency can be verified.

For ships and power plants operating on high sulphur fossil fuels in combination with CCS in the future and equipped with an exhaust gas cleaning system (scrubber) unit for SO_2 reduction a wet ESP for additional PM reduction could possibly be a new technology option. Particulate reduction in first laboratory tests has been in the order of > 97%. [36] However, the system will generate wastewater that needs handling; onboard or ashore.

Particle removal technology not only reduces pollutant emissions but also enables optimisation of all downstream equipment such as other exhaust aftertreatment, heat recovery or carbon capture systems due to the almost particle-free exhaust gas.

- General note

Summarizing, the main exhaust emission control technologies for all the emission compounds were attributed and their benefits and limitations were presented. For a complete exhaust aftertreatment system (EATS) architecture, their arrangement and combination are also important aspects. However, for these considerations general statements cannot be made, as the interactions of the involved chemical processes depends on numerous factors which vary among the various listed combinations. Proper design of a full EATS is certainly more than just a sum of all the functionalities. Negative interactions can cause additional issues, but using synergies and cross-sensitivities of the EATS functions can also yield more compact and better performing systems than expected from a mere consideration of the individual subcomponents. Once again, the benefit and role of CIMAC in providing a platform for industry-wide exchange to support the future development challenges is reiterated.

4 Future drivers for emission reduction

The wide variety of alternative fuels under discussion for the large engine industry is not driven by cost optimisation but mainly by the ambition to reduce climate impact – foreseeably, this type of fuel change will lead to higher costs. This simple fact has prompted the authorized institutions such as IMO for marine application to discuss regulation to foster solutions that reduce climate impact either decreasing their price tag and/or by increasing the cost for usage of the more climate-impacting fossil fuels. Particularly in the international global shipping industry, global concepts must be incorporated to ensure a level playing field. In these concepts for international shipping by IMO or by the European Union such as Fuel EU Maritime and Taxonomy (including stationary and marine sector) the full lifecycle of the fuel is being considered. In other words, instead of considering tank to propeller only, in the maritime sector, the full well to wake picture is being considered. Carbon capture technology would be regarded as part of the well to wake picture to be assessed. It is important to note, that in many current and upcoming regulations, depending on the sector, not only are CO_2 emissions being considered, but also climate-impacting emissions released by the fuel used, for example CH_4 and N_2O. Additionally, Black Carbon and its impact on Arctic ice melting is discussed at IMO.

Today the early trials of additional voluntary pricing in emissions are seen, as some merchant vessels are transporting goods with reduced carbon footprint for customers specifically requesting and paying a premium for it like IKEA, Nike or Walmart. [41] So far, this has been achieved by blending biofuels with the fossil fuel to achieve a lower carbon footprint than fossil fuels alone. In the near future, instead of a partial substitution, full replacement of the fossil fuel may be an option. However, as explained above, the limited availability of biofuels will require a move to other alternative fuels, as discussed here, to achieve the announced long-term GHG reduction ambitions.

Besides climate impacting emissions, there are new initiatives in which local pollutant emissions are also reduced beyond the legal requirements of e.g. IMO Emission Control Areas (ECA).

Likewise, these reductions are primarily motivated by final service customers paying a premium for the reduced emission of pollutants. Examples are found from some cruise ships and ferries as well as for construction and work vessels. The offshore wind industry as a renewable technology industry with exposure to the general public is a good example of the latter. Some classification societies have responded with voluntary low pollutant emission labels which are issued if the vessel is fulfilling more stringent emission levels than IMO Tier III.

The previously mentioned voluntary (ultra-)low emission profiles are used in some applications. With such voluntary labels the operators can document reducing emissions below current requirements and the reduction of emission components not currently regulated both in stationary and in marine. For some applications and engine power ranges, the technology has been demonstrated to achieve currently lowest emission levels for heavy-duty large engines in marine applications [42][43] and stationary applications. [44][45][29] For some other applications and power ranges further development is needed. Due to the costs of emission reduction technology, a robust and technology neutral legal framework is important to ensure effective emission reductions and to maintain a level playing field. For long-term strategic planning of the industry, a global alignment in regulations is desired. The reduced pollutant emissions would come on top of reduced climate impact achieved by the fuel switch.

In terms of new technology developments outside emission control systems, hybridisation and digitalisation will also support the efforts of pollutant abatement. For instance, hybridisation in large engine applications may enable further optimisation of engine operation and emission control system. Digitalisation generally assists in gathering operational and statistical data of systems operating in the field, which is a valuable foundation for optimisation.

5 Conclusions

In the future a much wider variety of fuels and engine concepts will be experienced, consequently, there will be much more diversity in exhaust gas compositions and emission compounds. Engine development and exhaust gas aftertreatment have the potential to address the expected pollutants, though some will still require further development efforts. As the interaction of exhaust gas aftertreatment technologies and engine optimisation becomes even more important for alternative fuels and low emission profiles, engine developers and exhaust gas aftertreatment designers must work closely together to solve the future emission challenges.

6 References

[1] CIMAC Working Group 5, White Paper on CCUS – Carbon Capture, Utilisation and Storage, [Online]. Available: https://www.cimac.com/cms/upload/workinggroups/WG5/CIMAC_Guideline_CCUS__Carbon_Capture_Utilisation_and_Storage_2022-08-09-Final.pdf [Accessed: May 27, 2025].

[2] S. McAllister, J. Y. Chen, and A. C. Fernandez-Pello, "Thermodynamics of combustion" in *Fundamentals of Combustion Processes*. New York, NY: Springer, 2011.

[3] CIMAC GHG Strategy Group, Position Paper and White Paper 1 and 2, [Online]. Available: https://www.cimac.com/publications/publications350/cimac-ghg-strategy-group-position-paper-and-white-papers.html [Accessed: May 27, 2025].

[4] T. da Silva Veras, T. S. Mozer, D. da Costa Rubim Messeder dos Santos, and A. da Silva César, "Hydrogen: Trends, production and characterization of the main process worldwide" *Int. J. Hydrogen Energy*, vol. 42, no. 4, pp. 2018–2033, 2017.

[5] Methanol Institute, Methanol Price and Supply/Demand, 2022. [Online]. Available: www.methanol.org/methanol-price-supply-demand [Accessed: May 27, 2025].

[6] M. E. Dry, "High quality diesel via the Fischer–Tropsch process – a review" *J. Chem. Technol. Biotechnol.*, vol. 70, pp. 43–50, 2002.

[7] European Chemicals Agency (ECHA), "REACH H_2: Annex IV/V of Regulation (EC) No 1907/2006 (REACH); NH_3: 01-2119488876-14 REACH; MeOH: 01-2119433307-44-xxxx; CH_4: Annex IV/V of Regulation (EC) No 1907/2006 (REACH); HVO: 01-2119450077-42-0000 / -0001 / -0002" [Online]. Available: https://echa.europa.eu/ [Accessed: May 27, 2025].

[8] ClassNK, "Alternative fuel guidance updates" The Motorship, [Online]. Available: https://www.motorship.com/alternative-fuels-and-lubricants/classnk-updates-alternative-fuel-guidance/1494052.article [Accessed: May 27, 2025].

ClassNK, "Guidelines and guidance documents" [Online]. Available: https://www.classnk.or.jp/account/en/Rules_Guidance/ssl/guidelines.aspx [Accessed: May 27, 2025].

[9] American Bureau of Shipping (ABS), Requirements for Liquefied Hydrogen Carriers, Oct. 2023. [Online]. Available: https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/342-requirements-for-liquefied-hydrogen-carriers_2023/342-liquefied-hydrogen-carriers-reqts-oct23.pdf [Accessed: May 27, 2025].

American Bureau of Shipping (ABS), Requirements for Hydrogen-Fueled Vessels, May 2023. [Online]. Available: https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/338-requirements-for-hydrogen-fueled-vessels/338-hydrogen-fueled-vessel-reqts-may23.pdf [Accessed: May 27, 2025].

American Bureau of Shipping (ABS), Requirements for Ammonia-Fueled Vessels, Sep. 2023. [Online]. Available: https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/325-requirements-for-ammonia-fueled-vessels_2023/325-ammonia-fueled-vessels-reqts-sep23.pdf [Accessed: May 27, 2025].

[10] Lloyd’s Register (LR), LR-RU-012: Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels, Notice No. 3, July 2023, [Online]. Available:

https://www.lr.org/en/knowledge/lloyds-register-rules/rules-and-regulations-for-ships-using-gases-or-low-flashpoint-fuels/ [Accessed: May 27, 2025].

[11] DNV, DNV-RU-SHIP Pt. 4 Ch. 3: Rotating Machinery – Drivers, July 2023. [Online]. Available: https://www.dnv.com/news/2023/dnv-has-published-the-july-2023-edition-of-the-rules-for-classification-of-ships-245133/ [Accessed: May 27, 2025].

DNV, DNV-RU-SHIP Pt. 6 Ch. 2: Propulsion, Power Generation and Auxiliary Systems, July 2023. [Online]. Available: https://www.dnv.com/news/2023/dnv-has-published-the-july-2023-edition-of-the-rules-for-classification-of-ships-245133/ [Accessed: May 27, 2025].

[12] IMO, MSC.1-Circ.1621: Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel, 11 November 2020. [Online]. Available: https://www.imo.org/en/OurWork/Safety/Pages/MSC-Circulars.aspx [Accessed: May 27, 2025].

[13] IMO, MSC.1-Circ.1687: Interim Guidelines for the Safety of Ships Using Ammonia as Fuel, Dec. 2024. [Online]. Available: https://www.imo.org/en/OurWork/Safety/Pages/MSC-Circulars.aspx [Accessed: May 27, 2025].

[14] K. Mollenhauer and K. Schreiner, "History and fundamental principles of the diesel engine" in *Handbook of Diesel Engines*, K. Mollenhauer and H. Tschöke, Eds. Berlin, Heidelberg: Springer, 2010.

[15] Y. B. Zel'dovich, "The oxidation of nitrogen in combustion explosions" *Acta Physicochimica U.S.S.R.*, vol. 21, p. 577–628, 1946.

[16] E. Sher, "Environmental aspects of air pollution" in *Handbook of Air Pollution from Internal Combustion Engines*. Boston, MA: Academic Press, 1998, pp. [page range missing].

[17] IPCC, Climate Change 2022: Mitigation of Climate Change, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2019. [Online]. Available: https://www.ipcc.ch/report/ar6/wg1/ [Accessed: May 27, 2025].

[18] M. Lackner, W. Y. Chen, and T. Suzuki, "Introduction to Climate Change Mitigation" in *Handbook of Climate Change Mitigation and Adaptation*, W. Y. Chen, T. Suzuki, and M. Lackner, Eds., Cham: Springer, 2017.

[19] R. Ryser, "The value of turbocharging for combustion and performance in the application of alternative fuels on large engines" in *6th RGMT Proceedings*, Rostock, 2020, pp. 237–254. Rostock, Germany: FVTR Forschungszentrum für Verbrennungsmotoren und Thermodynamik Rostock GmbH.

[20] L. B. Weger, J. Leitao, and M. G. Lawrence, "Expected impacts on greenhouse gas and air pollutant emissions due to a possible transition towards a hydrogen economy in German road transport" *Int. J. Hydrogen Energy*, vol. 46, no. 7, pp. 5875–5890, 2021.

[21] E. Renner and R. Wolke, "Formation of secondary inorganic aerosols by high ammonia emissions simulated by LM/MUSCAT" in *Air Pollution Modeling and Its Application XIX*, C. Borrego and A. I. Miranda, Eds., NATO Science for Peace and Security Series C: Environmental Security. Dordrecht: Springer, 2008.

[22] S. Helmers, F. H. Top, and L. W. Knapp, "Ammonia injuries in agriculture" *J. Iowa Med. Soc.*, vol. 61, no. 5, pp. 271–280, May 1971.

[23] G. A. Birken, P. J. Fabri, and L. C. Carey, "Acute ammonia intoxication complicating multiple trauma" *J. Trauma*, vol. 21, no. 9, pp. 820–822, Sep. 1981.

[24] National Research Council, Acute Exposure Guideline Levels for Selected Airborne Chemicals: Volume 6. Washington, DC: The National Academies Press, 2008. [Online]. Available: https://doi.org/10.17226/12018 [Accessed: May 27, 2025].

[25] IMO, MEPC.391(81): 2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels, 2024. [Online]. Available: https://www.imo.org/en/OurWork/Environment/Pages/MEPC.aspx [Accessed: May 27, 2025].

[26] G. Myhre et al., "Anthropogenic and natural radiative forcing" in *Climate Change 2013: The Physical Science Basis*, T. F. Stocker et al., Eds., Cambridge, UK and New York, NY, USA: Cambridge University Press, 2013.

[27] F. Dominici, R. D. Peng, M. L. Bell, L. Pham, A. McDermott, S. L. Zeger, and J. M. Samet, "Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases" *JAMA*, vol. 295, no. 10, pp. 1127–1134, 2006.

[28] T. C. Bond et al., "Bounding the role of black carbon in the climate system: A scientific assessment" *J. Geophys. Res. Atmos.*, vol. 118, no. 11, pp. 5380–5552, 2013.

[29] European Commission, Best Available Techniques (BAT) Reference Document for Large Combustion Plants (LCP BREF), 2017. [Online]. Available: https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/JRC_107769_LCPBref_2017.pdf [Accessed: May 27, 2025].

[30] K. Johansen, P. B. Kristensen, R. Mortensen, A. S. Simonsen, J. Phair, S. Mølgaard, and J. P. Hansen, Development of Catalytic Filter for Marine Engines, MUDP Report, April 2022. Copenhagen, Denmark: The Danish Environmental Protection Agency. [Online]. Available: https://www2.mst.dk/Udgiv/publications/2022/04/978-87-7038-416-2.pdf [Accessed: May 27, 2025].

[31] H. Winnes, E. Fridell, J. Ellis, B. Forsman, D. Williams, and H. Westermark, "Aftertreatment of methane slip from marine gas engines" Oct. 14, 2020. [Online]. Available: https://lighthouse.nu/images/pdf/FS12_2020-Aftertreatment-of-methane-slip-from-marine-gas-engines.pdf [Accessed: May 27, 2025].

[32] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, Reducing Methane Emissions Onboard Vessels, Oct. 2022. [Online]. Available: https://cms.zerocarbonshipping.com/media/uploads/publications/Reducing-methane-emissions-onboard-vessels.pdf [Accessed: May 27, 2025].

[33] Dürr Group, "Heat generation and emission reductions at landfills" 2019. [Online]. Available: https://www.durr-group.com/en/duerrmore/2019/heat-generation-and-emission-reductions-at-landfills [Accessed: May 27, 2025].

[34] F. Unfug, V. Bellucci, and G. Weisser, "Significant performance improvements by using a low-pressure EGR system for the new X-DF2.0" presented at the 30th CIMAC World Congress on Combustion Engines, Busan, South Korea, 2023, Paper No. 100.

[35] D. Cano Blanco, M. Elsener, J. D'Alessandri, D. Peitz, D. Ferri, and O. Kröcher, "Critical aspects in the catalytic emission control of exhaust gases containing NH_3, NO_x and N_2O" *Journal of Ammonia Energy*, vol. 2, no. 1, pp. 64–72, 2024.

[36] K. Lehtoranta, J. T. Kortelainen, D. Peitz, and J. Jokiluoma, "Reducing particle emissions from marine engines" MTZ Worldwide, vol. 85, pp. 56–65, Oct. 2024.

[37] G. Hellén and J. Ristimäki, "Particulate emissions of residual fuel operated diesel engines – background, particulate size distributions, measurement methods and potential abatement measures" presented at the 25th CIMAC World Congress on Combustion Engines, Vienna, Austria, 2007, Paper No. 56.

[38] D. Peitz, "BC after diesel particulate filters" presented at the 6th ICCT Workshop on Marine Black Carbon Emissions, Helsinki, Finland, Sept. 17, 2019. [Online]. Available: https://theicct.org/wp-content/uploads/2019/09/3_Peitz_Diesel_particulate_filters.pdf [Accessed: May 27, 2025].

[39] U.S. Environmental Protection Agency, Standards of Performance for Stationary Compression Ignition Internal Combustion Engines, Federal Register, vol. 76, no. 124, pp. 37954–38034, Jun. 28, 2011. [Online]. Available: https://www.govinfo.gov/content/pkg/FR-2011-06-28/pdf/2011-15004.pdf [Accessed: May 27, 2025].

[40] United Nations Economic Commission for Europe (UNECE), Guidance Document on Control Techniques for Emissions of Sulphur, Nitrogen Oxides, Volatile Organic Compounds and Particulate Matter (including PM10, PM2.5 and Black Carbon) from Stationary Sources, Apr. 2021, ch. "OO. New Stationary Engines" pp. 253–265. [Online]. Available: https://unece.org/sites/default/files/2021-04/ENG_G1500924.pdf [Accessed: May 27, 2025].

[41] A. Bhargava, S. Hoffman, and N. Jakic, "Climate sustainability in retail: Who will pay?" McKinsey & Company, Jul. 2022. [Online]. Available: https://www.mckinsey.com/industries/retail/our-insights/climate-sustainability-in-retail-who-will-pay [Accessed: May 27, 2025].

[42] D. Peitz, D. Gschwend, K. Christianen, and K. Lehtoranta, "Ultra-low emission medium-speed engine for EU Stage V" *MTZ Worldwide*, vol. 82, pp. 46–53, Nov. 2021.

[43] D. Peitz, D. Gschwend, S. Schiegg, Y. Loulidi, K. Lehtoranta, T. Murtonen, and H. Vesala, "Near zero emission medium speed engine for EU Stage V & ULEV" in *6th RGMT Proceedings*, Rostock, 2020, pp. 180–207. Rostock, Germany: FVTR Forschungszentrum für Verbrennungsmotoren und Thermodynamik Rostock GmbH.

[44] D. Peitz, M. Hanschke, and M. Kühnel, "Exhaust gas aftertreatment for stationary gas engines in times of energy transition and renewable fuels" in *12th Dessau Gas Engine Conference Proceedings*, Dessau, 2022

[45] K. Sandelin, D. Peitz, and H. Ott, "Emission control for engine test facilities" presented at the 29th CIMAC World Congress on Combustion Engines, Vancouver, Canada, 2019, Paper No. 455

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CIMAC is the leading global non-profit association promoting the development of ship propulsion, train drive and power generation. The association consists of National Member Associations and Corporate Members in America, Asia and Europe. CIMAC provides a forum for technical interchange with all parties interested in piston engines, gas turbine systems, non-shaftline propulsion systems, automation and controls, system integration and digitalization solutions.

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