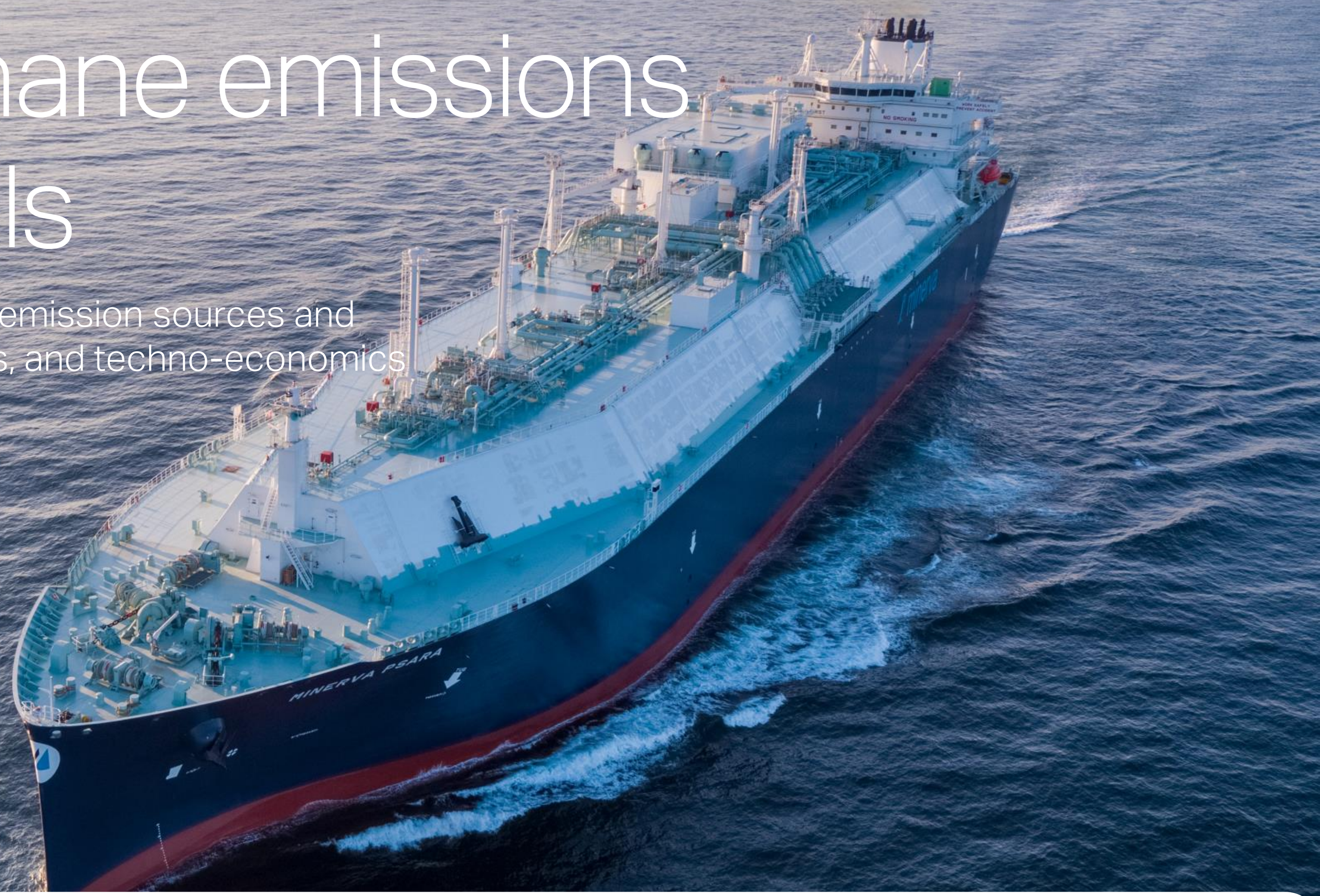
Welcome to the webinar – we will begin shortly…

Reducing methane emissions onboard vessels

An overview of regulatory drivers, methane emission sources and levels, reduction technologies and solutions, and techno-economics



Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

Working group members:

ABS, Alfa Laval, bp, Daphne Technology, Hitz Hitachi Zosen, MAN Energy Solutions Future in the making, Mitsubishi Heavy Industries, Mitsui & Co., Norden, NREL Transforming ENERGY, NYK Line Nippon Yusen Kaisha, Stolt Tankers, Sumitomo Corporation, TGE Marine, Topsoe, TotalEnergies, Volcano Volcano Co.,Ltd.

On Today's Agenda:

01 Introduction

02 Paper Highlights

03 Industry Perspectives:

- MAN Energy Solutions
- Daphne Technology
- Topsoe

04 Panel discussion & audience Q&A

05 Closing

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#methane

Accelerating the transition to zero carbon shipping

We set the course for a sustainable transition

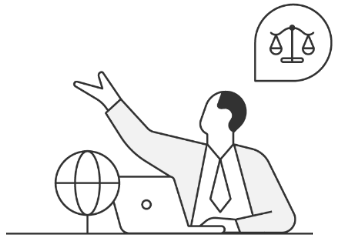
The Center consistently assesses, informs and guides the industry transition journey and is recognized as a change leader, trusted adviser and leading knowledge hub for maritime decarbonization.

The Center applies a holistic approach and promotes sustainable pathways that take environmental and social aspects into consideration, recognizing that the transition must be safe and just for all.

We drive collaborative research, development, and innovation

The Center offers a safe space for collaboration that unites players across the maritime value chain behind a shared mission.

The Center systematically informs and inspires transition pathways through applied research and innovation that removes uncertainties and barriers, creating solutions for maritime decarbonization.



We advocate regulatory reform

The Center seeks to influence global, regional and national decarbonization strategies and push for the needed policies and regulations to accelerate maritime decarbonization.

The Center bases its recommendations for enabling policy frameworks and global standards on data, research and science.

In line with Center values: Determination, Collaboration, Courage and Care and the right focus on diversity, health and inclusion to nurture an innovative and productive environment where people can thrive and grow.

This work is part of the Onboard Vessel Solutions Paper Series:

Vessel Emission Reduction Technologies & Solutions

The paper series covers the impact and role of vessel greenhouse gas and air pollutant emission reduction in maturing alternative fuel pathways.

Determining the Impact and Role of Onboard Vessel Emission Reduction

https://www.zerocarbonshipping.com/publications/determining-the-impact-and-role-of-onboard-vessel-emission-reduction/

Reducing Methane Emissions Onboard Vessels

https://www.zerocarbonshipping.com/publications/reducing-methane-emissions-onboard-vessels/

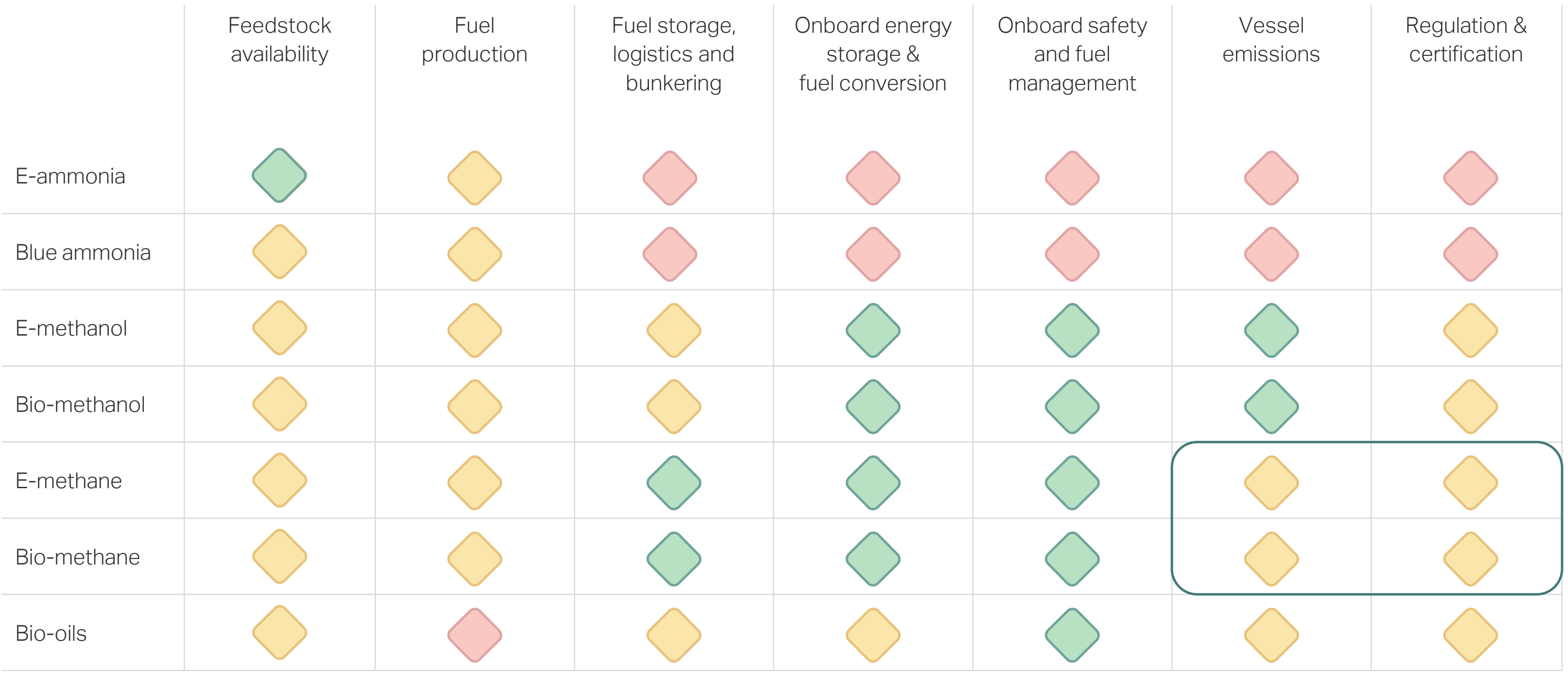
Managing Emissions from Ammonia-Fueled Vessels

Coming soon!

Managing Biodiesel Onboard Vessels and Quantifying their Emission Levels

Coming soon!

Fuel Pathway Maturity Map



Methane slip from engines is a central concern, and emission reduction technology is under development

Regulation of methane emissions across the entire value chain is essential.

MATURE

Solutions are available, none or marginal barriers identified.

SOLUTIONS IDENTIFIED

Solutions exist, but some challenges on e.g., maturity and availability.

MAJOR CHALLENGES

Solutions are not developed or lack specification.

submit your questions at slido.com using this code #methane

Emissions Web

Emission Type

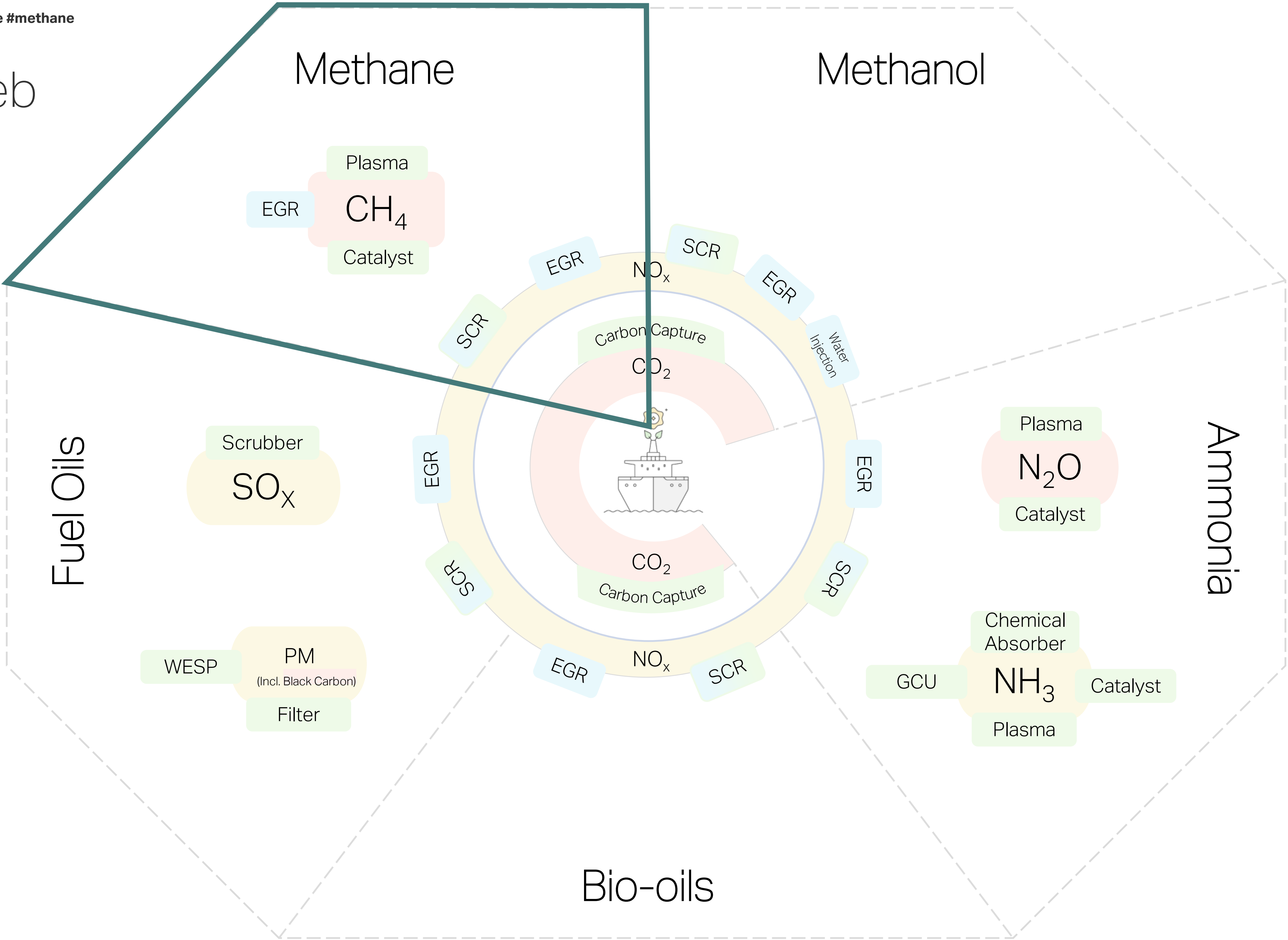
Greenhouse Gas
→ Global impact on the climate

Air pollutant
→ Local impact on human health and the environment

Reduction Technology

Engine technology
→ Fully integrated with engine

After treatment
→ Separate from engine, but integrated



Paper highlights

Working group approach

Regulatory Drivers → Onboard Methane Emission Sources → Current Methane Slip Levels per Engine Technology → Methane Reduction Technologies & Solutions → Vessel-Level Methane Emissions & Reduction Potential → Techno-Economic Analysis → Conclusions

Regulatory Outlook

Global

- Methane Pledge
- Lifecycle GHG Assessment
- EEDI Phase 4
- Measured during engine certification

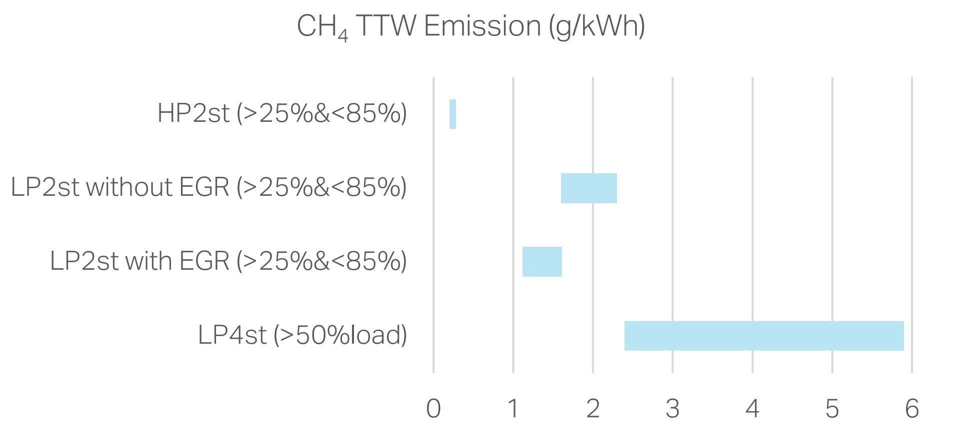
Regional

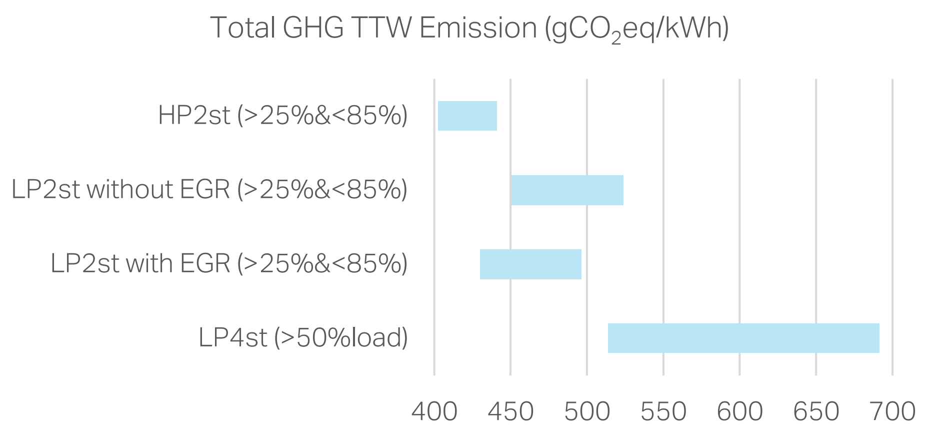
- EU ETS
- FuelEU
- Inclusion in MRV Regulation

Local

- Chinese regulations on marine engines applicable to vessels engaged in inland navigation

Methane slip emission levels from engines





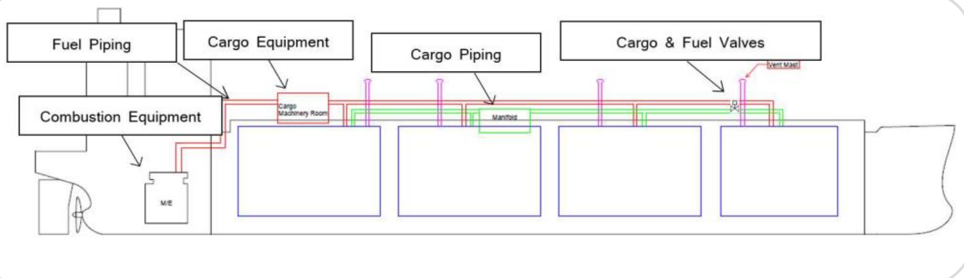
Engine Type	CH_4 slip (%wt)	GHG WtW (gCO_2eq/MJ)
HP2st (>25%&<85%)	0.19	76.6~77.9
LP2st without EGR (>25%&<85%)	1.1~1.4	81.3~83.1
LP2st with EGR (>25%&<85%)	0.8~1	79.5~80.9
LP4st (>50%load)	1.5~3.3	83.6~93.0

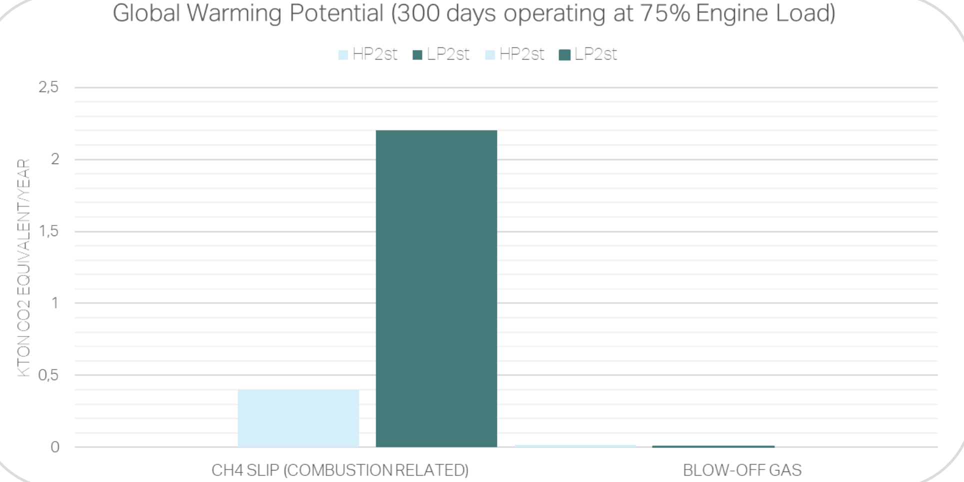
Non-engine methane emissions are difficult to quantify, but are expected to be marginal based on information available

Fugitive emissions

Operational releases

Emergency releases





Reduction technologies and solutions

Engine technology

→ Fully integrated with engine

- High pressure injection
- Exhaust gas recirculation (EGR)
- Engine tuning/control
- Component design optimization

After-treatment

→ Separate from engine, but integrated

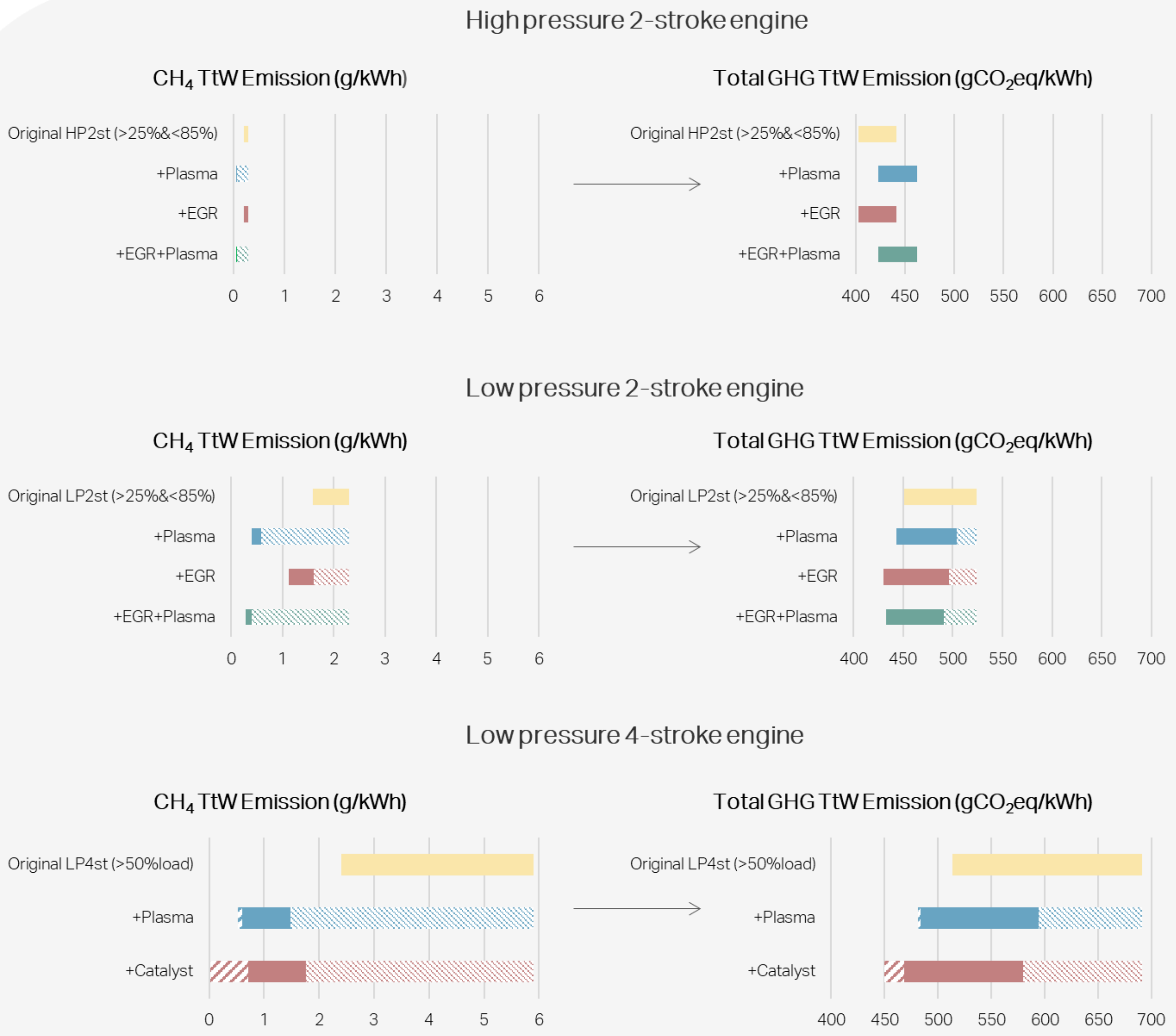
- Oxidation catalyst
- Plasma reduction

System solutions

→ System dimensioning, configuration and connected technologies

- Engine dimensioning
- Machinery arrangement
- Shaft generator
- Shore power

Methane slip reduction potential per engine type



Yellow Bar: Baseline engine emission value.
Hatched Bars: A technology's emission reduction potential.
Solid Bars: A technology's reduced emission range.
Hatched Lines: The hatched lines to the right indicate the reduction amount relative to the baseline engine technology. Hatched lines to the left indicate for some cases the maximum potential of the technology for some applications.

Vessel-level calculation model - holistic view on methane emissions, reduction potential and regulatory compliance

LNG Fueled LR2 Tanker

- HP2st & LP2st w EGR scenarios
- 1 ME Unit
- 3 AEs

174k LNG carrier

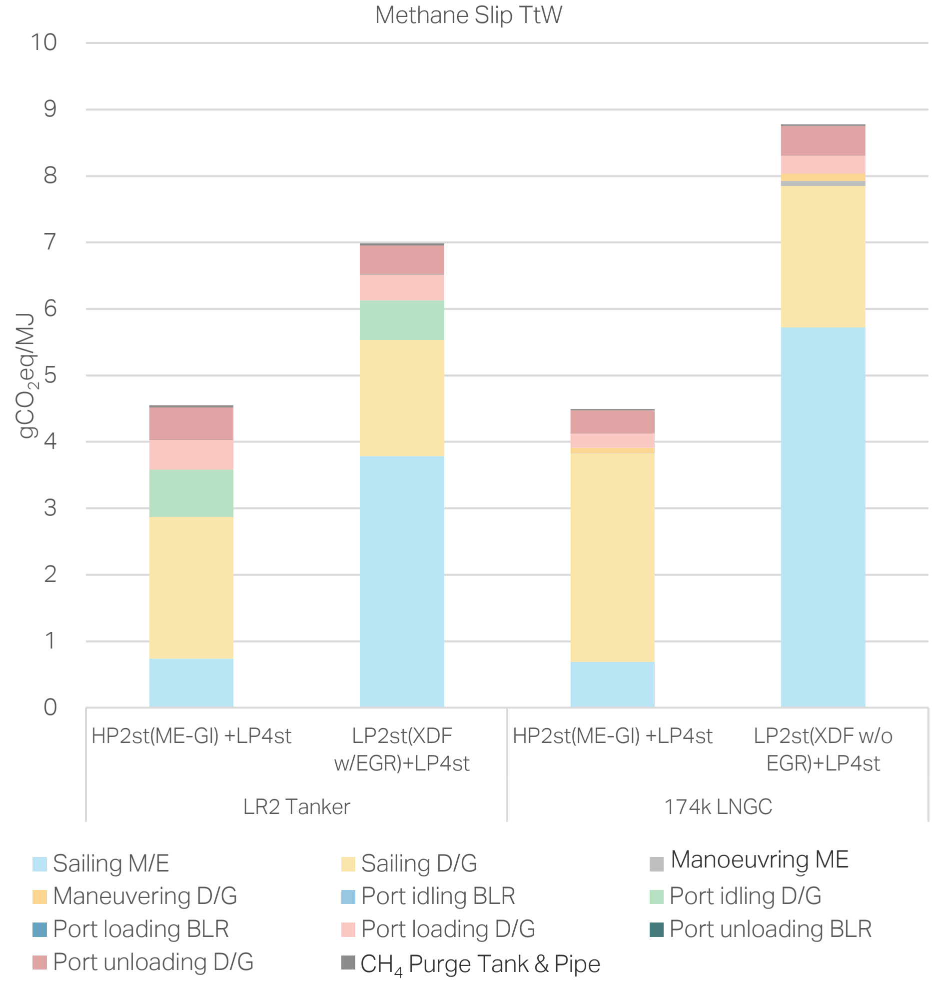
- HP2st & LP2st w/o EGR scenarios
- 2 ME units
- 4AEs

Fuel EU Methodology

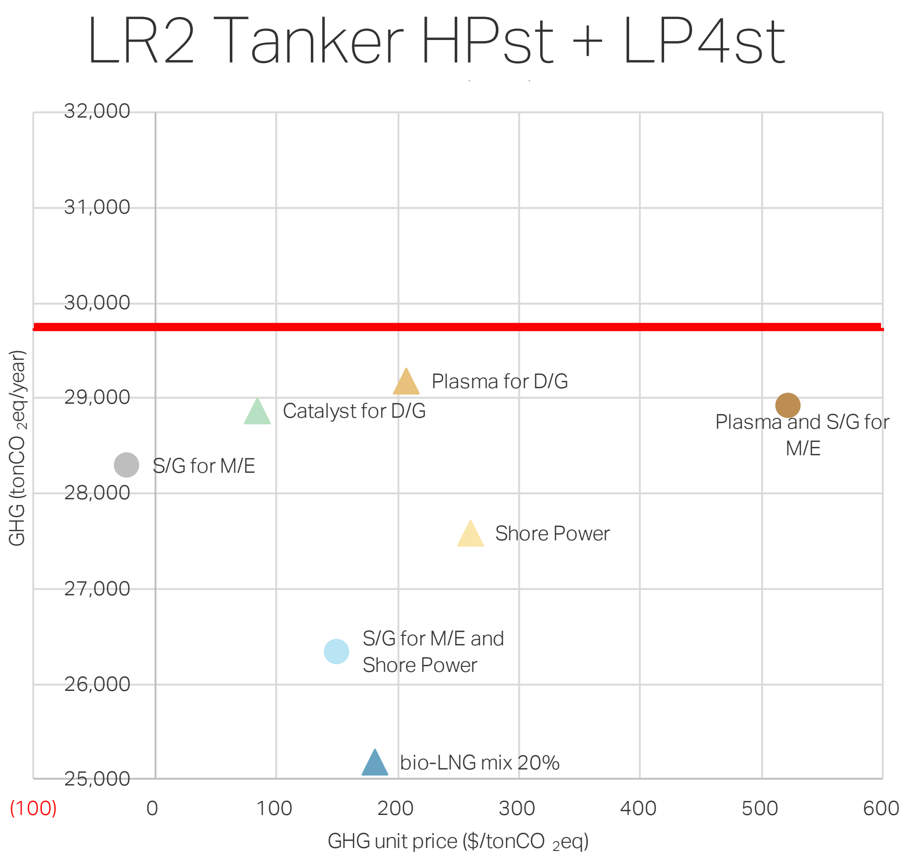
GHG intensity index	WtT	TtW
GHG intensity index $\left[\frac{gCO_{2eq}}{MJ}\right]$=	$\frac{\sum_i^{n\ fuel} M_i \times CO_{2eqWtT,i} \times LCVi + \sum_k^c E_k \times CO_{2eq\ electricity,k}}{\sum_i^{n\ fuel} M_i \times LCVi + \sum_k^c E_k}$	$+\frac{\sum_i^{n\ fuel} \sum_j^{m\ engine} M_{i,j} \times \left[\left(1-\frac{1}{100}C_{engine\ slip\ j}\right)\times(CO_{2eq,TtW,j})+\left(\frac{1}{100}C_{engine\ slip\ j} \times CO_{2eq\ TtW\ slippage,j}\right)\right]}{\sum_i^{n\ fuel} M_i \times LCVi+\sum_k^l E_k}$

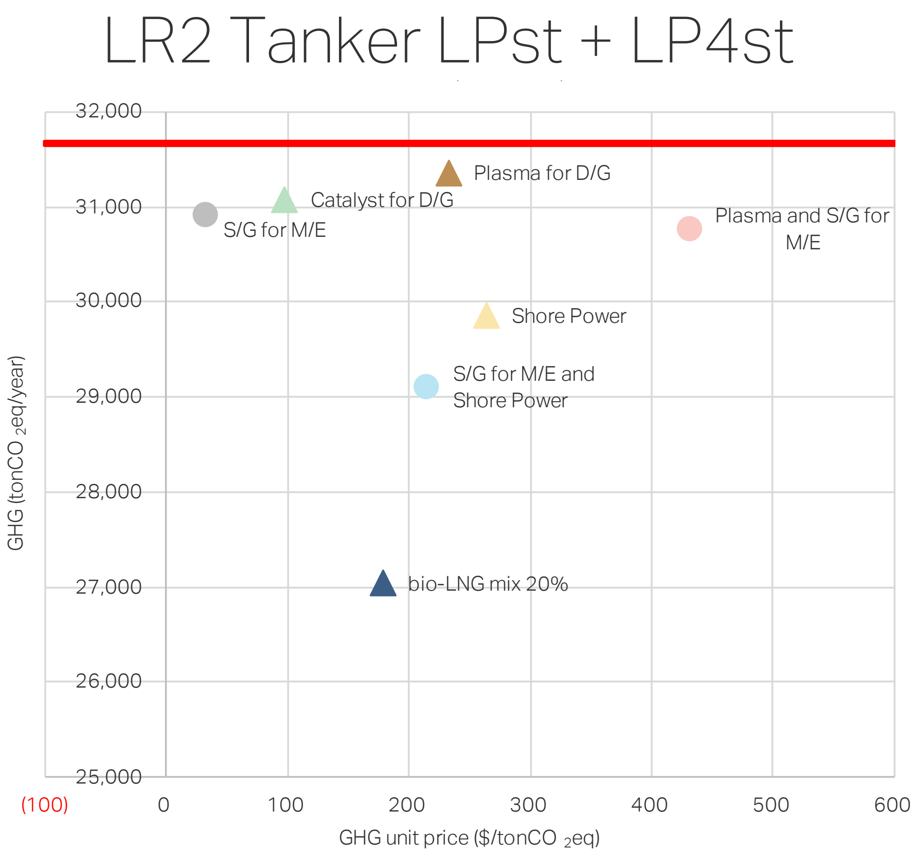
+

Techno-economic Analysis



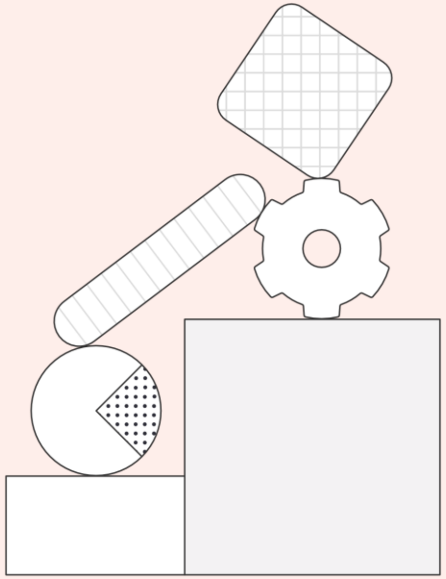
Techno-economic analysis





Conclusions

- A vessel’s total methane emissions should be considered.
- Cost-efficient[1] onboard vessel methane emission reduction is possible but limited for existing vessels is possible but limited for existing vessels.
- Reducing onboard vessel methane emissions are needed to increase viability of electro- and bio-methane fuel pathways.
- Proposed FuelEU for Maritime limits are not strict enough to activate onboard vessel methane emission reduction.
- Regulation is required for widespread adoption of onboard vessel methane emission reduction technologies and solutions.



[1] ‘Cost efficiency’ is defined here as an abatement cost less than about $200/ton CO_2-eq (which is assumed to be the approximate abatement cost for using bio-methane)

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Industry perspectives

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DAPHNE® TECHNOLOGY

TOPSOE

Our Panelists

Benjamin Attumaly
Secondee of MAN Energy Solutions to the Mærsk Mc-Kinney Center for Zero Carbon Shipping

Hans-Philipp Walther
Head of Exhaust Gas Aftertreatment at MAN-ES

Thomas F. Werner
Chief Product Officer at Daphne Technology

Janus Emil Münster-Swendsen
Secondee of Topsoe to the Mærsk Mc-Kinney Center for Zero Carbon Shipping

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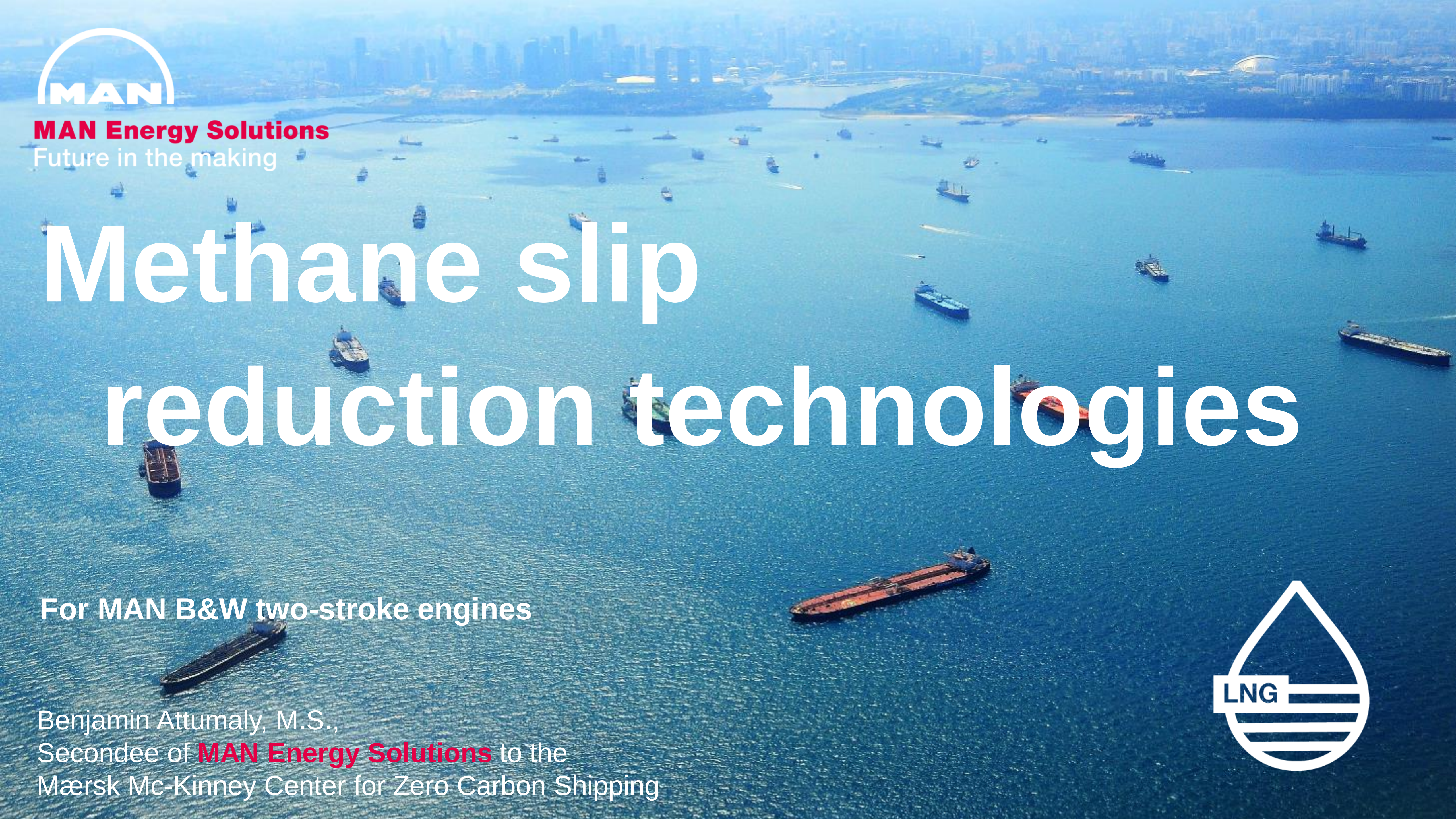
Future in the making



MAN Energy Solutions
Future in the making

Methane slip reduction technologies

For MAN B&W two-stroke engines

Benjamin Attumaly, M.S.,
Secondee of **MAN Energy Solutions** to the
Mærsk Mc-Kinney Center for Zero Carbon Shipping

LNG

Powering sustainable shipping by opening clear routes

MAN Energy Solutions supports all

LNG		Ethane	Methanol	LPG	Ammonia
ME-GI	**ME-GA**	**ME-GIE**	**ME-LGIM**	**ME-LGIP**	→ **2024**
498 engines	192 engines	33 engines	68 engines	134 engines	

As of August 2022

1
The importance of managing methane slip

The importance of managing methane slip

Global Warming Potential (GWP).

How strong is methane as a greenhouse gas?

GWP has been defined to enable comparison of the global warming impact for greenhouse gasses.

- The larger the GWP, the more a given gas impacts global warming compared to CO2.
- The period usually applied is **100 years**, as suggested by the **U**nited **N**ations **I**ntergovernmental **P**anel on the **C**limate **C**hange (IPCC)*.
- Methane has an estimated GWP of around **28** over 100 years. Over 20 years the GWP is estimated at around **86.**

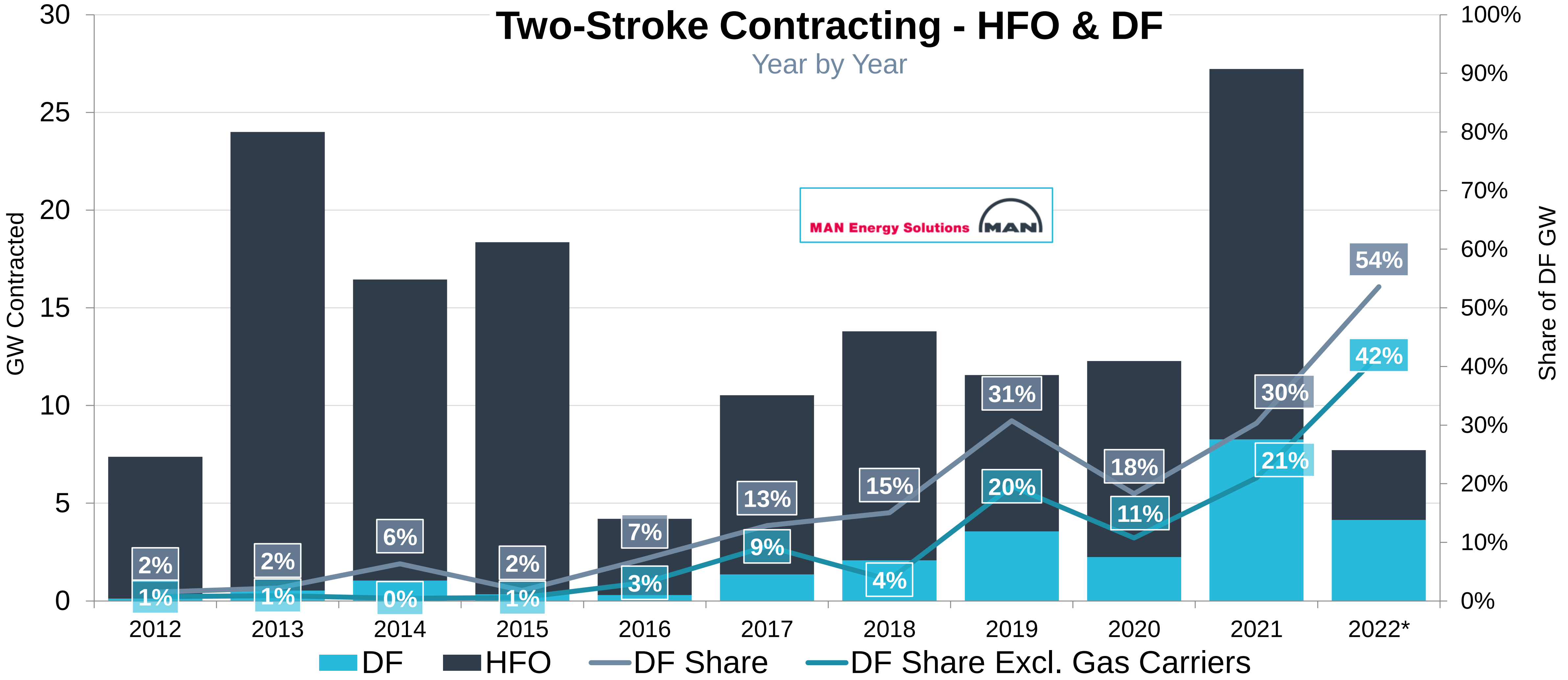
With the increase in LNG fueled engines in shipping, emissions from methane slip are an important focus area for the maritime industry

*https://unfccc.int/process-and-meetings/transparency-and-reporting/methods-for-climate-change-transparency/common-metrics

LNG = Liquefied Natural Gas; fossil fuel containing 80-99% methane

The importance of managing methane slip

Historical two-stroke dual-fuel LNG engine contracting

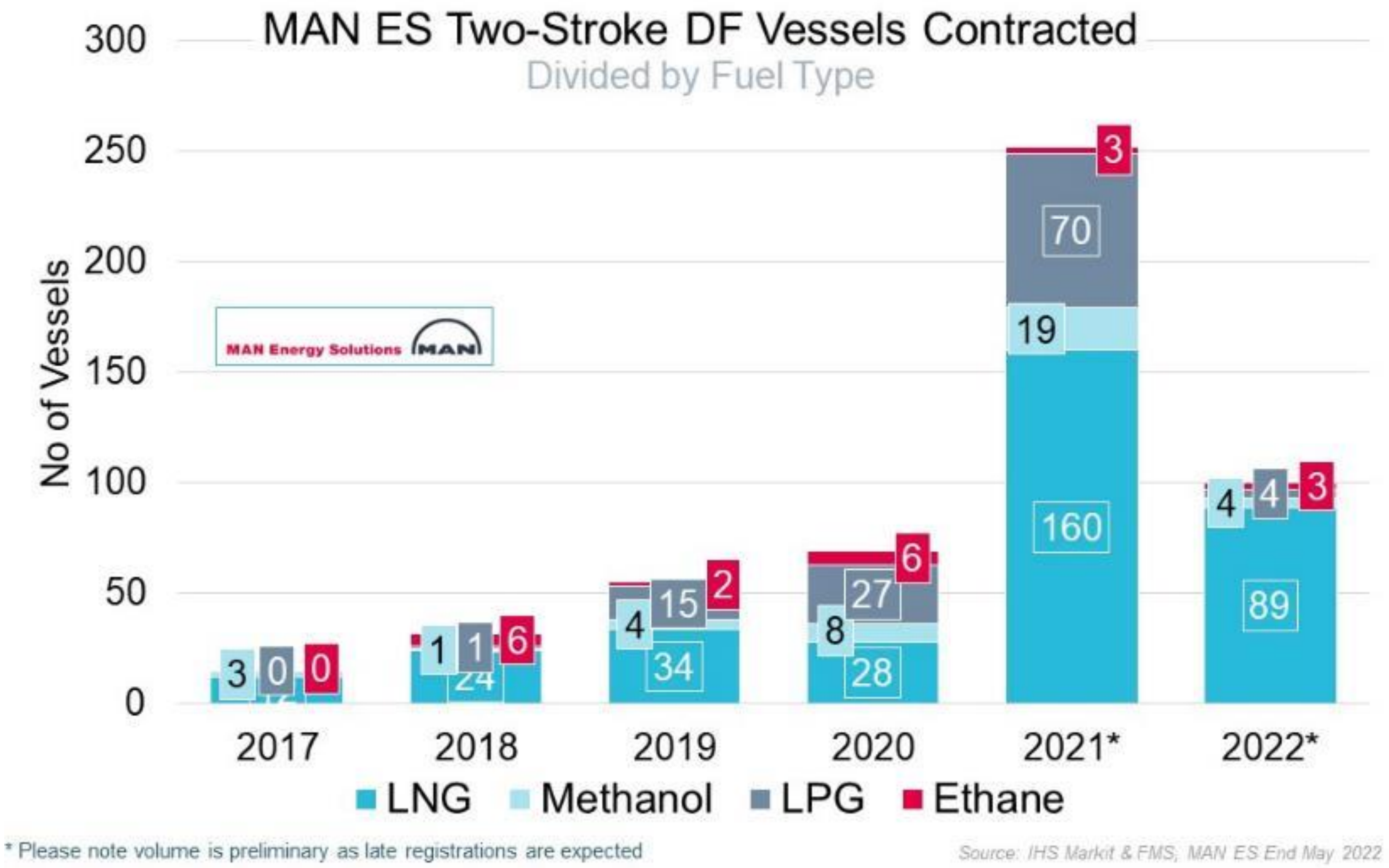


* Preliminary Year to Date (end May 2022)

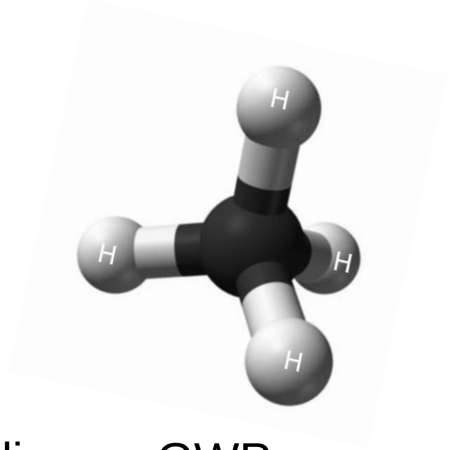
Source: IHS Markit

The importance of managing methane slip

LNG is seeing large scale adoption as a marine fuel



The importance of managing methane slip



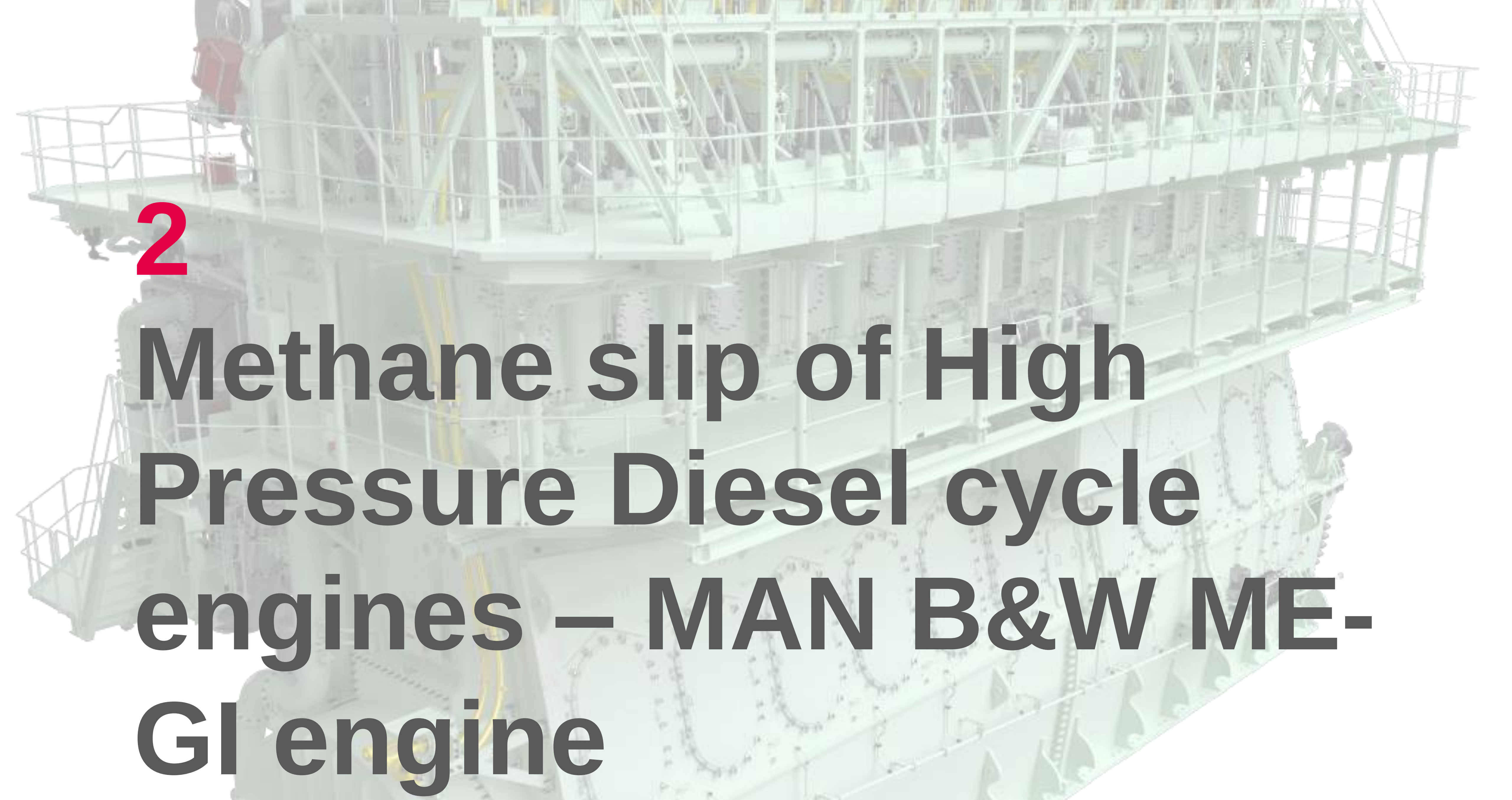
What are the benefits of LNG as a marine fuel?

Benefits of LNG-fueled two-stroke engines.

- ~ 99% reduction of Sulphur Oxide emissions
- ~ 20-25% reduction of Green House Gas emissions compared to conventional fuel depending on GWP factor)*
- ~ 90% reduction of Particulate Matter emissions
- Enables drop-in of bio-methane or Synthetic Natural Gas (SNG) as marine fuel

The GHG reduction depends on the methane slip and efficiency of the engines

*Including methane slip and CO_2 emissions from main and auxiliary systems for a ME-GI powered VLCC (Tank-to-Wake)



2

Methane slip of High Pressure Diesel cycle engines – MAN B&W ME-GI engine

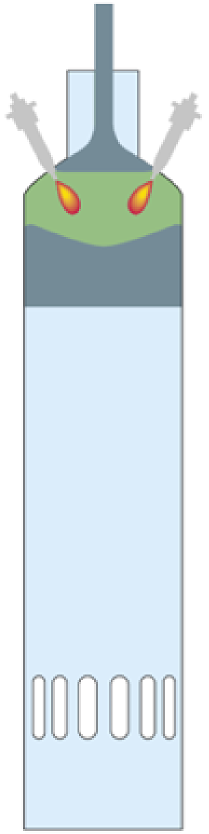
Methane slip of High-Pressure Diesel cycle engines

Basic principles – neither Direct slip nor Combustion slip

Sources of methane slip from Diesel cycle high-pressure LNG-fueled engines

Complete combustion leading to negligible methane slip.

- No overlapping of gas injection and exhaust valve timing
- Gas is injected at top-dead center
- The properties of the Diesel cycle allows us to guarantee a methane slip of less than 0,28 g/kWh for the entire load range for all ME-GI engines (even lower at high loads)



Gas injection and ignition

Methane slip of the MAN B&W ME-GI engine

How do we achieve extremely low methane-slip emissions from our ME-GI engine?

Diesel cycle

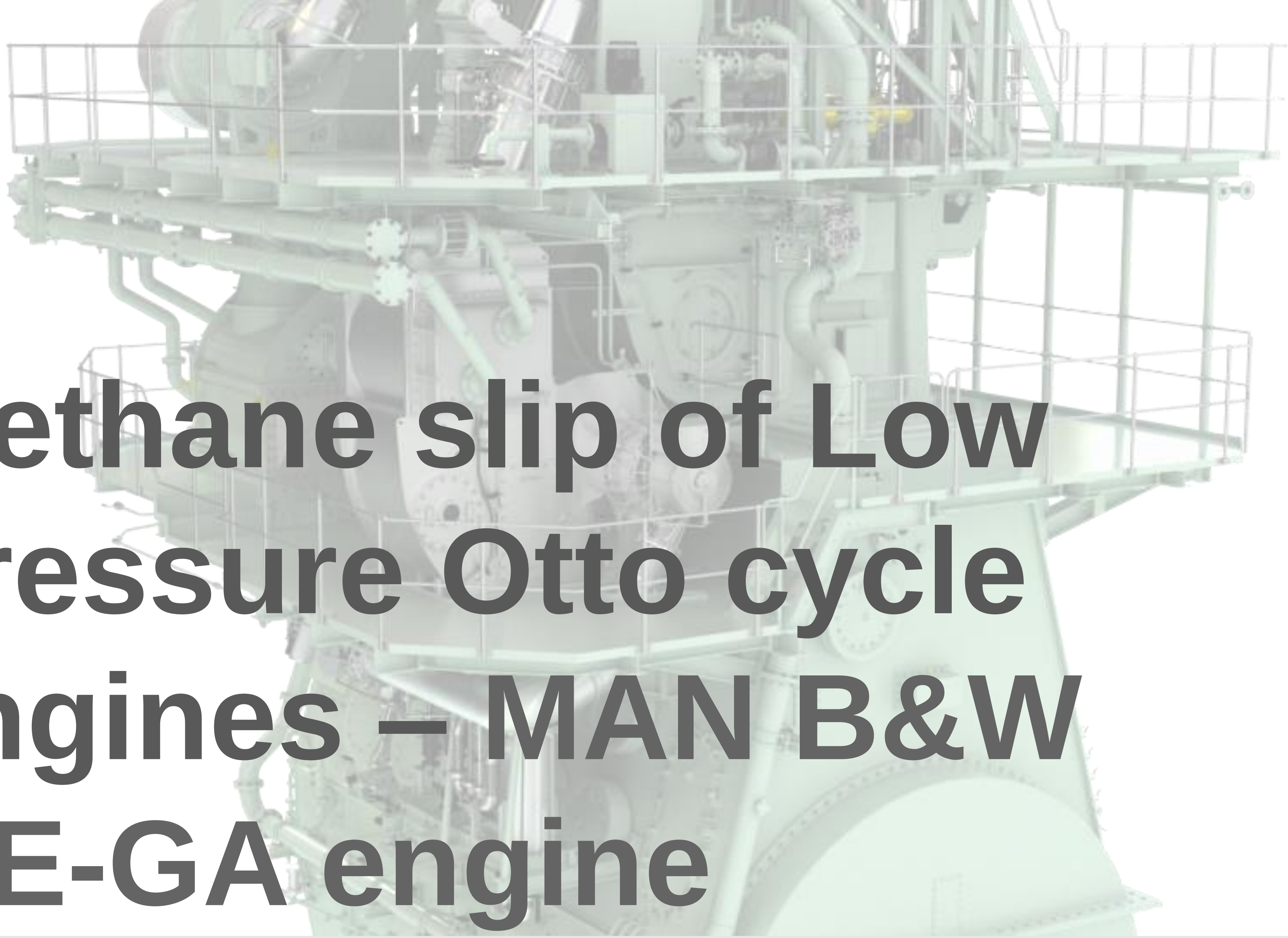
This cycle is reflected by very high combustion temperatures as well as a rich mixture leading to a complete combustion

High compression ratio

Diesel cycle allows a higher compression ratio compared to Otto cycle engines, leading to higher fuel efficiency and lower methane slip emission

Combustion chamber design and components

improved to reduce pockets where gas can hide during combustion



3

Methane slip of Low Pressure Otto cycle engines – MAN B&W ME-GA engine

MAN B&W ME-GA engine

Filling a gap in our engine portfolio

The MAN B&W ME-GA engine, our Low-Pressure Otto Cycle engine, is developed specifically targeting the LNG Carrier market.

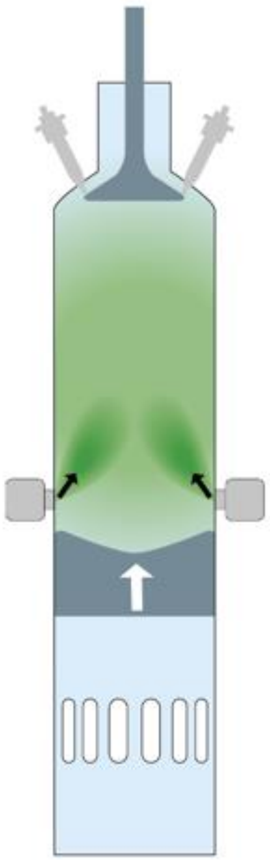
Methane slip of Low-Pressure Otto cycle LNG-fueled engines

Basic principles – Direct slip

Sources of methane slip from Otto cycle low-pressure LNG-fueled engines:
(1) Direct slip and **(2) Combustion slip.**

Direct slip happens when:

- Gas is admitted when the cylinder is “open”
- A small amount of the gas can therefore flow directly through the engine
- However, second generation 2-stroke Otto-cycle engines such as the **MAN B&W ME-GA are designed with <u>nil</u> direct methane slip**
- Position of gas admission valve, exhaust valve timing and gas admission timing is chosen so direct methane slip is avoided



Gas injection

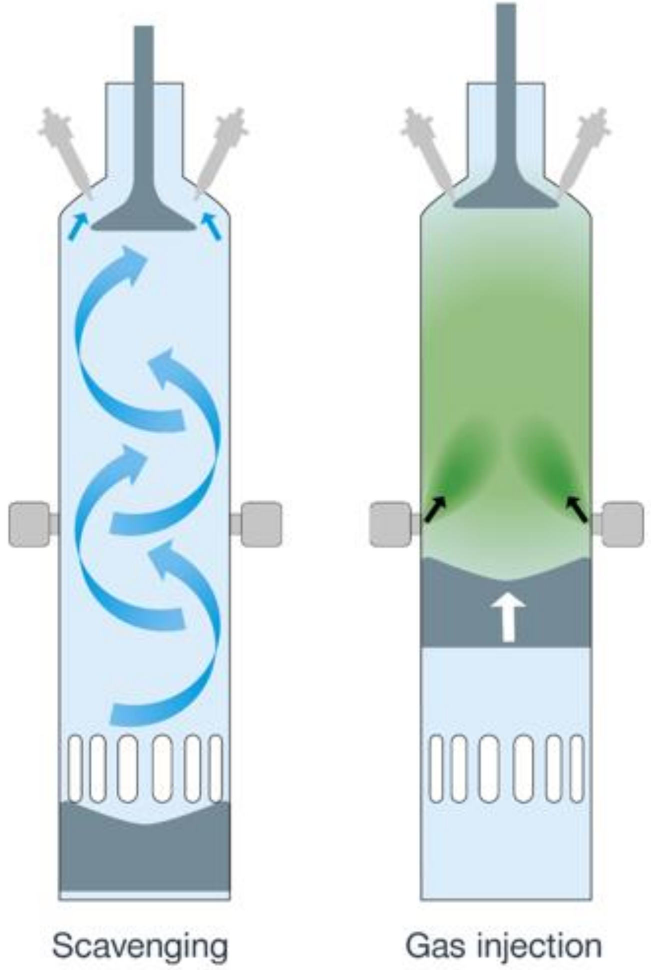
Methane slip of Low-Pressure Otto cycle LNG-fueled engines

Basic principles – Combustion slip

Sources of methane slip from Otto cycle low-pressure LNG-fueled engines:

The combustion slip – lean and cold mixes

- As gas is admitted and mixed with scavenging air, rich and lean parts will be created
- Consequently the rich and lean parts will reach different temperatures
- The lean and cold parts will only be partly combusted, leading to methane slip



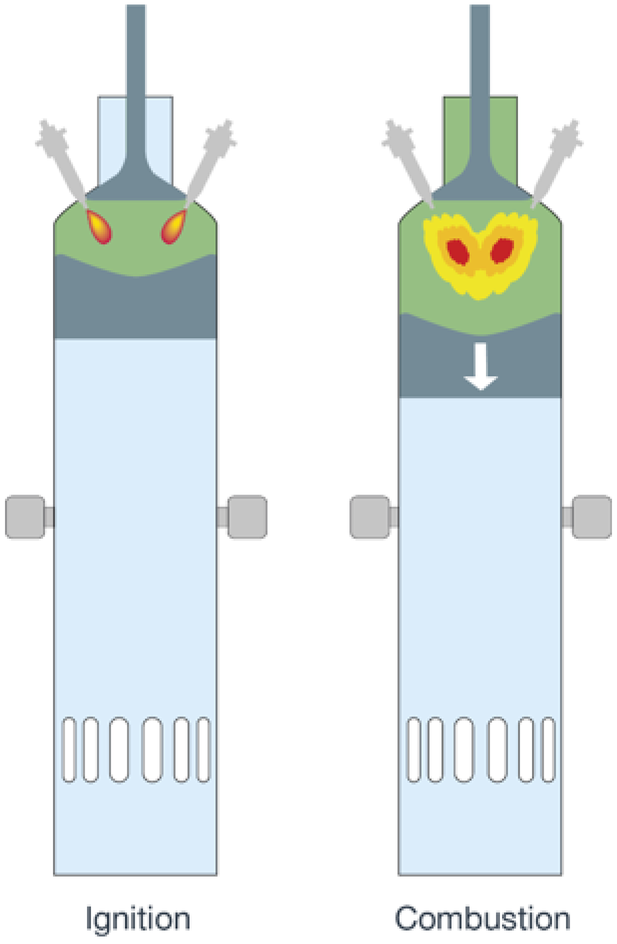
Methane slip of Low-Pressure Otto cycle LNG-fueled engines

Basic principles – Combustion slip

Sources of methane slip from Otto cycle low-pressure LNG-fueled engines:

The combustion slip – load-dependent methane slip

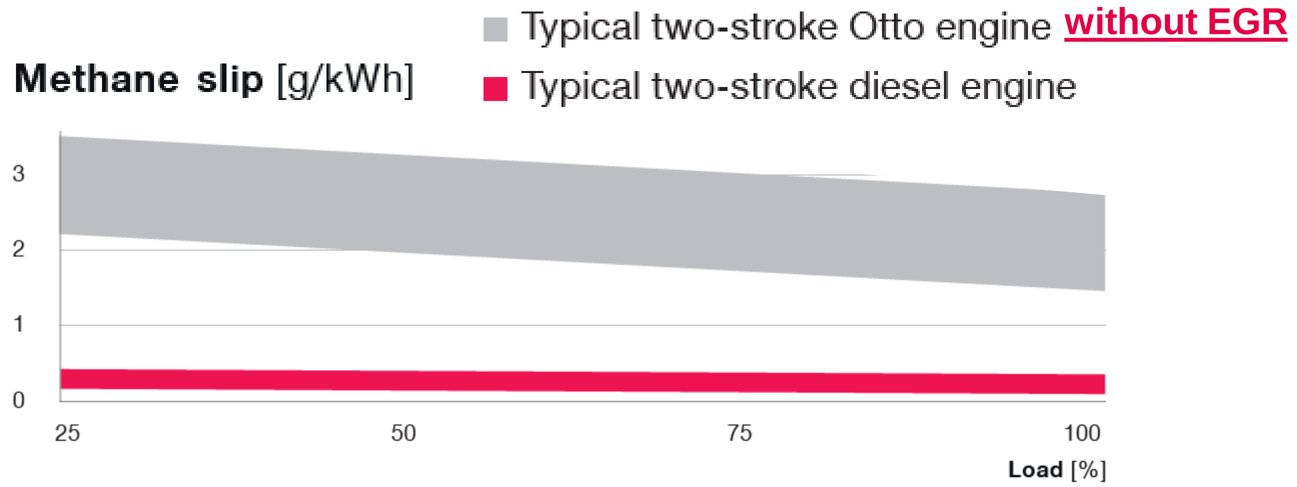
- As load is decreased on Otto cycle engines, lean-mixtures will be occur more frequently
- Combined with reduced temperatures, this can significantly increase the methane slip



Methane slip of the MAN B&W ME-GA engine

The MAN B&W ME-GA comes in one standard version with an integrated EGR

For Otto cycle LNG-fueled engines, <u>EGR</u> can reduce methane slip emissions by upwards of 50%

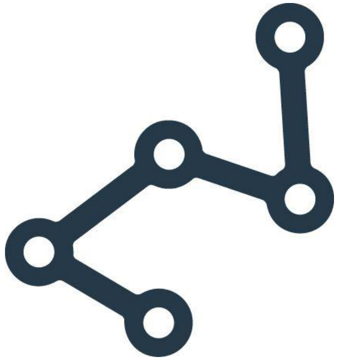


Methane emissions in gas mode – comparison of different engine types

Methane slip of the MAN B&W ME-GA engine

Exhaust Gas Recirculation and other measures

How can EGR and other measures reduce methane slip emissions on ME-GA?

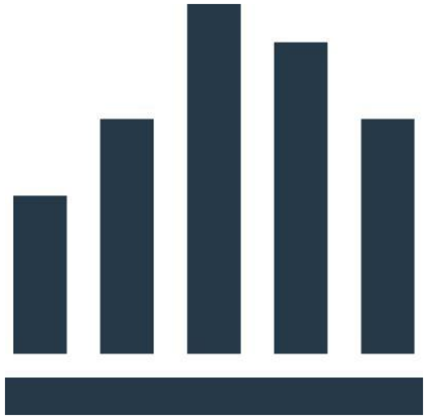


Improved mixture

EGR allows us to use a gas-to-air mixing strategy that has improved combustion efficiency and better cycle-to-cycle stability

Compression ratio

EGR allows a higher compression ratio, leading to improved fuel efficiency and lower methane slip emission



EGR rates

EGR allows for a reduction in methane slip as the exhaust gas is given a 2nd chance to burn

Combustion chamber design and components

improved to reduce pockets where gas can hide during combustion

4 Summary

Summary

Methane slip reduction technologies for MAN B&W two-stroke engines

- The High-Pressure technology as demonstrated MAN B&W ME-GI has solved the issue of methane slip
- ME-GI has a guaranteed load-dependent negligible methane slip of 0,20-0,28 g/kWh
- A second generation Low-Pressure Otto cycle-based engine such as the MAN B&W ME-GA with EGR can reduce methane slip on Otto cycle engines upwards of 50%
- Overall, the ME-GA engine with EGR has a load dependent methane slip around 4-6 times higher than ME-GI

MAN Energy Solutions
Future in the making

Thank you very much!

Name Author
Department
Day, Month, Year

MAN Energy Solutions
Future in the making

MAN

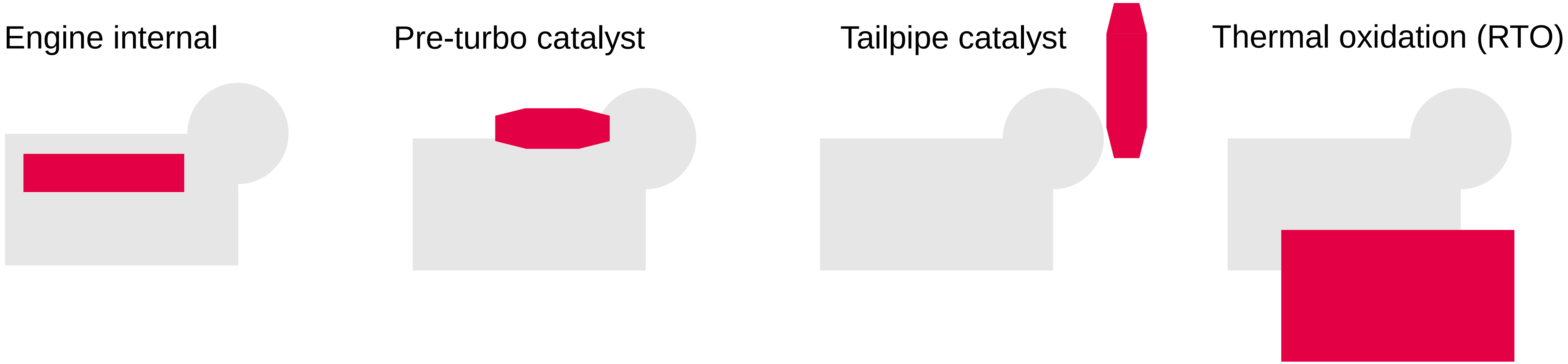
Methane slip reduction 4S engines

Dr.-Ing. Hans-Philipp Walther
Head of Exhaust Gas Aftertreatment

Fundamental ways to achieve methane oxidation

Internal and external measures

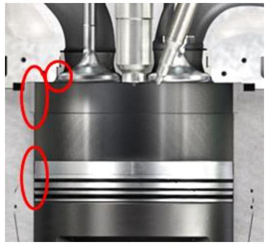
- **Methane oxidation requires a certain temperature level**
- **This threshold can be reduced by a catalyst**



Measures for methane slip reduction

DF engines for Marine Applications (New Built & Field Engines)

Engine internal

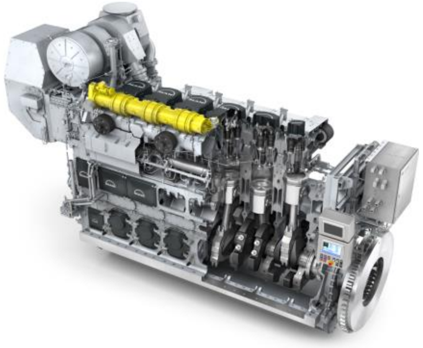


- Crevice volume reduction
- Closed Crankcase Ventilation (CCV)
- Combustion process optimization

Engine Control

- Adaptive Combustion Control (ACC)
- Skip Firing

System approach



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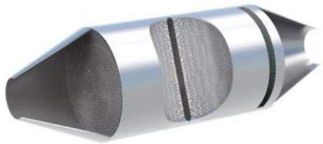
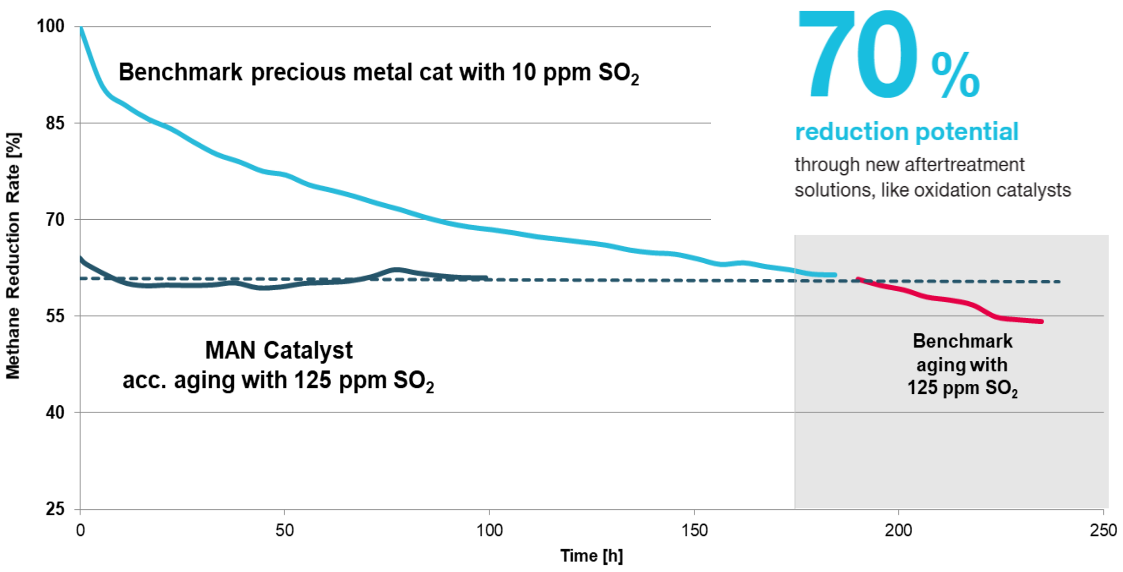
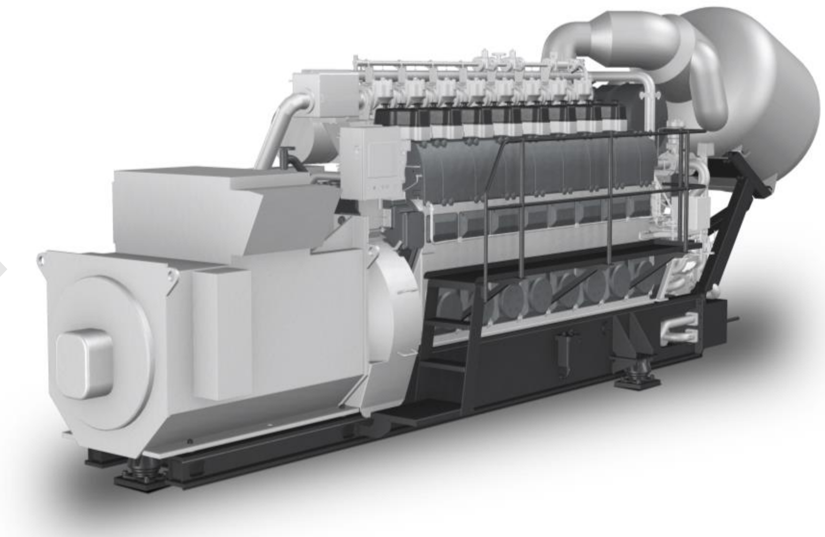


- Engine setting: Tier III w/ SCR
- Methane catalyst

Methane Oxidation Catalyst

Funded projects IMOKAT I & II





Focus on engine dynamics and catalyst performance & ageing

Full scale methane catalyst test in 2023

Summary

- Focus shift from poisonous substances to climate impact (GHG)
  Legislation is the driver for the implementation of environmental technologies

- Dual Fuel engines operating on LNG have the potential to reduce CO_2 emissions by at least 25%
  With sustainable fuels (e.g. bio-based; e-fuels) even further GHG emission reductions are achievable

- Unburnt gas (CH_4 slip) is diminishing the total GHG reduction potential

- Methane slip demands both engine optimization and aftertreatment solutions
  Methane catalyst technologies to reduce the CH_4-slip are developed to push the potential of Dual Fuel & SI engines to full extent

MAN Energy Solutions
Future in the making

Thank you very much!

Dr.-Ing. Hans-Philipp Walther
EERTA – Exhaust Gas Aftertreatment
Hans-Philipp.Walther@man-es.com

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This data serves informational purposes only and is especially not guaranteed in any way.
Depending on the subsequent specific individual projects, the relevant data may be subject to changes and will be assessed and determined individually for each project. This will depend on the particular characteristics of each individual project, especially specific site and operational conditions.

Daphne Technology

DAPHNE®
TECHNOLOGY

DAPHNE® TECHNOLOGY

NO_x SO_x CH_4 N_2O NH_3 CO_2

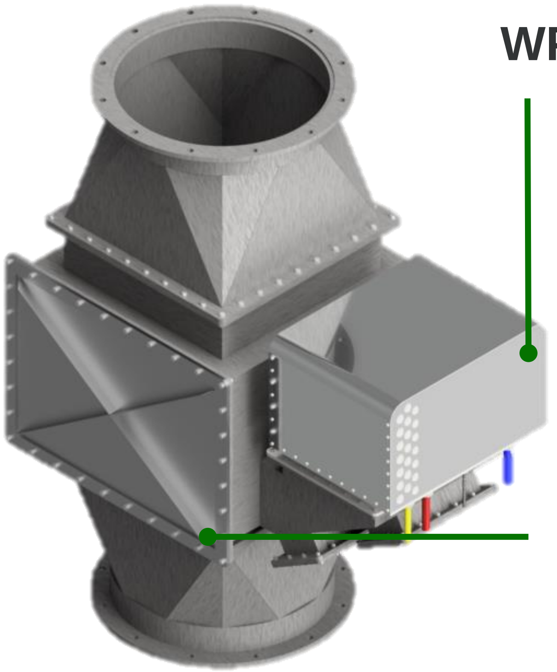
Reducing methane emissions onboard vessels

Thomas Werner

October 2022

SlipPure™

Removes methane emissions from the exhaust gas of LNG engines

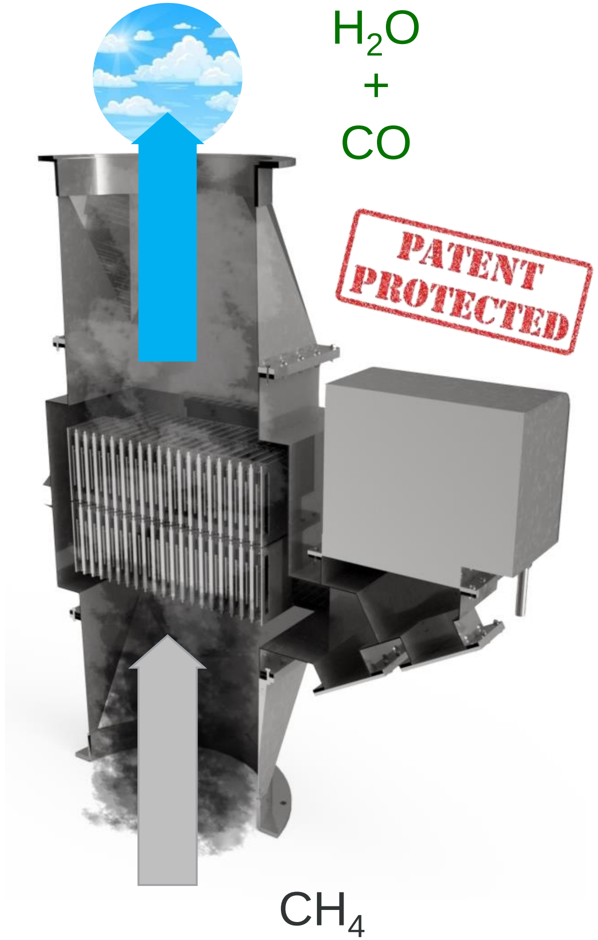


WPP™ Power Supply

Electrical Energy → Chemical Energy

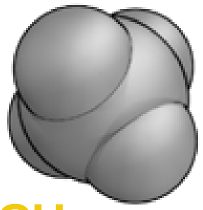
Cartridge

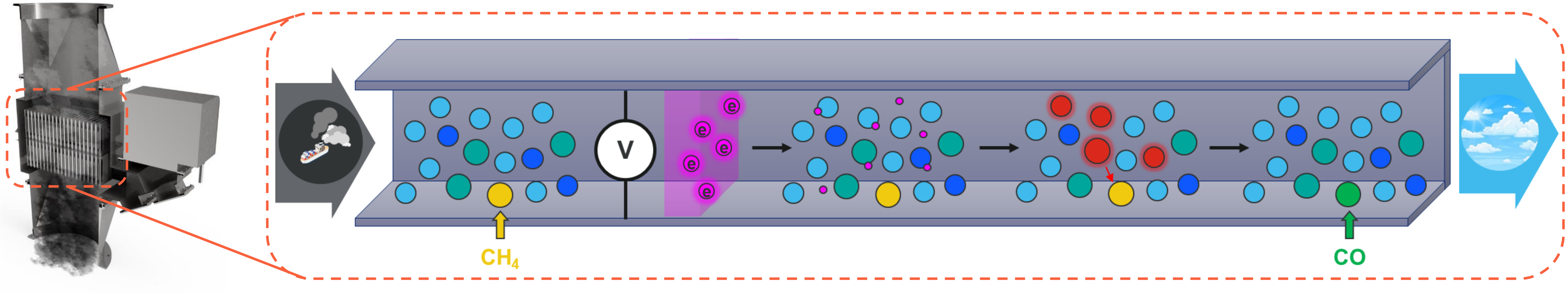
Pollutant removal



How does it Work

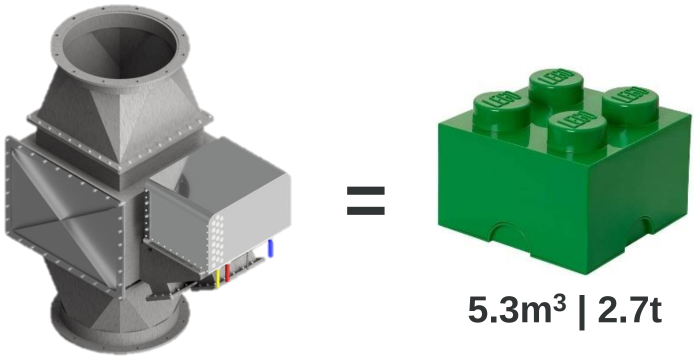
The hydroxyl radical and high energy electrons

WPP™ Power Supply → e^- Energetic electron → OH• Hydroxyl radical +  CH_4 → CO Carbon monoxide + H_2O



Modular Installation

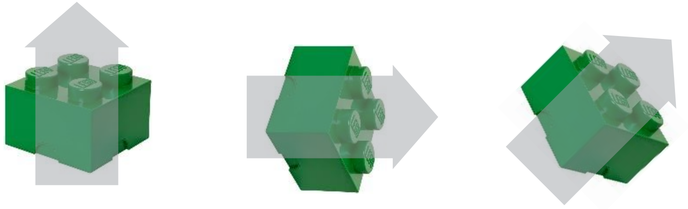
Entry Module – 1.5 MW Engine Size



5.3m³ | 2.7t

Spatial Possibilities

Vertical | Horizontal | Angled



Configuration Examples

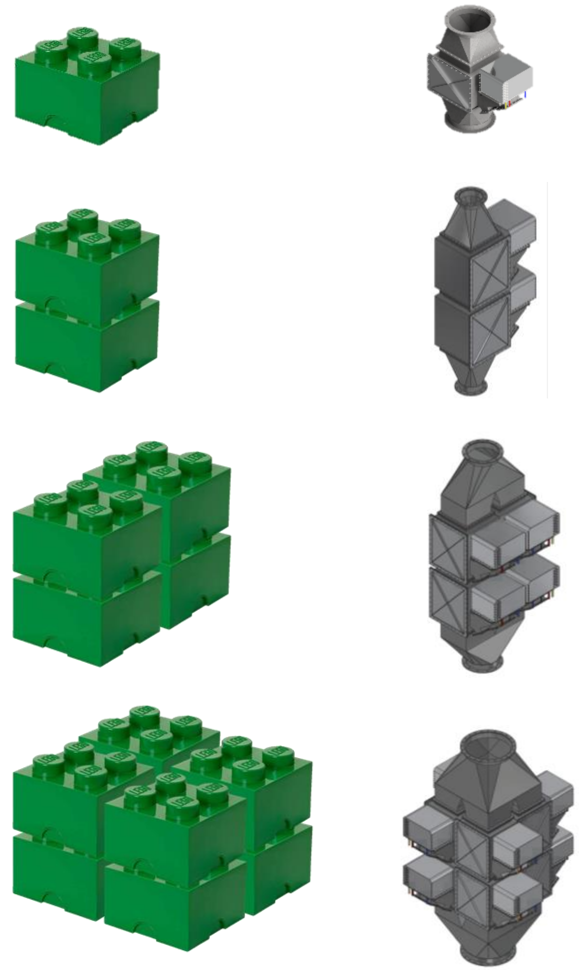
Engine Size

1.5 MW

3 MW

6 MW

12 MW



DAPHNE TECHNOLOGY

Next Steps

Q3 2021

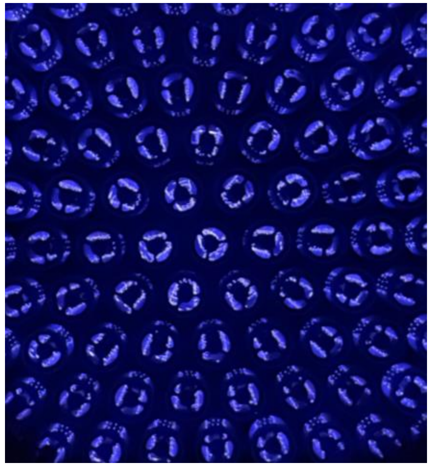
78% methane removal
(4.0 g/kWh)

Q4 2022

Land-based testing
700 kW

Q2 – Q3 2023

Pilot
Installed in operation



- Wide temperature range of operation (180 - <450 °C)
- Backpressure from cartridge(s) within engine tolerance
- Engine independent (2- and 4-stroke)
- Control system reacts instantaneously to changes in engine (load)
- Can be installed after economizer
- Not affected by SO_x in exhaust gas
- Not affected by high humidity in exhaust gas (>10%)

Thank You

for your attention

daphnetechnology.com

NO_x SO_x CH_4 N_2O NH_3 CO_2

Topsoe

TOPSOE

TOPSOE
CH_4 SLIP CATALYST

By Janus Münster-Swendsen
Janus.Munster-Swendsen@zerocarbonshipping.com
jems@topsoe.com

TOPSOE

LNG AS MARINE FUEL
CATALYTIC SLIP TREATMENT POSSIBLE FOR 4-STROKE ENGINES

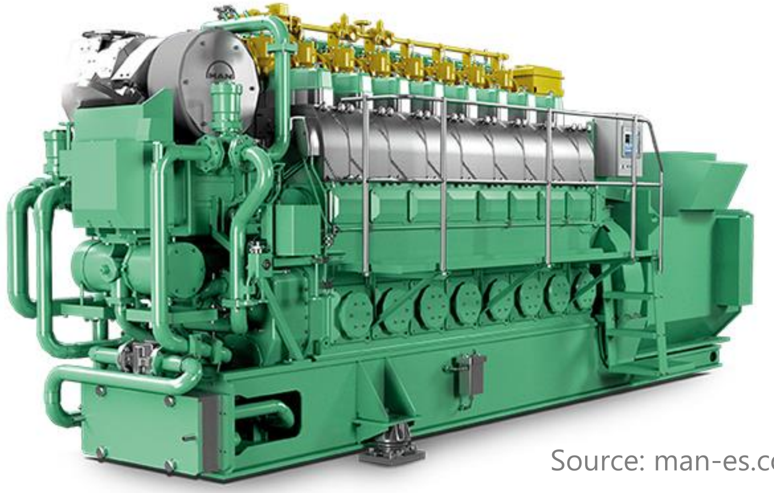
2-stroke Dual fuel engines

- Temperatures too low for catalytic CH_4 oxidation
- High pressure fuel injection can reduce slip

Source: man-es.com

4-stroke Dual fuel engines

- Catalytic CH_4 possible with:
  - High temperature (also possibly location upstream turbocharger)
  - low sulfur support fuel



Source: man-es.com

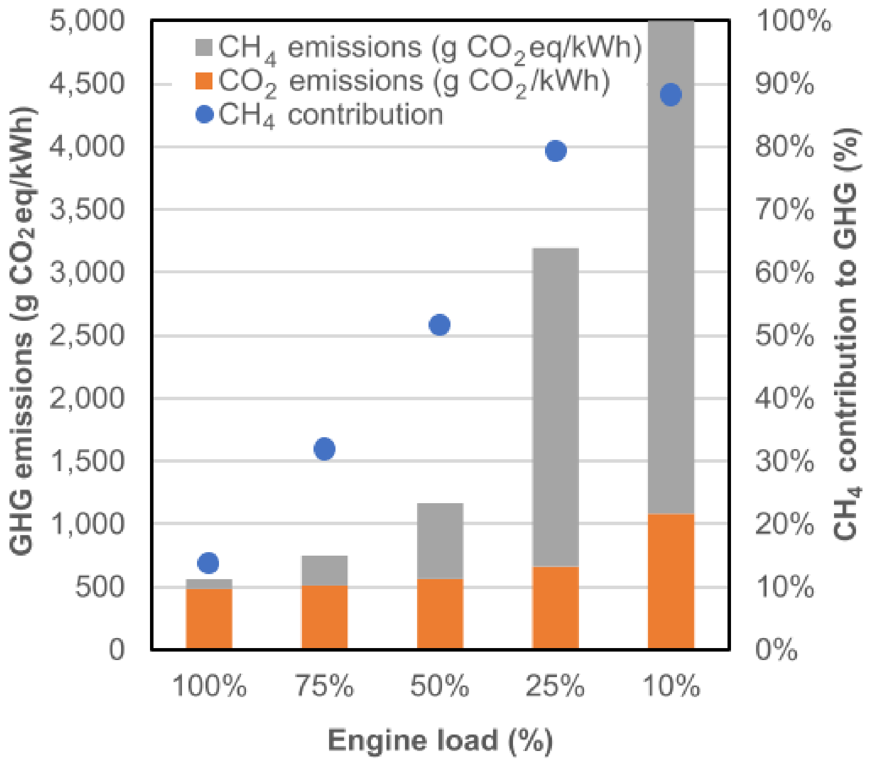
POTENTIALLY SIGNIFICANT PROBLEM
REGULATION NEEDED FOR ACTION TO TAKE PLACE

Article with measured emissions from LNG carrier:

- Methane slip accounts for **35% of total GHG emissions**
- Aux. engine slip worst at low loads

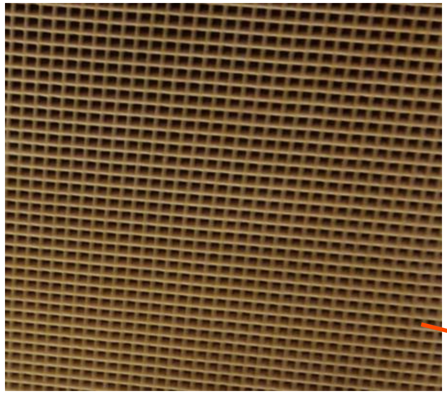
So:

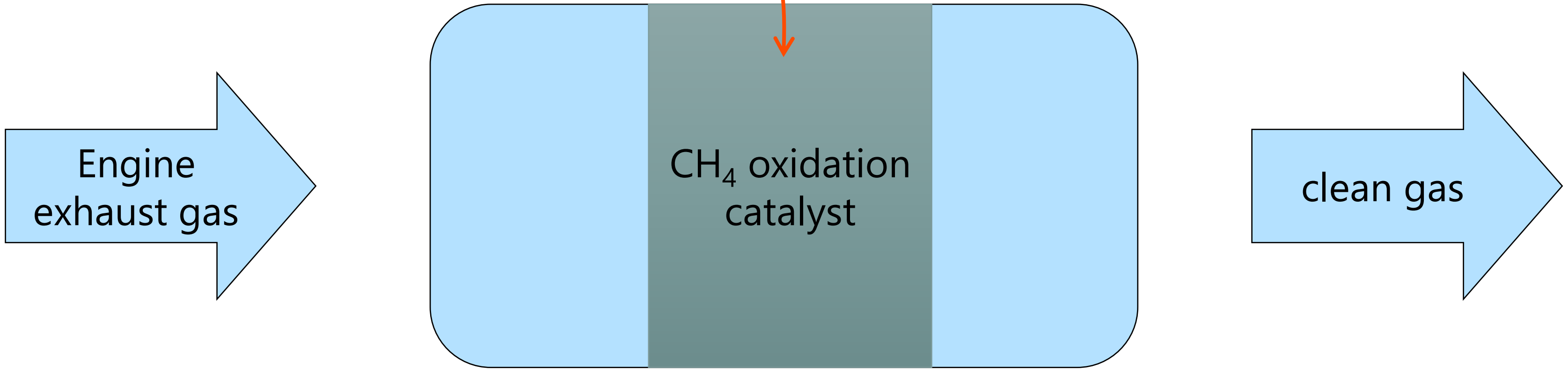
- Better understanding of actual CH_4 emissions is needed
- Low load operation should be minimized



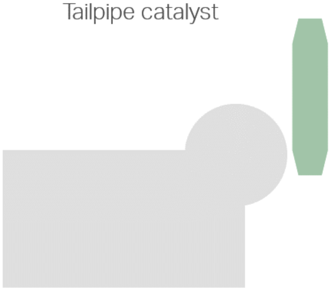
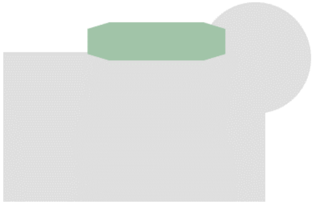
Source: Paul Balcome et al., *Total Methane and CO2 Emissions from Liquefied Natural Gas Carrier Ships: The First Primary Measurements*, 2022

FULL SLIP CONVERSION POSSIBLE
FOR 4 STROKE ENGINES WITH LOW SULFUR SUPPORT FUEL





PAPER CONTAINS 2 SCENARIOS

	Scenario 1: LR2 tanker Aux. engines	Scenario 2: LNG carrier, Aux. engines
Tailpipe catalyst 	**T>461°C** >99% conversion	**T<420°C** ~60% conversion
Pre-turbo catalyst 	>99% conversion	>99% conversion

TIMELINE

- Catalyst development & Internal lab testing ✓
- External lab testing
- External test bed testing

On the way

- On-board demonstration

- We are ready ☺

SUMMING UP

- Methane slip can fully removed by suitable catalyst when conditions are right
- Sulfur levels in pilot fuels must be controlled
- Tail pipe retrofits are possible
- Topsoe are ready for on-board demonstration
- No adaptation without regulation

Join at

slido.com

#methane

Panel discussion

Join at

slido.com

#methane

Thank you for joining!

The recording & presentation will be shared with all participants shortly.

Let's stay in touch

Visit our website www.zerocarbonshipping.com and make sure to follow us on LinkedIn to stay up to date with the latest news and events.

Upcoming Projects

→ **Methane Emission Regulation**
Proposing onboard emission regulations to increase- fuel pathway maturity.

→ **Onboard Emission Measurement**
Quantifying onboard emissions through integrated emission measurement.

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping