Ammonia combustion challenges for IC engines

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Ammonia Energy Conference 2021 – Australia

Future fuels and emissions

Kjeld Aabo
Director New technologies
Sales and Promotion Two stroke Marine
Member of WG ISO 8217 & Chairman CIMAC Fuel

MAN Energy Solutions
Future in the making

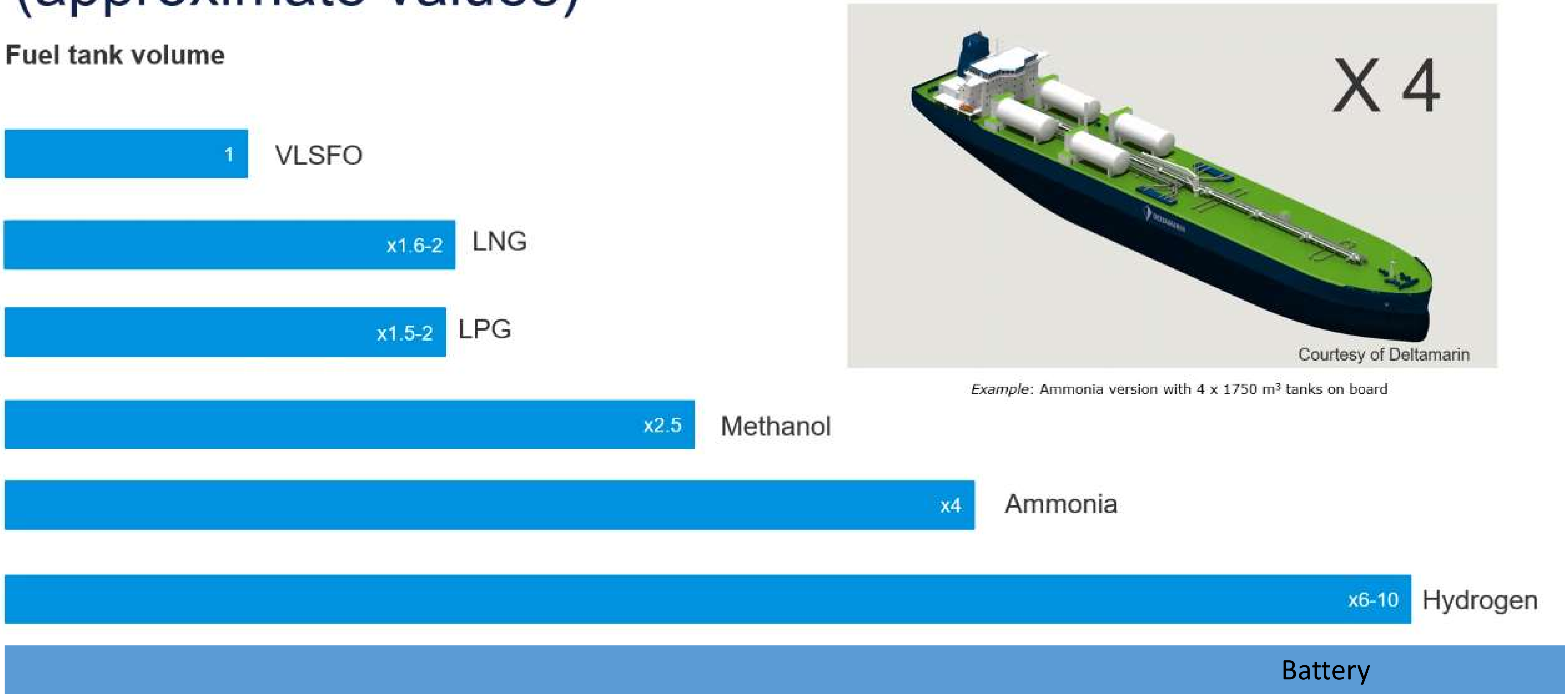
Why ammonia ?

	Hydrogen	Liq. NG	Methanol	LSHFO	Gasoline	Ammonia
Boiling point (°C)	-253	-162	65	160-750	27-225	-33
Vapor pressure @ 20°C (kPa)	N/A	N/A	13		5	857
Density (20°C, 1 bar) (kg/m³)	0.08	0.66	790	920 - 1060	740	0.71
Standard storage form	gas					Liquid
Storage pressure (bar) at 20°C	700					10
Storage density (kg/m³)	39.7	194	790	920 - 1060	740	610
Low Heat Value (MJ/kg)	120	49	19.9	42.7	44	18.8
Energy density (storage conditions) (MJ/l)	8.52	20.7	15.72	36.3	32	12.82
Heat of vaporization (kJ/kg)	461	510	1168	?	180-350	1370

- The cost of storage and transportation
- The volume of tank

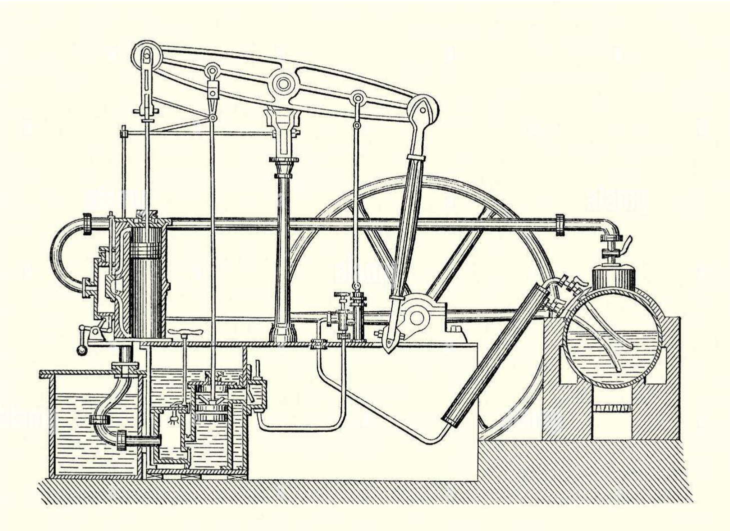
Alternative fuels will require more fuel volume (approximate values)

Fuel tank volume



Example: Ammonia version with 4 x 1750 m³ tanks on board

The use of NH_3 as fuel for vehicles = an old story



Ammonia Engine : French engineer, Delaporte (1870)

NH_3 as fuel for vehicles = an old story

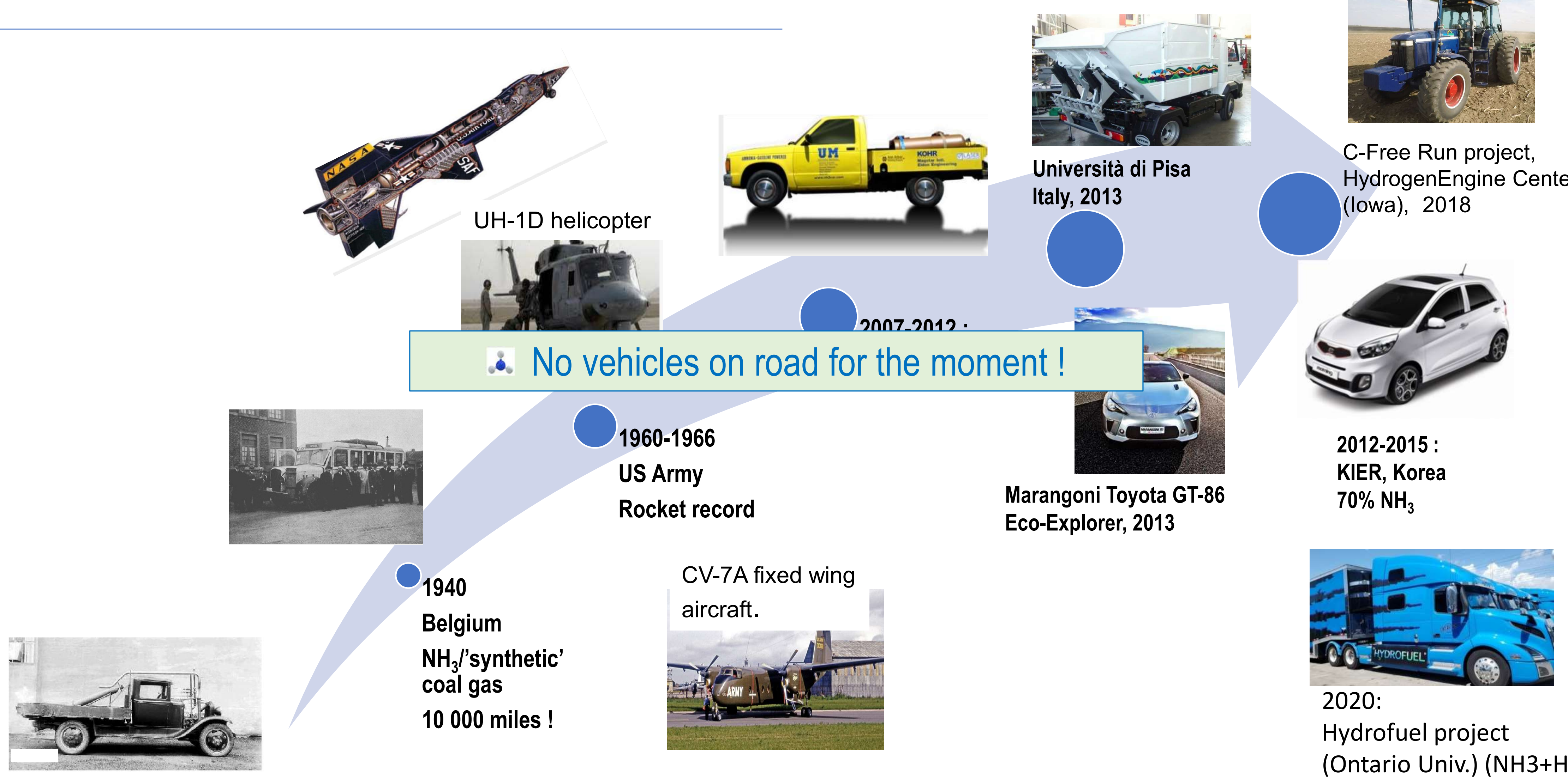


Fig. 4 – Norsk Hydro power company first converted truck to run on ammonia [79].

Some recent examples : Spark Ignition Engine

CFR
Gas PFI

Iowa university, DTU
NH_3+Gasoline
2012-2013

Twin Lombardini (2 cyl./0.25 l)
Gas PFI
LPG injector

Pisa University
NH_3+H_2
Range Extender
Frigo et al.
IJHE 2012

GM engine (4 cyl/0.6 l)
Gas PFI
Direct gas Inj
EMULSION

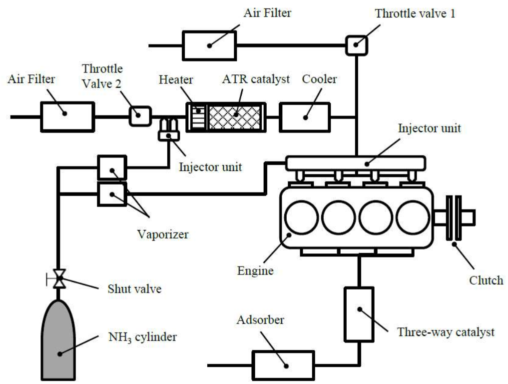
Texas university
Gasoline+ethanol (max30%)+NH_3 (17%)
Haputhanthri et al.
ASME 2017

Heavy duty
(6 cyl./1.8l)
Premixed PFI – CR 10.5

KIMM/KIER
Natural Gas + NH_3 (50%)
Oh et al.
FUEL 2021

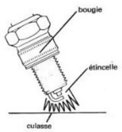
4 cyl./0.9l
Gaseous PFI – CR 9

Toyota
NH_3 + H_2 Thermal Reformer
cold start + SCR catalyst
Koike et al.
IJHE 2021



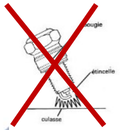
Some recent examples : Compression Ignition Engine

Yammar Engine (0.3 l)
Liquid premixture GDI (200 b)



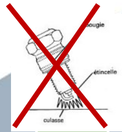
Iowa Energy Center
Dual-Fuel Premixture
DME (min 40% /NH_3)
Ryu et al. 2014

3 cyl.CI engine
CR 17.5 (0.54l)
Diesel DI



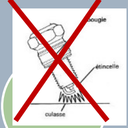
KIER
Diesel min 62%/NH_3
Dual Fuel
Woo, NH3 conference, 2014

Single cylinder
research engine (0.5l)
Gas fully premixed



Louvain-VRIJE –
Université d'Orléans
HCCI
NH_3+H_2
Pochet et al., PROCI 2018

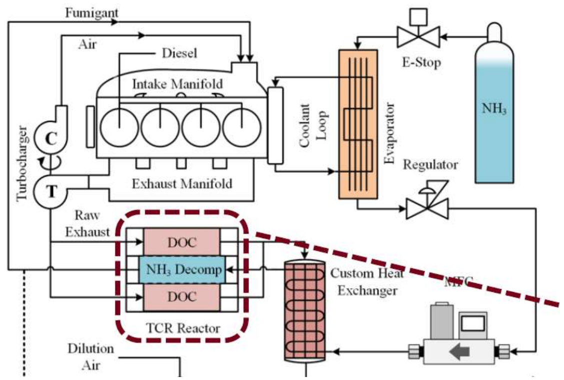
John Deere,
4 cyl. (1.125l)
CR 17
Diesel DI



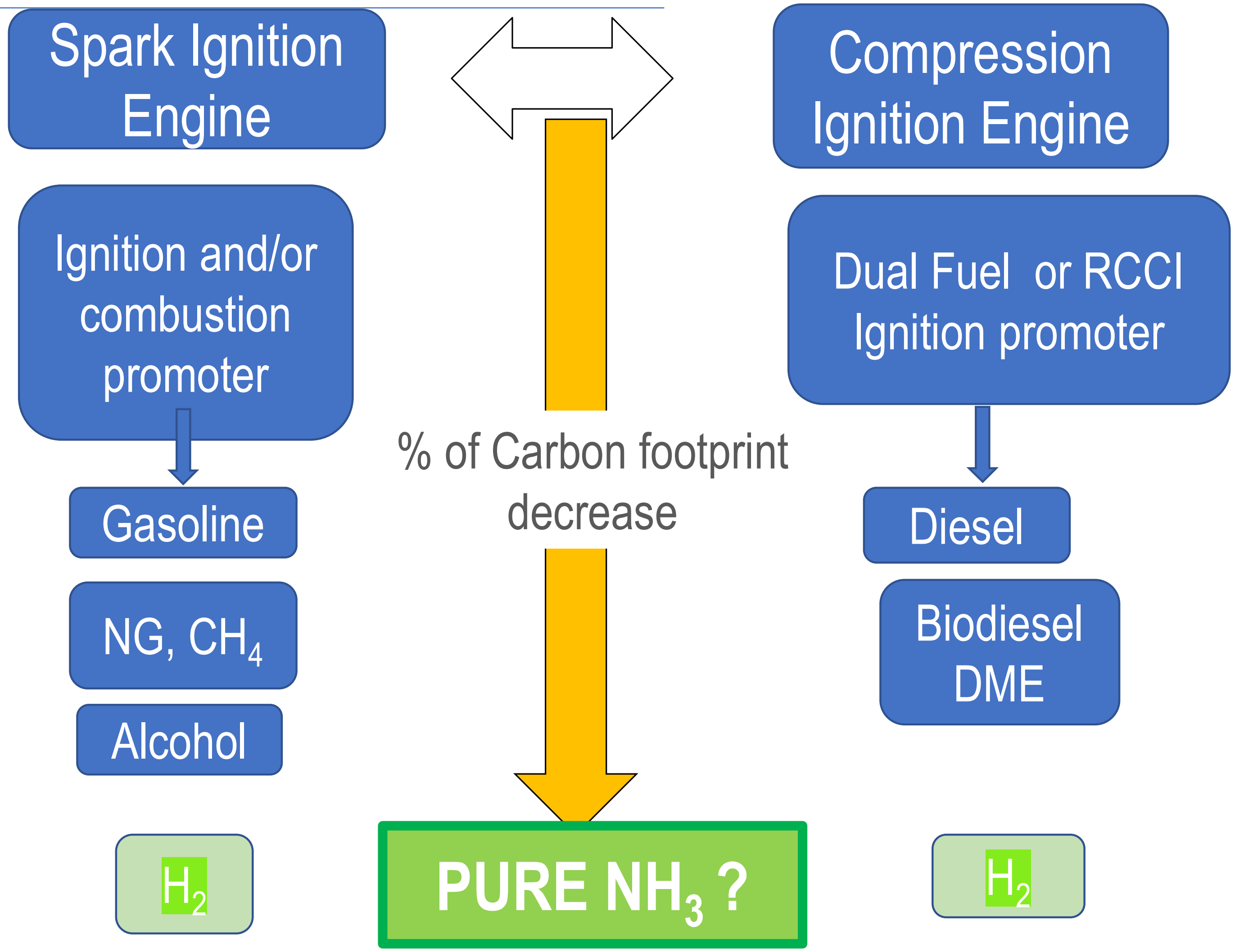
T.E. Murphy Engine
Research Lab
(Minneapolis)
Diesel (45% in Energy)/NH_3
Thermal Chemical Recuperation
- seed with H_2
Northrop et al.
NH3 event 2021

Caterpillar,
1 cyl. (2.44l)
CR 16.25, 900 rpm (8b), Diesel DI

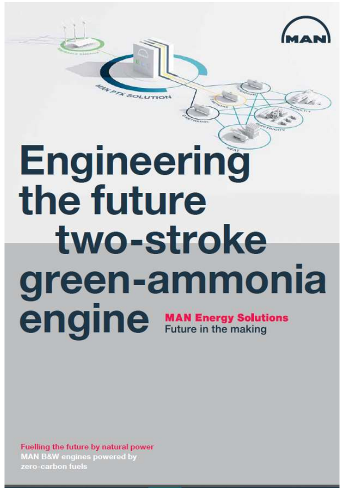
NRC
Diesel (60% in Energy)/NH_3
Dual Fuel
Split Diesel injection = reduction of unburnt NH_3
Yousefi et al. 2021



Case of NH_3 as fuel for ICE



Ammonia for Marine Engines



It is observed that ammonia is a promising alternative fuel for achieving IMO 2050 targets, but there are no experimental results of ammonia-fuelled mid- or heavy-duty engines [25], including marine diesel engines, and there is a lack of case studies to show the benefits of ammonia for maritime transportation. Therefore, in this paper, a case study with ammonia-fuelled general cargo ship is done for

The case ship represents both short and moderate voyages. There are three fuel options in the study. The first one is MDO only, the second one is 60% ammonia and 40% MDO dual-fuel, and the last one is 95% ammonia and 5% MDO dual-fuel. One of the novelties of the study is considering two different ammonia proportions at the case study. Another novelty of the study is three different ammonia types are classified according to their production method are considered. The current international maritime regulations target tank-to-propeller emissions [40]. Thus, all ammonia types are seen as reducing the carbon intensity of maritime

Using ammonia and reducing the energy fraction of MDO results in decreasing SO_X and PM emissions, due to the sulfur-free structure of ammonia. Besides its CO_2 reduction potential, using ammonia on marine diesel engines improves air quality and reduces acidification due to the reduction of mentioned emissions. It is also shown that 60% ammonia energy fraction reduces NO_X emissions, but the SCR is required to comply with the NO_X limits when 95% ammonia energy fraction is used. The only concern with using ammonia is N_2O emission. The case study showed that the N_2O emissions increase with the increase of ammonia energy fraction and this leads to a reduction in the environmental benefit of ammonia. Until N_2O emission control measures, advanced combustion concepts, after-treatment units, etc., are developed for marine diesel engines, 60% ammonia energy fraction is the most reasonable choice if all emission types (CO_2, NO_X, N_2O, SO_X, and PM) are considered.

Global ammonia combustion characteristics

- stoichiometric combustion properties (25°C, 1 atm)

higher fuel consumption : fuel tank

	Hydrogen	LNG	Methanol	FO	Ammonia
Stoichiometric air/fuel ratio (kg/kg)	34.2	17.65	6.46	14.6	6.06
Flammability limits in air (vol.%)	4.5-75	5-17	6.7-36	1.3-7.6	15-30
Laminar burning velocity (cm/s)	210	38	40	40 ?	7
Auto-ignition temperature (°C)	537	595	440	>225	651
Research octane number (-)	>120	120	109	0	>120
Adiabatic flame temperature (°C) [	2110	1950	1880	2030	1880

No good combustion properties even for SI or CI engines!

very low flame speed

high auto-ignition temperature

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Research gaps for clean and efficient NH_3 engine

Challenges	Impacts	Research needs (Experiments & modeling)
Hard to ignite	Cold start Need ignition strategy/promoter	(Auto-) Ignition properties of NH_3 blends & related chemical kinetics
Narrow flammability	Stability/operability problems	Extinction and stability characteristics of NH_3 blends
Slow flame propagation	Stability/operability problems Depleted thermal efficiency	Flame propagation characteristics & chemical kinetics of NH_3 blends
Fuel-bound nitrogen	Pollutant emissions	Chemistry and physics of low-emission combustion modes