Combustion Technology Assessment
Technological Advancements

ADVANCED POWER & ENERGY PROGRAM
UNIVERSITY of CALIFORNIA · IRVINE

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TWG Workshop #2

May 29, 2024

Outline

- Regulatory Perspective
- Technological advancements on Tier 4 marine/marinized engines and aftertreatment
- Commercially availability update for Tier 4 marine/marinized engines
- Alternative fuels

Tier 4 Technology Overview

- **Tier 4 is an emissions standard created by the EPA in order to regulate marine engine emissions.**
  - **Applies to both Category 1 and 2 engines.**
- **Typically (but not always) requires an after treatment system such as SCR to meet the required NOx levels.**
- **CARB's Tier 4 + DPF levels require additional reductions in PM (use of a DPF)**

SCR

Pollutant	CARB Tier 4+DPF (Category 1/2 Engines) (<1400kW)	EPA Tier 4 (Category 1/2 Engines) (600-1400 kW)	IMO III (@1800 RPM)	EU Stage V (IWP-v-5 IWP-c-4) (>1000 kW)
NOx (g/kWh)	1.8	1.8	2.01	0.4
HC (g/kWh)	0.19	0.19	N/A	0.19
PM (g/kWh)	0.0067	0.04	N/A	0.01
PN (#/kWh)	N/A	N/A	N/A	1×10^{12}
CO (g/kWh)	5	5	N/A	3.5

DPF

Tier 4 Technology Overview

- **CARB's Harbor Craft Rule dates for compliance based on engine model year and vessel type.**
  - **Applicable for Main and Auxiliary Engines.**
  - **Must comply with most stringent emissions standard: CARB's Tier 4 + DPF, (Tier 3 + DPF if no Tier 4 engine is available, Tier 4 off-road if an auxiliary engine).**

Compliance Dates for Any Pre-Tier 1 and Tier 1 Certified Engines on All Regulated In-Use Vessels

Engine Model Year	Compliance Date
1993 and earlier	December 31, 2023
1994-2001	December 31, 2024
2002 and later	December 31, 2025

Compliance Dates for Tier 2, Tier 3, or Tier 4 Engines on Ferries (Except Short-Run Ferries), Pilot Vessels, All Tug/Towboats, and Push Boats

Engine Model Year and Vessel Category	Compliance Date
2009 and earlier (Except Pilot Vessels)	December 31, 2024
2012 and Earlier Pilot Vessels	December 31, 2025
2010 - 2012 All Other Vessels	December 31, 2025
2013 - 2015	December 31, 2026
2016 - 2019	December 31, 2027
2020 - 2021	December 31, 2028
2022 and later	December 31, 2029

Compliance Dates for Tier 2, Tier 3, or Tier 4 Engines on Research Vessels, Commercial Passenger Fishing Vessels, and In-Use Excursion Vessels

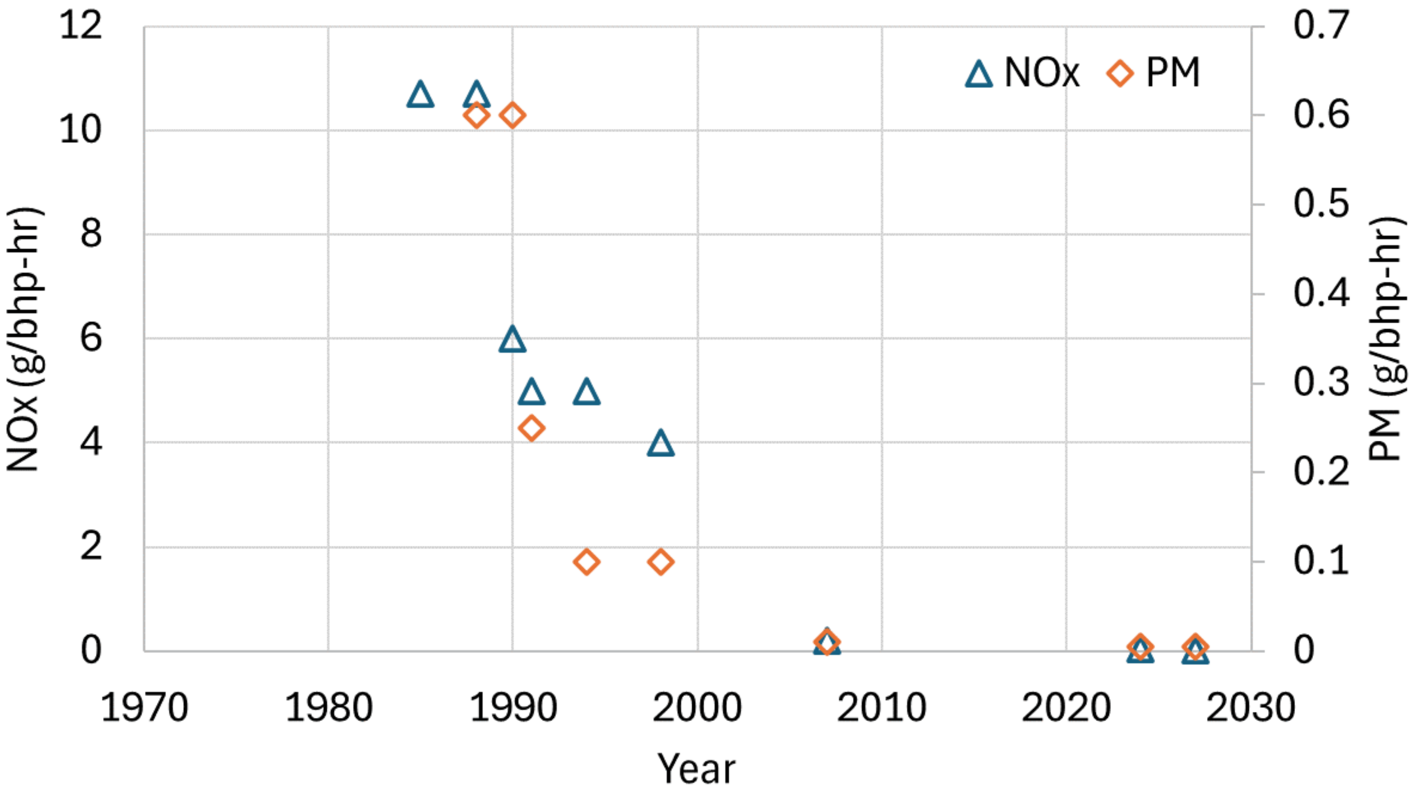
Engine Model Year	Compliance Date
2010 and earlier	December 31, 2026
2011 - 2012	December 31, 2027
2013 - 2014	December 31, 2028
2015 - 2017	December 31, 2029
2018 and later	December 31, 2030

Compliance Dates for Tier 3, Tier 3, or Tier 4 Engines on Barges, Dredges, Crew and Supply Vessels, and Workboats

Engine Model Year	Compliance Date
2009 and earlier	December 31, 2028
2010 - 2013	December 31, 2029
2014 - 2017	December 31, 2030
2018 and later	December 31, 2031

Tier 4 Engines

- **Regulatory Perspective (on-road EPA/CA)**
  - **Trends are similar for EU**



Data: https://dieselnet.com/standards/us/hd.php

2024
NOx:
0.05 g/bhp-hr or
0.067 g/kW-hr

PM
0.005 g/bhp-hr or
0.0067 g/kW-hr

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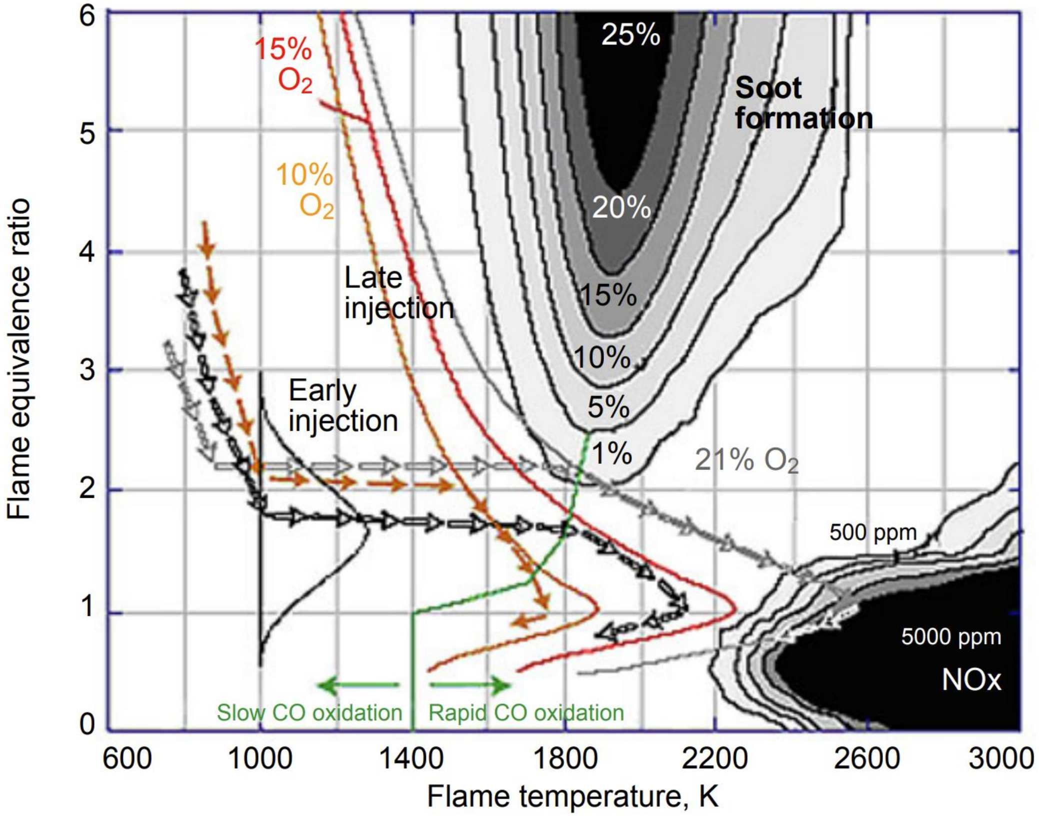
- Commercially availability update for Tier 4 marine/marinized engines
- Alternative fuels

Tier 4 Engines

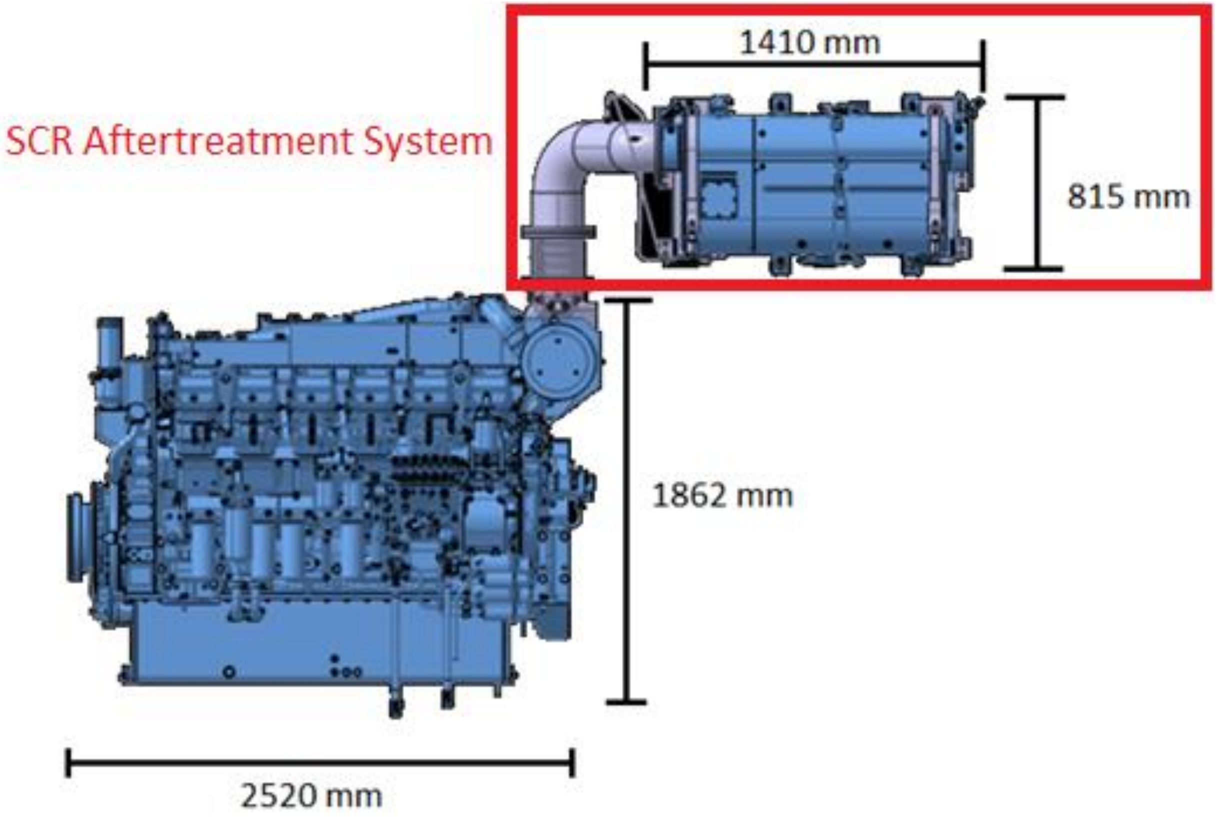
- **Advanced combustion technologies have reduced NOx and PM emissions**
  - **Diesel (compression ignition) technology offers high fuel efficiency, power, and robustness**
  - **Advanced combustion technology for diesel**
    - **"Low Temperature Combustion (LTC)" /1**
      - **Premixed Charge Compression Ignition**
      - **Tailoring of fuel/air mixing with common rail high pressure electronic injection**
      - **Tailoring injection timing**
      - **Exhaust gas recirculation**
      - **Water injection**
    - **Significant emission reduction**
- **Incorporation of aftertreatment provides 1-2 orders of magnitude further reduction**



Johnson (2008). Diesel Engine Emissions and Their Control, Plat Met Rev, Vol 52(1), pp 23-37
Sandia National Laboratories

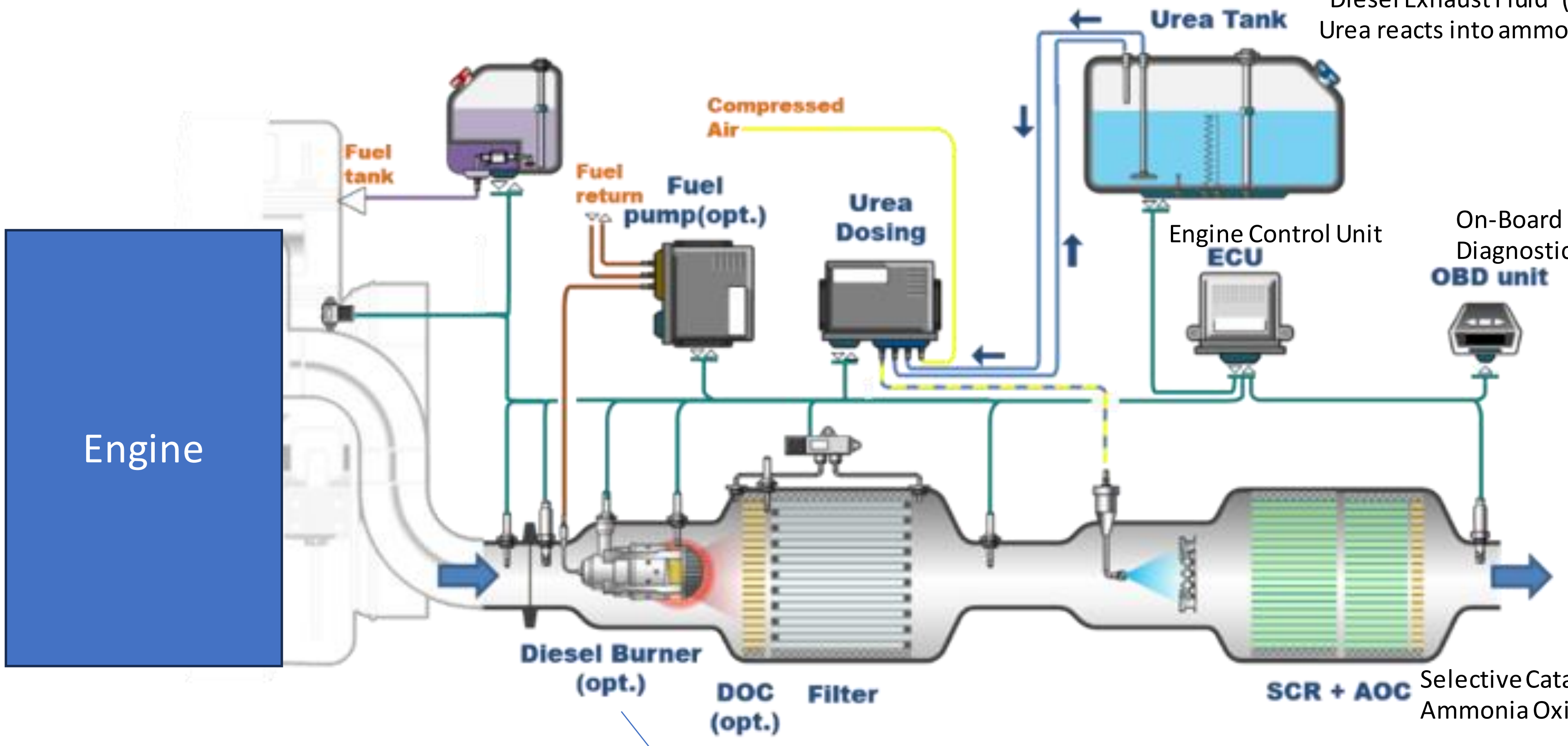
1. https://www.energy.gov/eere/vehicles/advanced-engine-and-fuels-technologies

- **Many (not all) Tier 4 engines have distinct aftertreatment equipment than can, in principle, be added to a diesel engine exhaust system**
  - **Aftertreatment adds volume/weight compared to basic engine**
    - **Example: Mitsubishi S12R Selective Catalytic Reduction (SCR) system-->**
  - **The SCR uses ammonia to convert NOx into N_2 and water with aid of a catalyst (and heat)**
    - **$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O$**
    - **Ammonia from decomposition of urea which is contained in diesel exhaust fluid (DEF)**
  - **The SCR module is one component in the aftertreatment system**



- ***Potential* components in state-of-art aftertreatment system**
  - **Diesel Exhaust Fluid (i.e., Urea) + selective catalytic reduction (SCR)—focus on NOx**
  - **Diesel Particulate Filter (DPF) (+ Diesel Oxidation Catalyst—DOC)—focus on PM, (CO, THC)**

"Diesel Exhaust Fluid" (DEF): ~33% Urea/67% water
Urea reacts into ammonia and CO_2



Selective Catalytic Reduction Unit
Ammonia Oxidation Catalytst

	without DPF+SCR (g/kWh)	with DPF+SCR (g/kWh)	Reduction Efficiency
PM	0.036	0.006	83%
NOx	4.676	0.536	89%
CO	0.33	0.028	92%
THC	0.311	0.004	99%

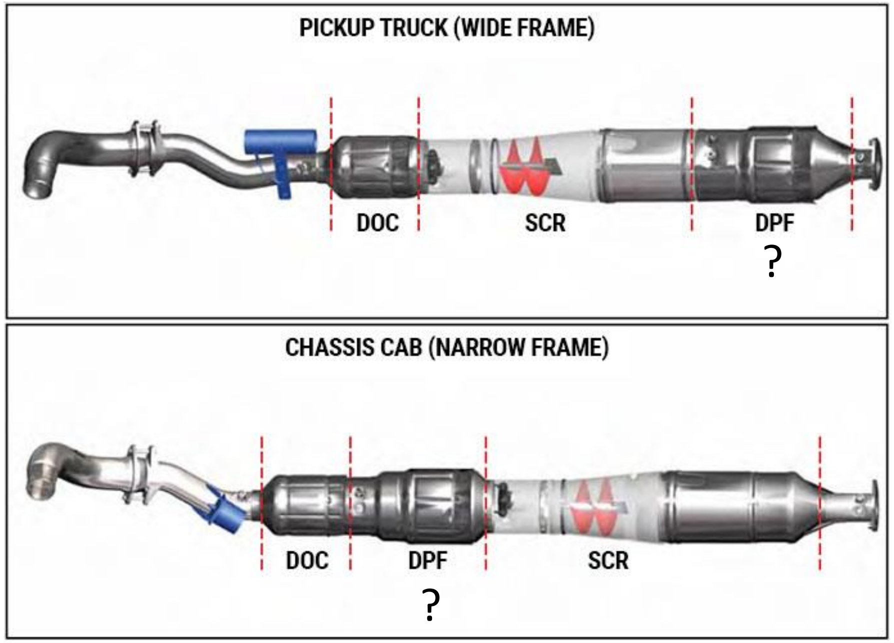
Test Engine : DV11(10,964cc / 420ps)

Passive: >572 F
Active: ~1000 F

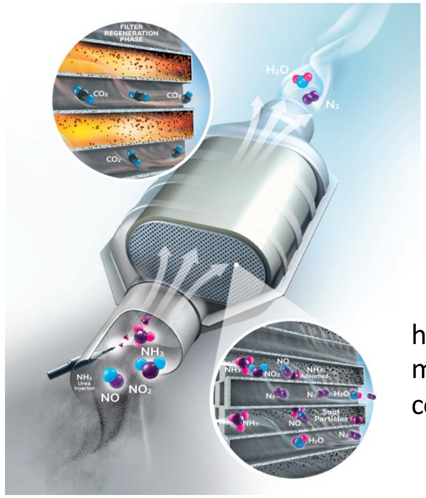
http://www.cleanearth.kr/en/products/dpf-scr.php

Tier 4 engine technology

- **DPF location**
  - Majority are upstream of SCR
    - may reduce fouling DEF/SCR subsystems[1]
    - Higher near engine temperatures facilitates passive regen (less fuel, higher efficiency)
    - Implies separating engine and SCR to install DPF onto existing system
  - Post SCR installations do exist for on road
    - Ford Powerstroke 6.7
  - No post SCR DPF examples identified for maritime applications
  - Development of integrated SCR-DPF system noted for on-road HDV
    - Johnson Matthey SCRF® (Selective Catalytic Reduction Filter)



https://www.dieselhub.com/powerstroke/6.7-power-stroke.html



https://matthey.com/products-and-markets/transport/mobile-emissions-control/diesel-applications/scrf-technology

1. https://learndiesels.com/aftertreatment-101

Tier 4 Engines

- **Example modular SCR add on (Mitsubishi)**

Pacific Marine Expo, Nov 2023

- **Example modular SCR add on (Cummins)**
  - **HH4000 (750-820 hp) to HH24000 (1800-2200hp)**

Pacific Marine Expo, Nov 2023

Add
<--This
To
That-->

- **Exhaust Gas Recirculation (EGR/FGR) is another strategy to reduce NOx emissions**

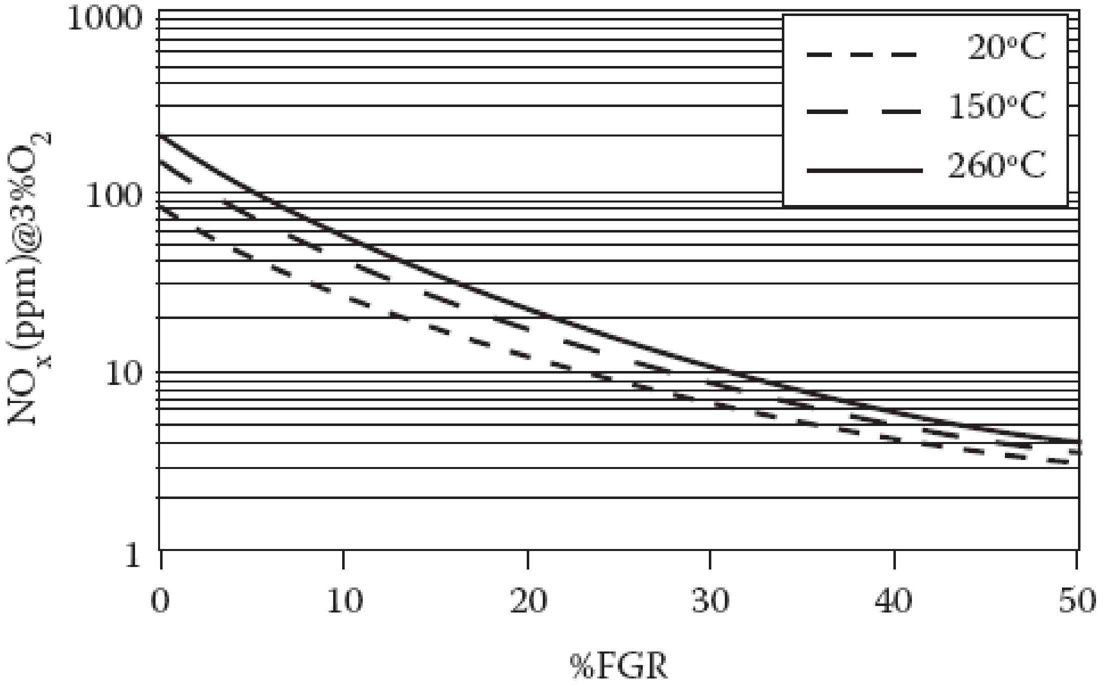
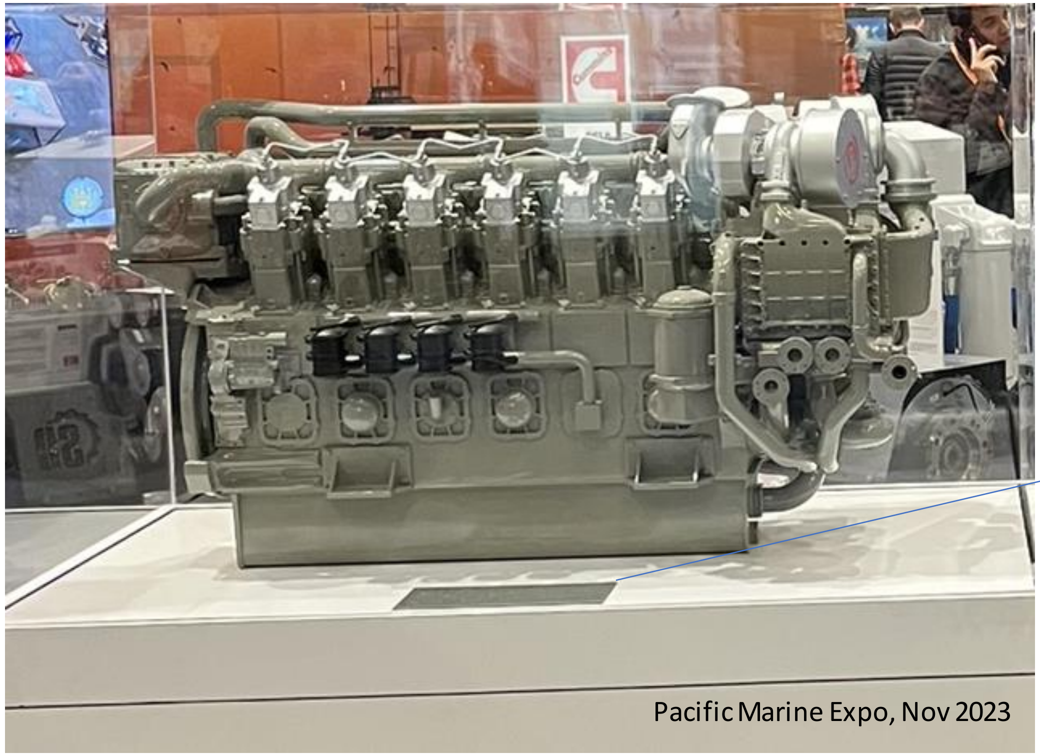
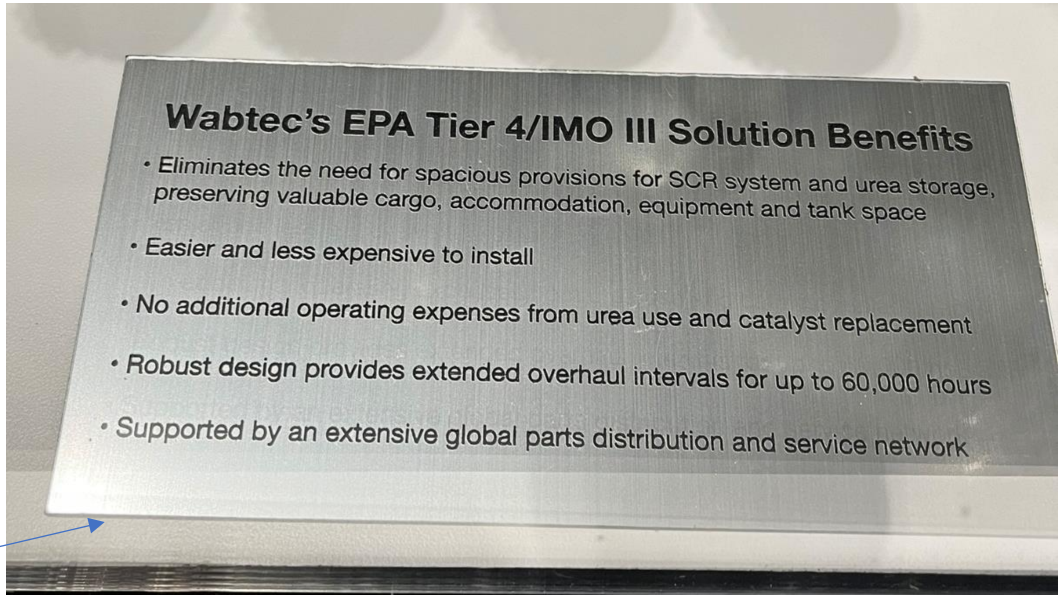


Figure 6.11 Emissions from a high swirl burner with natural gas-firing as a function of flue gas recirculation (FGR) for three air preheat levels. (From Baukal, C. E. and Schwartz, R. E., eds., *The John Zink Combustion Handbook*, CRC Press, Boca Raton, FL, 2001, p. 584, by permission.)

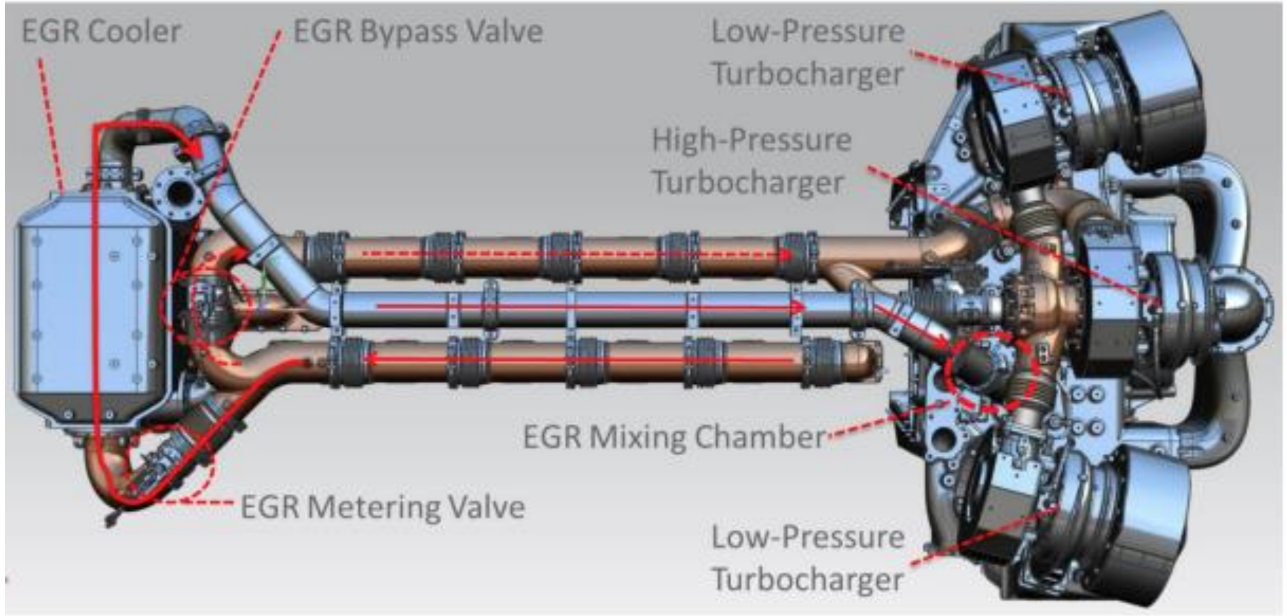
- **Exhaust Gas Recirculation (EGR)**
  - **Benefits include no DEF tank and no SCR**
  - **Commercially available (Wabtec)**


Pacific Marine Expo, Nov 2023



Tier 4 Engines

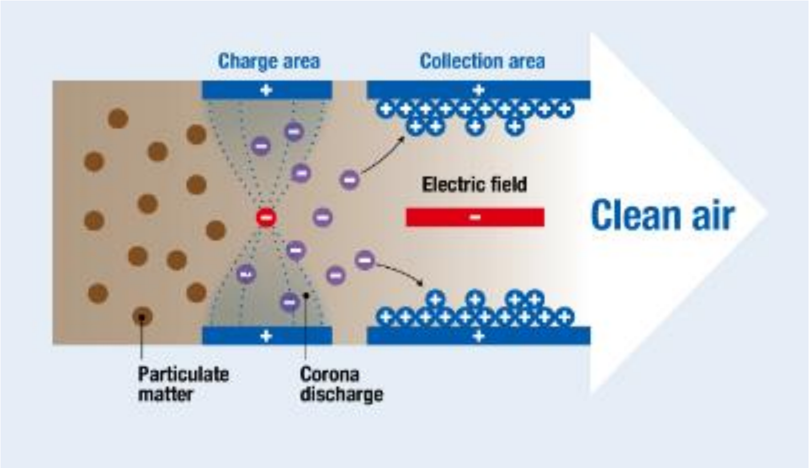
- **EGR Approach (Wabtec)**
- **Allows their L250 and V250 line of engines to reach Tier 4 NOx levels without SCR**
- **Wabtec 250 MDC Series engines are currently the only Tier 4 engines using EGR instead of SCR**

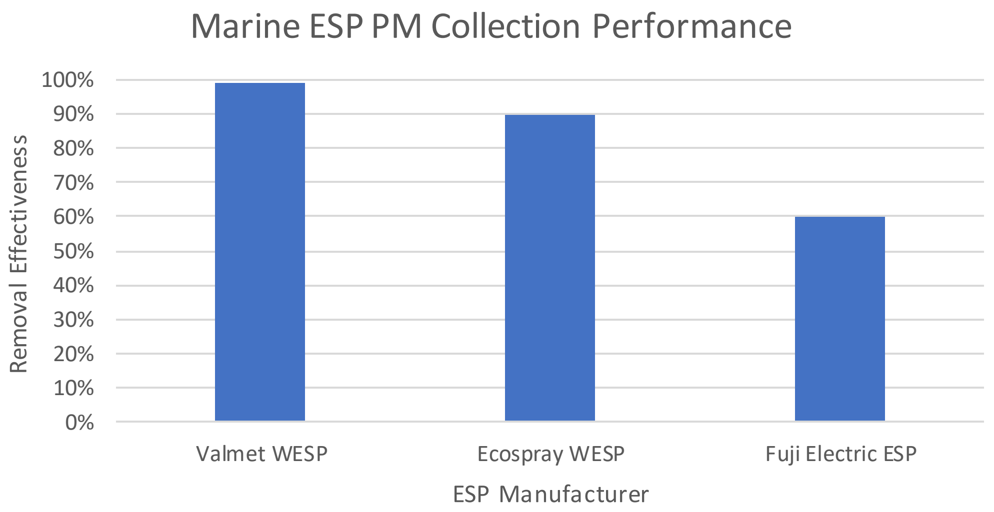


Wabtec White Paper, EPA T4 / IMO III emissions compliance without urea after-treatment https://www.wabteccorp.com/EPA-T4-IMO-III-emissions-compliance-without-urea-after-treatment.pdf?inline

Tier 4 Engine Technology

- **Alternates to DPF**
  - **Electrostatic precipitators**
    - **Some development underway for marine applications, not really commercial**
    - **Ecospray, Valmet, Fuji Electric are developing**





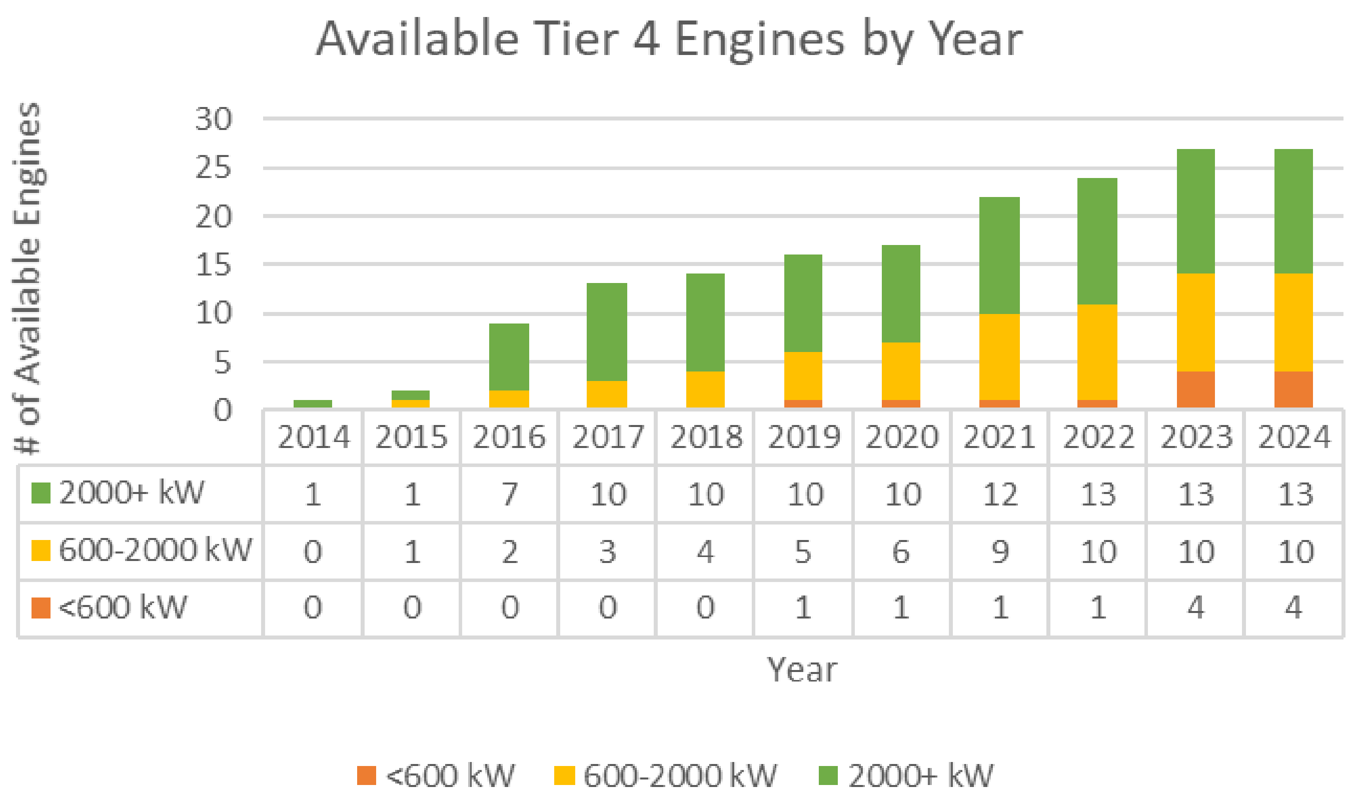
  - **Large physical size implies fitment concerns**
    - **May limit use to OGV (Valmet, Ecospray)**
  - **ESPs at harbor craft scale are not as effective as DPFs (Fuji Electric ESP)**
    - **Current performance won't meet CARB's Level 3 Verification requirements to remove at least 85% of diesel PM**

Outline

- Regulatory Perspective
- Technological advancements on Tier 4 marine/marinized engines and aftertreatment
- **Commercially availability update for Tier 4 marine/marinized engines**
- **Alternative fuels**

Commercially available Tier 4 engines

- **The number of engines available continues to steadily increase**
  - **Recent growth in smaller engines (<600 kW)**



	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
2000+ kW	1	1	7	10	10	10	10	12	13	13	13
600-2000 kW	0	1	2	3	4	5	6	9	10	10	10
<600 kW	0	0	0	0	0	1	1	1	1	4	4

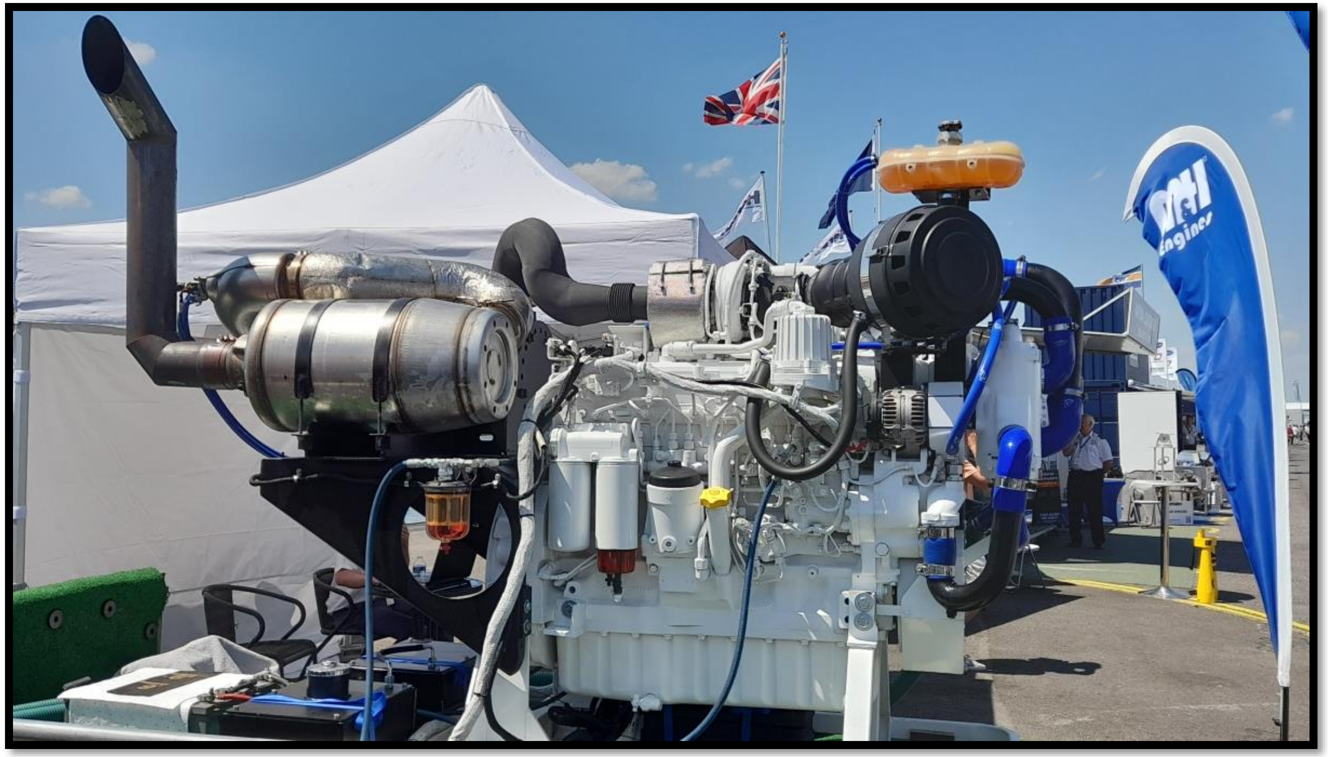
Commercially available Tier 4 engines

- **As of March 2024 (sorted by power output)**
  - **Typically 4-stroke, > 600 kW, no DPF, and equipped with SCR**
    - **Several exceptions: M&H Engineering (DPF; <600kW), Baudouin (<600kW), MAN (DPF), Wabtec (EGR)**

Manufacturer	Model	Cylinders	Stroke	DPF	SCR	Turbo	Emissions Compliance	Weight (kg)	EPA Category	Power Range (kW)	Year Available
M&H Engineering	M&H John Deere 4045MD	6	4	Yes	Yes	Yes	Tier 4, IMO III, Stage V	570	1	55-130	2023
M&H Engineering	M&H John Deere 6068MD	6	4	Yes	Yes	Yes	Tier 4, IMO III, Stage V	785	1	169-224	2023
M&H Engineering	M&H John Deere 6090MD	6	4	Yes	Yes	Yes	Tier 4, IMO III, Stage V	1097	1	205-317	2023
Baudouin	6M-26.3	6	4	No	Yes	Yes	Tier 4, IMO III	2185	1	441-599	2019
Yanmar	6AYEM-GTWS	6	4	No	Yes	Yes	Tier 4, IMO III	2418	1	670-749	2021
MAN Diesel	D2862 Series	12	4	Yes	Yes	Yes	Tier 4, IMO III	2270	1	749-1066	2020
Caterpillar	C32	12	4	No	Yes	Yes	Tier 4, IMO III	3248	1	746-1081	2018
Cummins	QSK38	12	4	No	Yes	Yes	Tier 4, IMO III	5270	1	746-1119	2022
Mitsubishi	S12-R	12	4	No	Yes	Yes	Tier 4, IMO III	5350	1	840-1270	2021
Baudouin	12M-26.3	12	4	No	Yes	Yes	Tier 4, IMO III	3615	1	883-1214	2019
Caterpillar	3512E	12	4	No	Yes	Yes	Tier 4, IMO III	8193	1	1000-1901	2015
MTU	12V-4000M 05	12	4	No	Yes	Yes	Tier 4, IMO III	8000	1	1119-1932	2021
EMD 710 Series	8E 23	8	2	No	Yes	Yes	Tier 4, IMO III	14742	2	1249-1864	2016
Cummins	QSK60	12	4	No	Yes	Yes	Tier 4, IMO III	10154	1	1491-2013	2022
EMD 710 Series	12E 23	12	2	No	Yes	Yes	Tier 4, IMO III	19414	2	1561-2237	2016
EMD 710 Series	12E 23B	12	2	No	Yes	Yes	Tier 4, IMO III	23133	2	1561-2237	2016
GE	6L250 MDC	6	4	No	No	Yes	Tier 4, IMO III	19944	2	1700-1900	2017
MTU	16V-4000M 05	16	4	No	Yes	Yes	Tier 4, IMO III	9300	1	1840-2576	2021
Caterpillar	3516E	16	4	No	Yes	Yes	Tier 4, IMO III	9620	1	1865-2525	2014
GE	8L250 MDC	8	4	No	No	Yes	Tier 4, IMO III	23356	2	2250-2500	2016
MTU	20V-4000M 05	20	4	No	Yes	Yes	Tier 4, IMO III	11600	1	2300-3220	2021
Caterpillar	C280-8	8	4	No	Yes	Yes	Tier 4, IMO III	19000	2	2460-2530	2017
EMD 710 Series	16E 23	16	2	No	Yes	Yes	Tier 4, IMO III	22589	2	2479-2983	2016
EMD 710 Series	20E 23	20	2	No	Yes	Yes	Tier 4, IMO III	25719	2	3098-3729	2016
GE	12V250 MDC	12	4	No	No	Yes	Tier 4, IMO III	27080	2	3150-3500	2016
Caterpillar	C280-12	12	4	No	Yes	Yes	Tier 4, IMO III	26036	2	3700-4060	2017
GE	16V250 MDC	16	4	No	No	Yes	Tier 4, IMO III	35788	2	4200-4700	2017

Commercially available Tier 4 engines

- **M&H Engineering Tier 4 marine engines (< 600 kW)**
  - Marinized John Deere designs
  - Line of 3 engines marinized in 2023, equipped with DPFs.
  - Currently the smallest output Tier 4 certified engines commercially available
    - 130, 224, 317 kW options

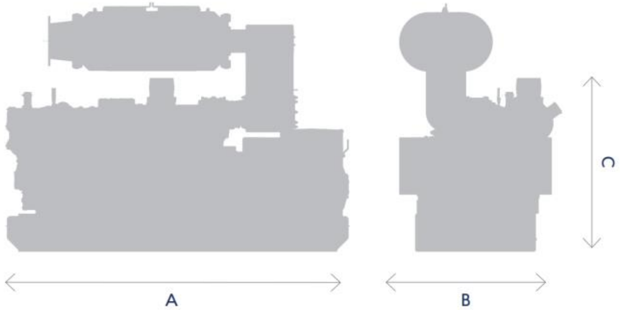


Commercially available Tier 4 engines

- **Baudouin 6M26.3 Engines (IMO 3/ EPA 4/Stage V) Certified (< 600kW)**
  - **In-line 6 configuration**
  - **441, 515, 552, 599 kW**

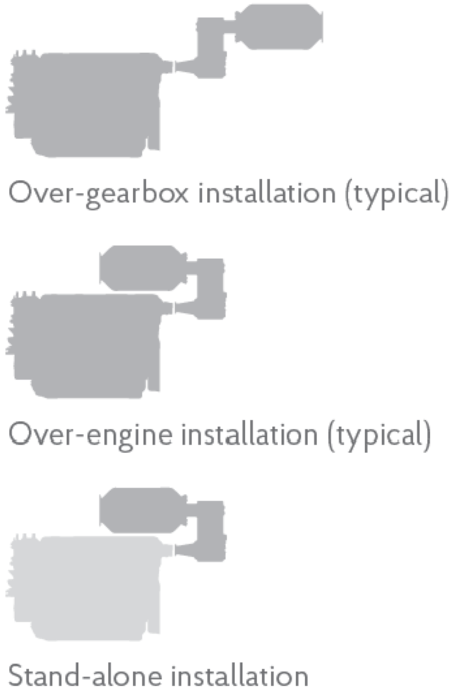
Auxiliary Genset

	A	B	C	Weight
520 KVA @ 50 Hz	3003	1428	1992	3960
590 KVA @ 60 Hz	3003	1428	1992	3828



Propulsion Engines

Adaptable Configurations

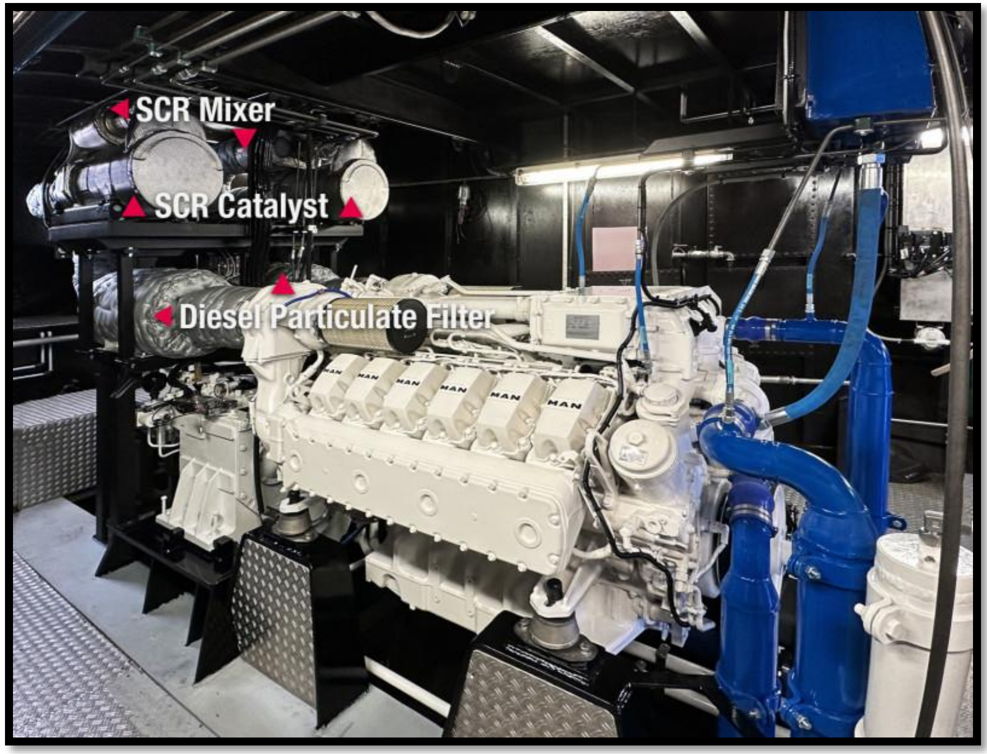


Marine Product Guide (2003). Baudouin Moteurs

Baudouin also offers 883-1200 kW options (12M26.3 engine line)…

Commercially available Tier 4 engines

- **MAN Engines (DPF)**
- **Line of marine engines that include a DOC, DPF, and SCR in the aftertreatment system**
- **Engines meet CARB's in-use performance standards**
  - **3 engines at 3 power ratings are available, all are based on the 12-cylinder MAN D2862**
    - **D2862 LE44A (Heavy Duty): 735 kW (1000 hp) @1800 RPM**
    - **D2862 LE43B (Medium Duty): 882 kW (1200 hp) @2100 RPM**
    - **D2862 LE48B (Medium Duty): 1066 kW (1450 hp) @2100 RPM**

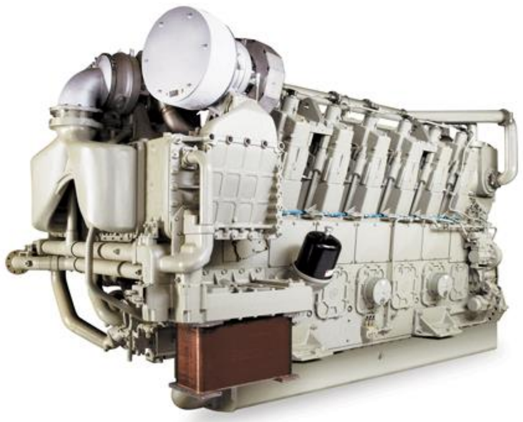


Commercial Marine Product Line (2023). MAN Engines

Commercially available Tier 4 engines

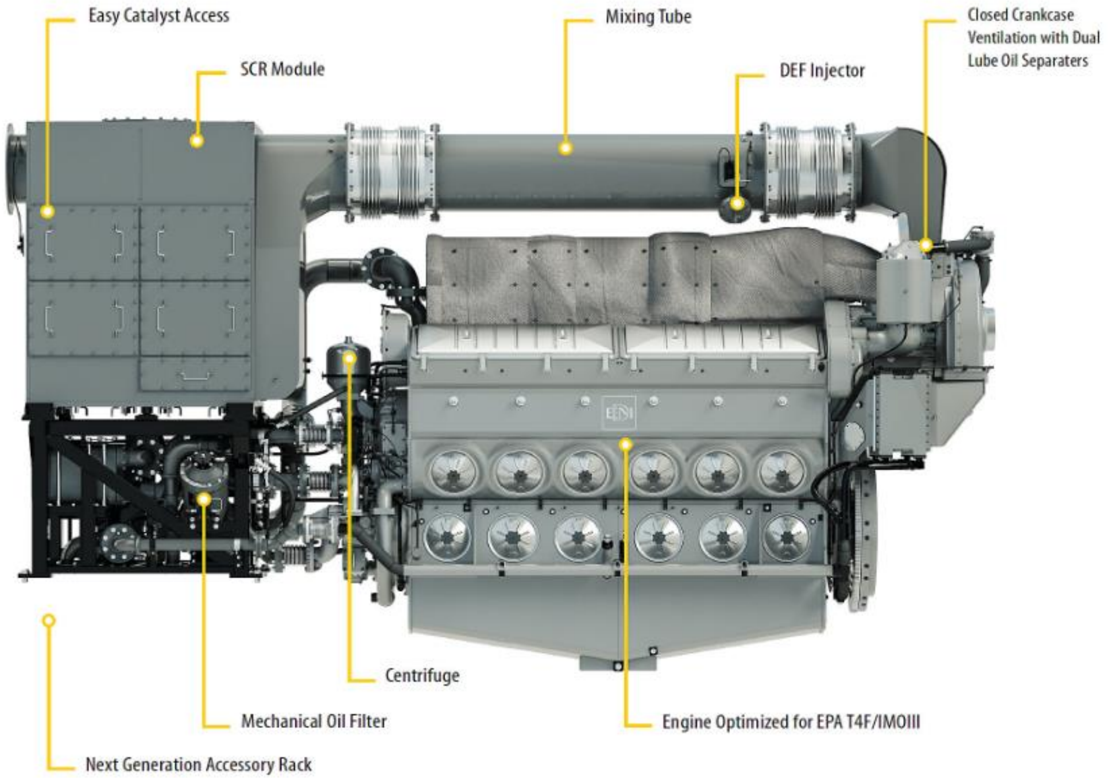
- **Wabtec L250/V250 series (uses EGR/No SCR)**
- **Category 2 (5- 30 liters/cylinder) engines**
  - **As alluded to earlier, these engines achieve Tier 4 NOx levels with EGR alone.**
  - **L250: Offered in 6 (1700 kW – 1900 kW) or 8 (2250 kW – 2500 kW) cylinder inline configurations.**
  - **V250: Offered in 12 (3150 kW – 3500 kW) or 16 cylinder (4200 kW – 4700 kW) V configurations.**


6 Cylinder L250


12 Cylinder V250

Commercially available Tier 4 engines

- **Progress Rail EMD 710 Series (2-Stroke)**
  - **The EMD 710 series of engines is unique as they are 2-stroke instead of 4-stroke.**
    - **Offered in V-configurations of 8, 12, 16, and 20 cylinders, all of which are Category 2 engines**
    - **Only line of Tier 4 engines with a 2-stroke design**
  - **EMD 710 series engines are produced for locomotive, marine, and stationary applications**



12-Cylinder 12E 23

Example California Installations

- P/V Golden Gate pilot boat
- WETA Gemini high speed ferry
- Alta June tugboat

Example Installation: P/V Golden Gate

The P/V Golden Gate is an example of a new vessel with Tier 4 technology being used to replace an older vessel w/Tier 2

Type: Pilot Run Vessel

Vocation: Pilot services for ocean-going vessels at high speeds (25 knots sustained; >30 knots[/1,2]) with high levels of maneuverability and near constant operation

Location: San Francisco Bay, dock located at Pier 9

1. www.marine-pilots.com/videos/1003951-introducing-new-pilot-boat-golden-gate
2. www.bairdmaritime.com/work-boat-world/pilotage/vessel-review-golden-gate-versatile-pilot-boat-to-serve-san-francisco-bay-area

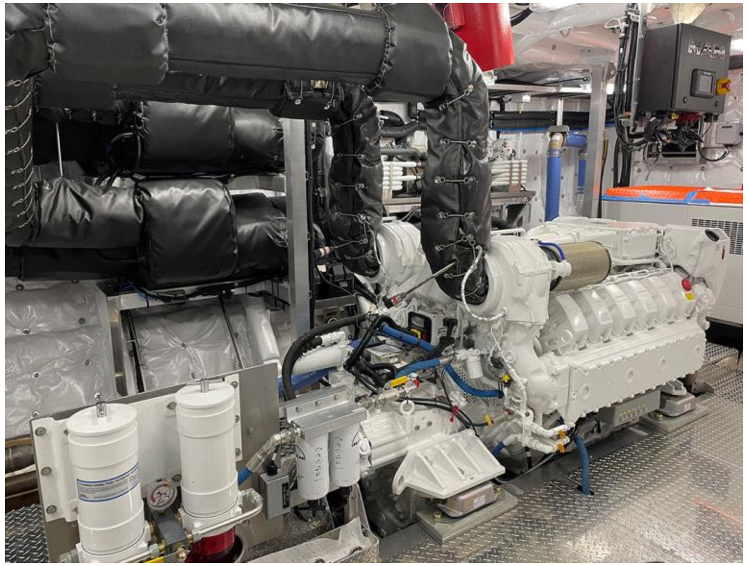
Example Installation: P/V Golden Gate

Old Vessel Specifications:

- Length: 69’
- Beam: 20’
- Engines: Dual Tier 2 main engines

New Vessel Specifications:

- Length: 73’
- Beam: 20’
- Engines: Dual MAN D2862 LE 438 (882kW) Tier 4 main engines, DPFs not installed, but the ship was ***designed for*** their addition before 2028, when it will be mandated
- Shore to Ship power when docked at Pier 9
- Snow & Company incorporated refined Carmarc aluminum hull design (>2.3 knot speed increase/9% efficiency increase)



https://professionalmariner.com/article/golden-gate-a-future-proof-pilot-boat-for-s-f-bay/

Example Installation: P/V Golden Gate

- The new Golden Gate is an improvement over the old Golden Gate through increased safety, comfort, and a lower environmental footprint (higher efficiency, lower emissions)
  - Estimated 70% reduction in NOx
  - Estimated 80% reduction in PM

- The new Golden Gate was able to replace the old Golden Gate while still retaining the old vessel's responsibilities and capabilities. (2 crew, 12 passengers)

Example Installation: WETA Gemini high speed ferry

The WETA Gemini Fleet is an example of a vessel being retrofit with Tier 4 technology in place of a full vessel replacement

Type: High-Speed Catamaran Ferries

Vocation: Ferry services for passengers at high speeds (25 knots) between Richmond and South San Francisco

Location: San Francisco Bay, docks located at Pier 41, Richmond, and South San Francisco.

Example Installation: WETA Gemini high speed ferry

Vessel Specifications (Gemini, Pisces, Scorpio, Taurus)

- Length: 112’
- Beam: 28’

Old Engine Specifications:

Dual MTU Tier 2 main engines

New Engine Specifications:

Engines: Dual MAN Tier 4 D28620
V-12 24.2L 1450 hp light duty main engines

Example Installation: WETA Gemini high speed ferry

- The repowered Gemini fleet is able to maintain its routes with reductions in emissions due to their cleaner engines
  - Estimated 92% reduction in NOx
  - Estimated 80% reduction in PM

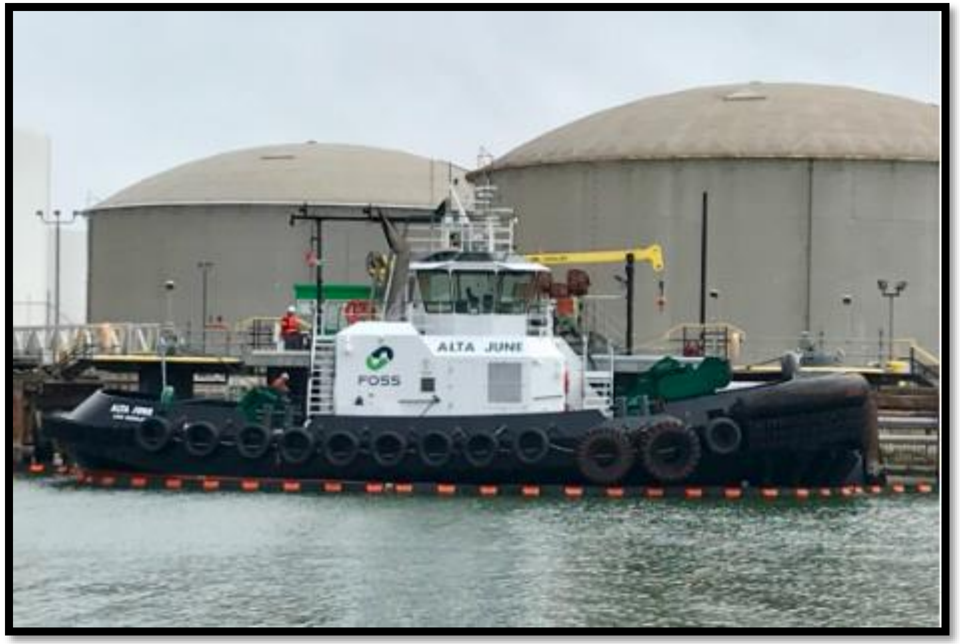
Example Installation: Alta June

The Alta June is an example of a tugboat that was repowered with Tier 4 engines.

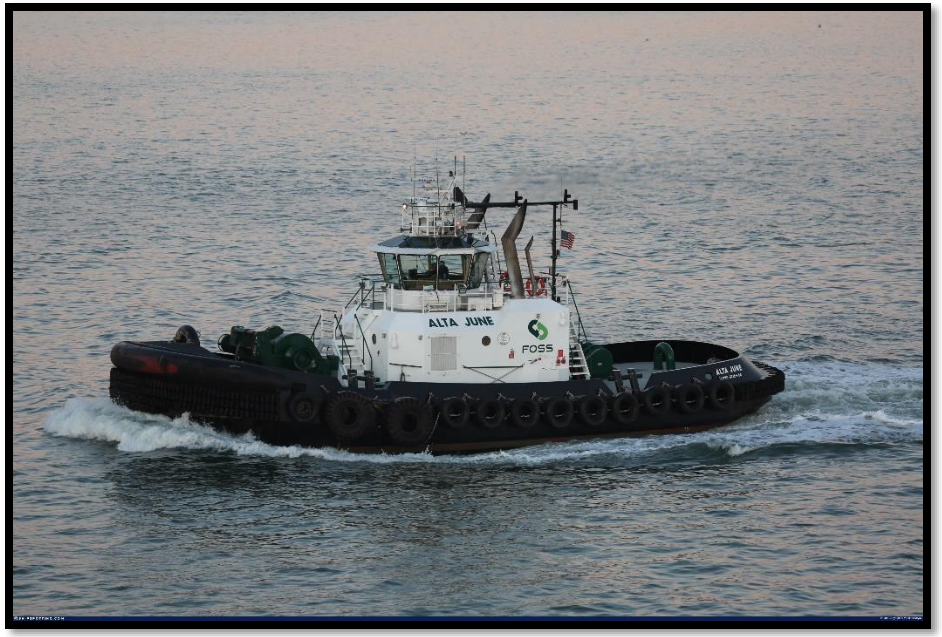
Type: Escort/Ship Assist Tug.

Vocation: Harbor Ship Assistance in Northern California.

Location: Richmond, CA.

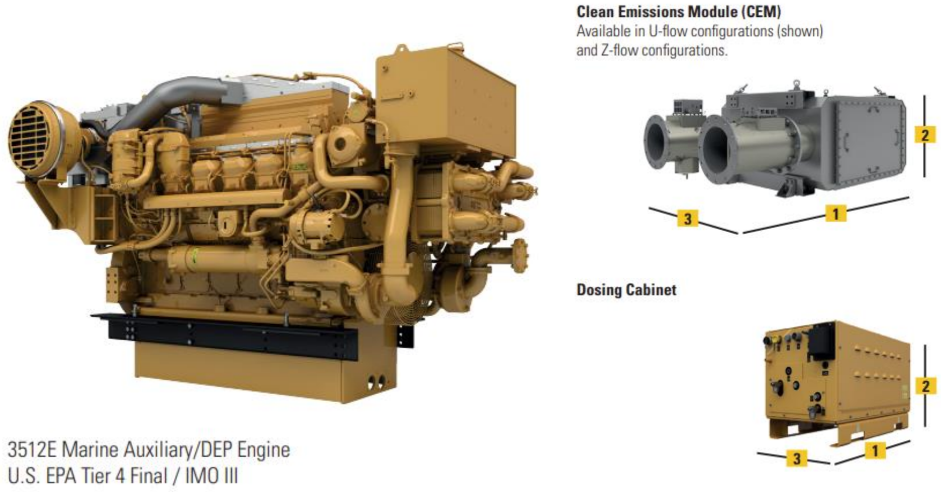


Example Installation: Alta June



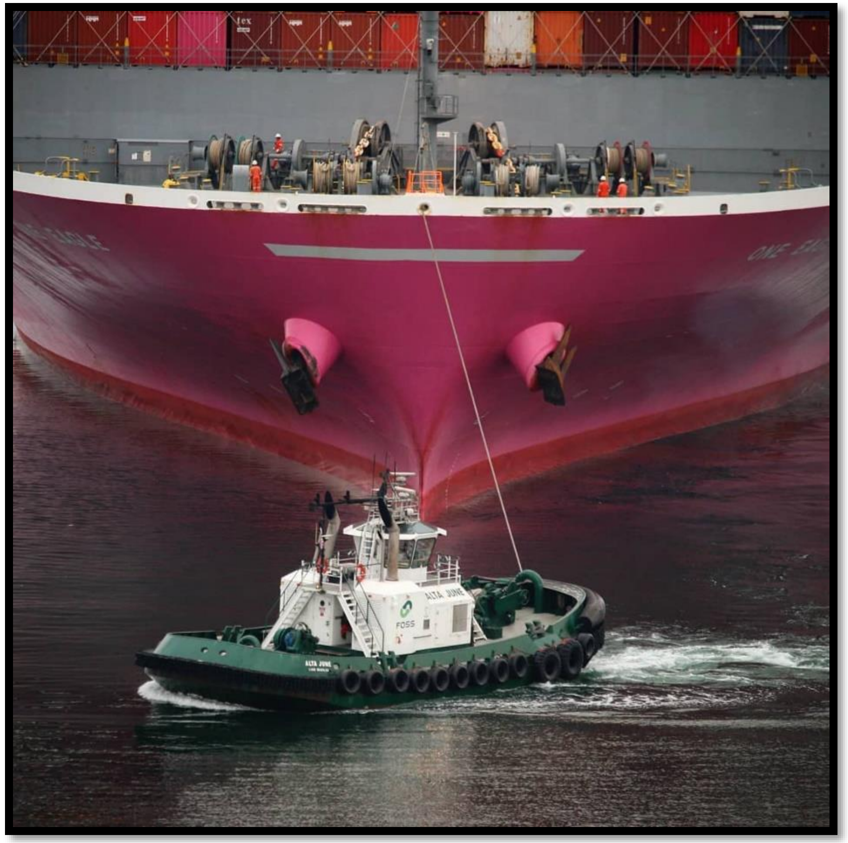
- **The vessel was built in 2008 by Foss Maritime Shipyard in Rainier, OR**
  - Length: 78’
  - Beam: 34’
  - Engines: Originally powered by dual Tier 2 CAT 3512B engines rated for 5080 hp combined.

- **The vessel was repowered in 2022 by Bay Ship and Yacht in Alameda, CA.**
  - Repowered with dual Tier 4 CAT 3512E V-12 engines rated for 5100 hp combined.
  - Required additional equipment for the SCR system



Example Installation: Alta June

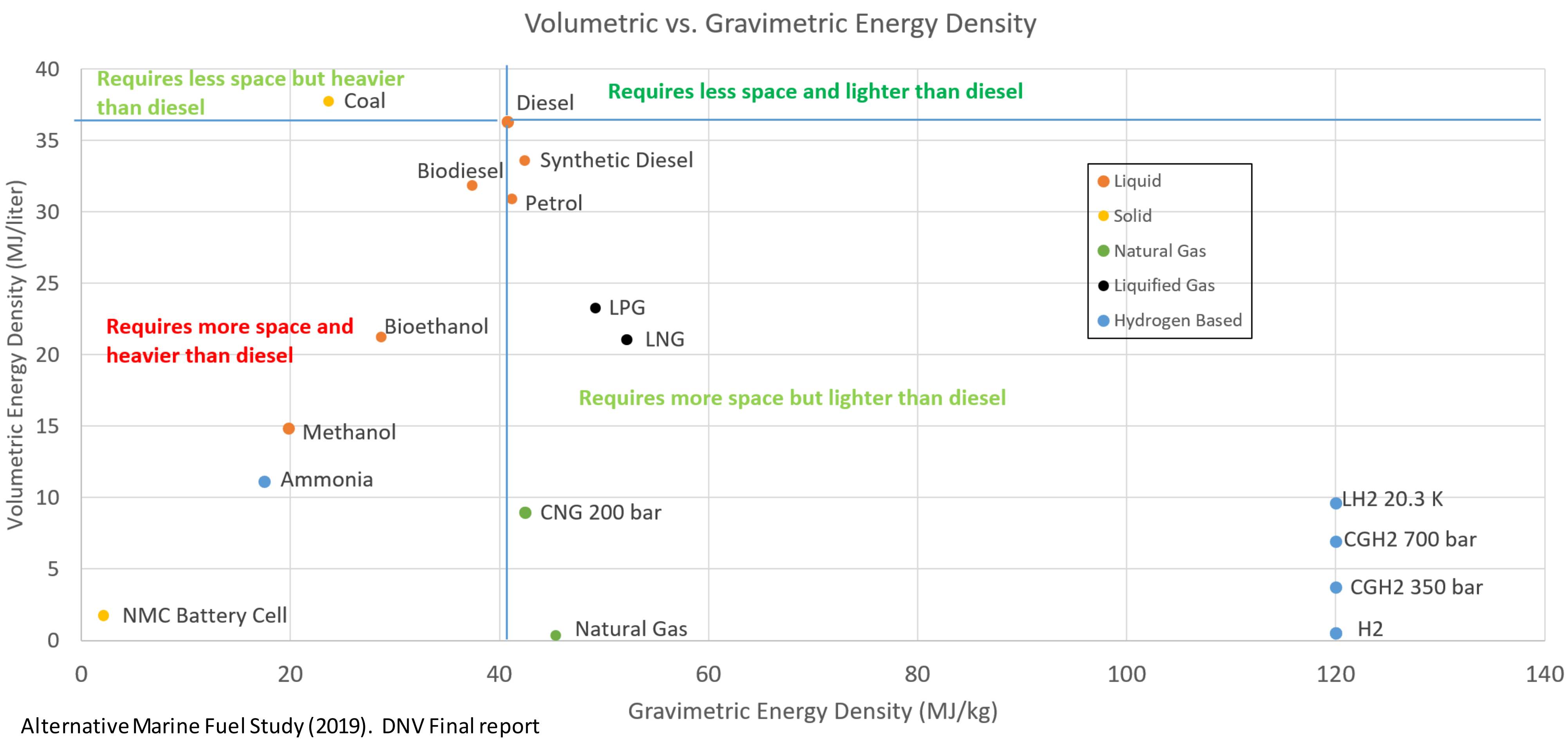
- **The Repowered Alta June engines have roughly the same power output as the previous engines, allowing the tug to perform the same tasks as before with lower emissions**
  - **Estimated 70% reduction in NOx**
  - **Estimated 80% reduction in PM**



Outline

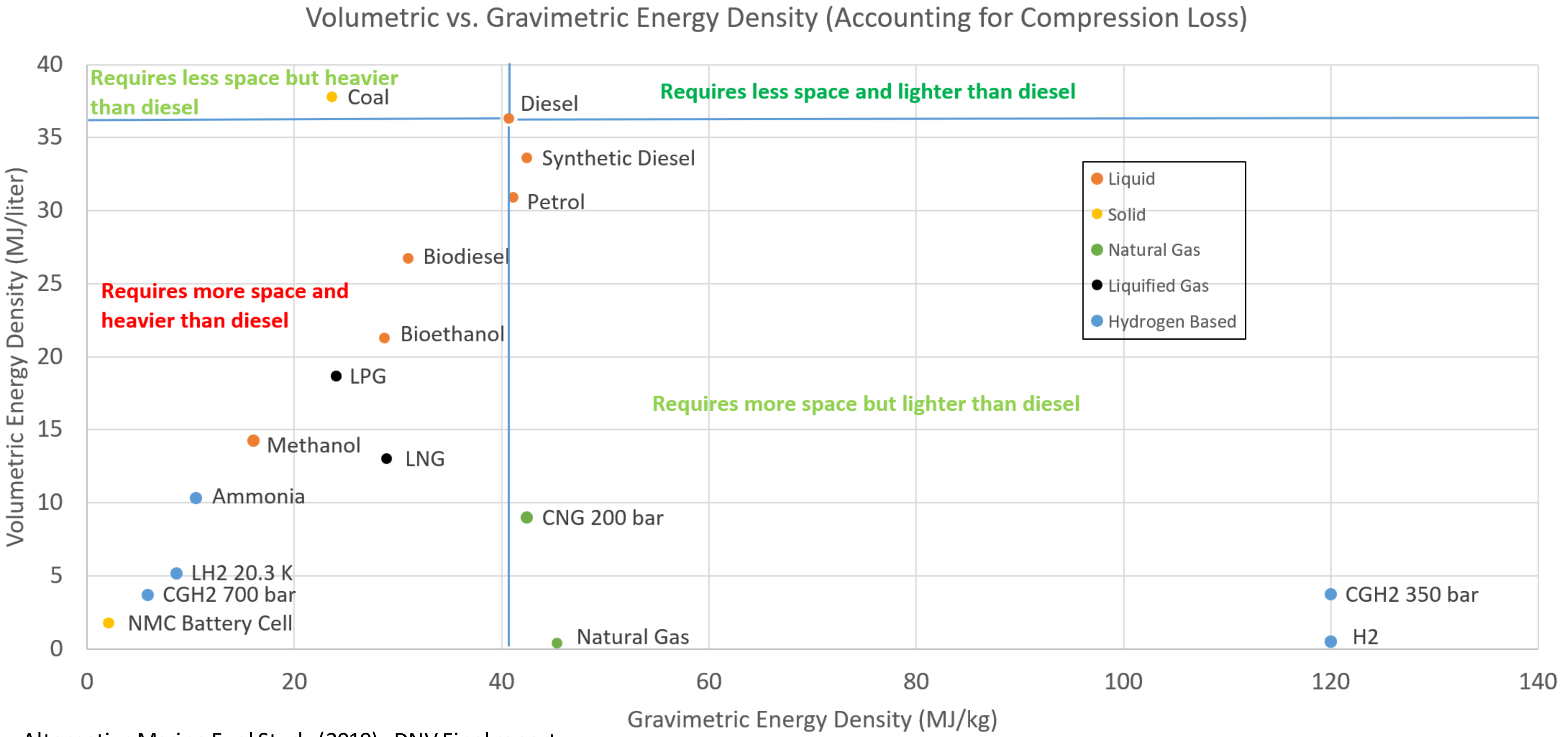
- Regulatory Perspective
- Technological advancements on Tier 4 marine/marinized engines and aftertreatment
- Commercially availability update for Tier 4 marine/marinized engines
- **Alternative fuels**

- **Many alternative fuel options to consider**



Alternative Marine Fuel Study (2019). DNV Final report

- **Accounting for compression/transport losses changes perspective**



Alternative Marine Fuel Study (2019). DNV Final report

- **OEM perspective (MAN)**

Energy storage type/chemical structure	Energy content, LHV	Energy density	Fuel tank size relative to MGO	Supply pressure	Emission reduction compared to HFO Tier II [%]			
	[MJ/kg]	[MJ/L]		[bar]	SO_x	NO_x	CO_2	PM
Ammonia (NH_3) (liquid, -33°C)	18.6	12.7 (-33°C) 10.6 (45°C)	2.8 (-33°C)*1 3.4 (45°C)*1	80	100	Compliant with regulation	~90	~90
Methanol (CH_3OH) (65°C)	19.9	14.9	2.4	10	90–97	30–50	11	90
LPG (liquid, -42°C)	46.0	26.7	1.3*2	50	90–100	10–15	13–18	90
LNG (liquid, -162°C)	50.0	21.2	1.7*2	300	90–99	20–30	24	90
LEG (liquid, -89°C)	47.5	25.8	1.4*2	380	90–97	30–50	15	90
MGO	42.7	35.7	1.0	7–8				
Hydrogen (H_2) (liquid, -253°C)	120	8.5	4.2					

1) The relative fuel tank size for ammonia has been provided for both cooled (-33°C) and pressurised tanks (45°C)

2) Assuming fully refrigerated media

- **No "silver bullet" for diesel replacement**

Energy Source:	Fossil (without CCS)					Bio	Renewable		
Fuel:	HFO + Scrubber	Low Sulphur Fuels	LNG*	Methanol*	LPG*	HVO (Advanced Biodiesel)	Ammonia	Hydrogen	Fully-electric
High Priority Parameters	**Baseline**								
Energy Density									
Technological Maturity									
Local Emissions									
GHG Emissions									
Energy Cost									Varies Regionally
Capital Cost - Converter									
Capital Cost - Storage									
Bunkering availibility									
Commercial Readiness									Case by Case
Other Key parameters									
Flammability									
Toxicity									
Regulations and guidelines									
Global production capacity and locations									
			Attributes Relative to Diesel						
*Potential to be produced renewably			Positive				Negative		

2019_DNVStudy_Alternative-Marine-Fuels-Study_final_report_25.09.19.pdf.

Alternative Fuels

- **General EH&S Considerations (Reed and Forrest, 2022)**

		Synthetic Diesel	Hydrogen	Methane	Ammonia	Methanol	DME
Safety and Health	Fire	High flammability, difficult to suppress/fight.	High flammability, potential flame jetting, difficult to suppress/fight	High flammability, difficult to suppress/fight	Narrow flammability range under high heat	High flammability, water jets may not be sufficient	High flammability, difficult to suppress/fight.
	Explosion	Not classified as an explosion risk	High explosion energy	Explosive under some circumstances	Generally non-explosive but can explode if pressurized	Vapor can form explosive mixture	Non-explosive
	Leak Propensity	Not difficult to contain	Small molecule – difficult to seal Seal material compatibility issues	Prone to leak but manageable	Not difficult to contain Seal material compatibility	Not difficult to contain. Seal material compatibility	Not difficult to contain
	Detection	Leaks are visible and produce odor	Odorless and non-visible flame but sensors available to detect	Odorized, colorless vapor, sensors available to detect	Strong odor, colorless vapor, sensors available to detect	Significant odor and leaks visible	Significant odor and leaks are visible
	Temp & Pressure	Transported and stored at room temperature under low pressure	Transported and stored at high pressure; may be cryo liquid	Transported and stored at mid to high pressure; may be cryo liquid	Transported and stored at room temperature under low pressure	Transported and stored at room temperature under low pressure	Transported and stored at room temperature under low pressure
	Reactivity	Not classified as reactive but reacts with strong oxidants + corrosive	Embrittlement and corrosion risk under some conditions	Corrosion risk, embrittlement risk at high hydrogen fractions	Acids, hypochlorites	Reactive with oxidants	Low reactivity
	Toxicity	Toxic if ingested or aspirated	Non-toxic	Non-toxic	Toxic	Toxic if ingested; can cause blindness and death	Toxic
	Asphyxiation	Low likelihood of exposure to concentrated vapor	In closed areas	In closed areas	In closed areas, 2500 to 4500 ppm fatal in 30 minutes	In closed areas	In closed areas
	Long Term Exposure	No long-term exposure risks/hazards reported	Not an issue and highly unlikely to occur	Not an issue and highly unlikely to occur	Not an issue for long term exposure under 100 ppm	Organ toxicity	Carcinogen – risk for workers
Environment	Water and Land	Water and soil contaminant	Will dissipate as gas if spilled	Will dissipate as gas if spilled	Ammonia, products like fertilizer may contaminate groundwater	Highly biodegradable; no bio-accumulation; toxic to some fish	Contaminant
	Climate Impact	Not greenhouse gases	Not a greenhouse gas	Highly potent GHG if emitted directly	By-products (e.g.CO2) during SMR and N2O from combustion	Major GHG reduction when feedstock is renewable	Major GHG reduction when feedstock is renewable
	Criteria Pollutants	NOx, CO, HC, PM when combusted, generally lower than diesel	May generate incremental NOx when combusted, PM reduced	Generally lower NOx and PM when combusted	Strong NOx precursor	NOx, CO, VOC emissions, generally lower than diesel	NOx, CO, VOC emissions

Low Impact	Medium Impact	High Impact

Reed and Forrest (2022). Assessment of Environmental, Health, and Safety Issues Related to the Introduction of Alternative Fuel Energy Carriers, LCRI Technology Update

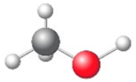
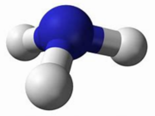
Alternative Fuels for Engines

- **Challenges**
  - Physical Space (volumetric density)
  - Storage pressures/liquification requirements
  - Tank requirements/space (e.g., hydrogen, ammonia, methanol)
  - Shore side infrastructure
    - Bunkering
    - Innovation (e.g., ZEI FT Case, RIX Industries, GenCell FOX)
      - Molecule converters or enablers

- **Practical trade-offs evident**
  - Methanol is more expensive to produce but ammonia is more expensive to handle……
  - MAN Energy Solutions: Hard to see any fuel dominating by 2030….
  - Ammonia on the dock???
  - Hydrogen—public perception

Alternative Fuels

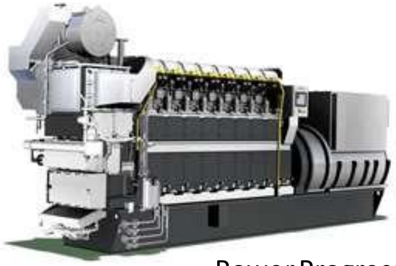
- **Carbon free fuels have significantly different combustion behavior compared to diesel and methane**
  - **Boiling point (storage)**
  - **Heating value (energy density)**
  - **Flammability limits**
  - **Stoichiometric F/A**
  - **Flame speed**
  - **Flame temperature**
  - **Autoignition temperature**
  - **Radiative properties**
  - **Ignitability**
  - **Flame appearance**

		Diesel Fuel				
Formula		C8-C25	CH_4	C_3HOH	H_2	NH_3
MW	Gm/mol	~200	16	32	2	17
Boiling Point	Deg-C	210-235	-161	64.7	-253	-33
Heating Value	BTU/scf		915		275	365
Heating Value	MJ/kg	45.6	50	22.9	120	18.6
Flammability Limits (STD)	%	0.6-7.5	5-15	6-36	4-75	16-25
Flammability Limits	Equiv Ratio		0.5-1.7	0.55-4.32	0.1-7.1	0.63-1.4
AFT (STD, stoic)	Kelvins	2366	2223	2143	2320	2073
Flame Speed, max	cm/s	80--85	30-40	50-60	200-300	6-7
Min Autoignition Temp	Deg K	483	903	738	844	924
RON	Iso-octane = 100	25-40	120	109	63	130
Flame Appearance		Orange/blue	Bluish	Blue/violet	Clear	Whiteish/yellow

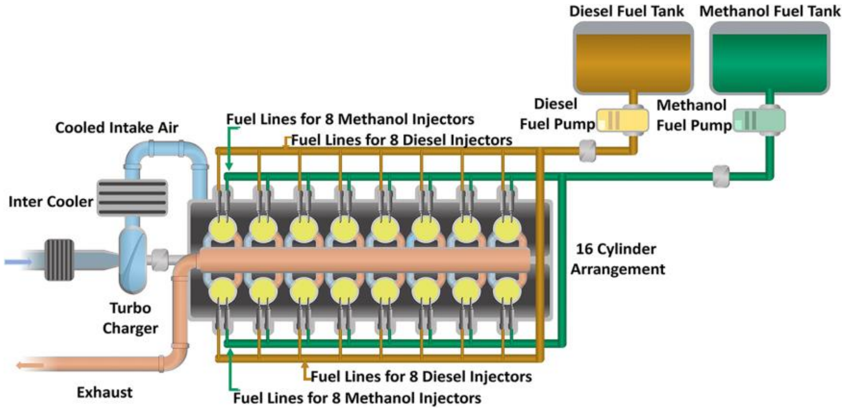
- **Active development by OEMs for engine technology (OGV first?)**
  - **Methanol: Wärtsilä 20, 31, 32 (type approval certified 2022 IMO Tier III), 46F, 46TS**
    - **MethanolPac storage and supply system**

Power Progress, 05 Dec 2023
https://www.powerprogress.com/wartsila-to-add-four-methanol-marine-engines/8033587.article

- **Methanol: MAN Energy Solutions 6L21/31DF (dual fuel)**

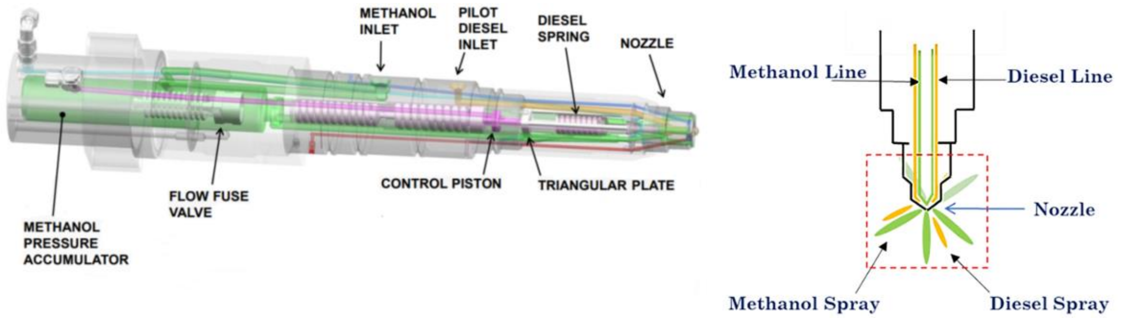


Power Progress, 17 Apr 2024
https://www.powerprogress.com/news/
three-man-methanol-fueled-gen-sets-for-chemical-tanker/8036771.article



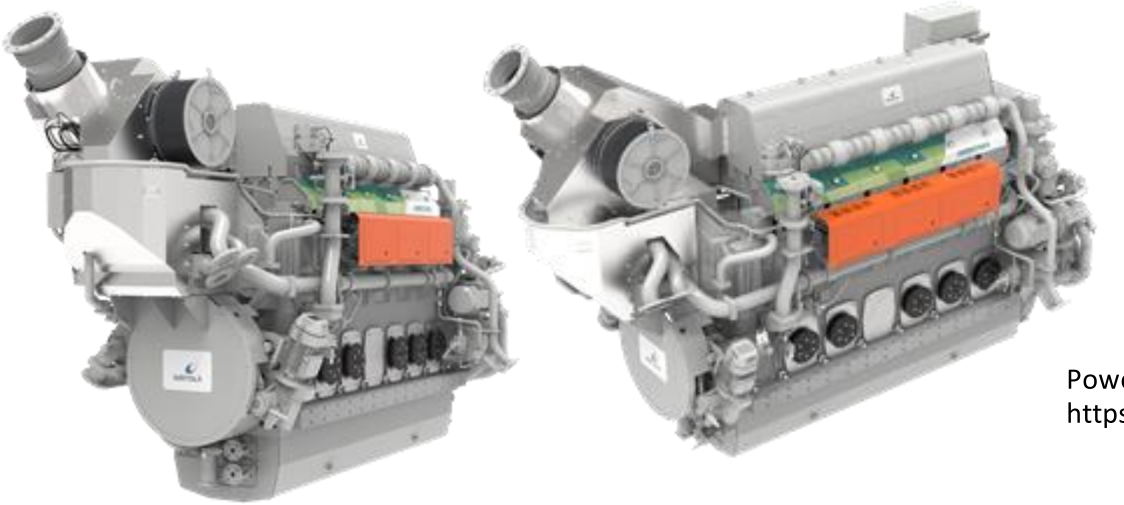
Curran, et al., (2024). The future of ship engines: Renewable fuels and enabling technologies for decarbonization, International J. of Engine Research, Vol 25(1), ppm 85-110

- **Methanol/Dual Fuel**
  - High Pressure Direct Injection
  - Can tailor timing of each fuel
  - Generally need some diesel to initiate combustion
  - O atom in methanol changes the fuel air requirements (less air needed to react fuel)
  - Toxic



Curran, et al., (2024). The future of ship engines: Renewable fuels and enabling technologies for decarbonization, International J. of Engine Research, Vol 25(1), ppm 85-110

- **Active development by OEMs for engine technology**
  - **Wärtsilä 25 Ammonia engine commercially available as of Nov 2023**



IMO Tier III and Tier 2 emissions compliant when used with SCR

AmmoniaPAC fuel system

Wärtsilä NOx ReducerSCR system

Power Progress, 17 Nov 2023
https://www.powerprogress.com/wartsilas-ammonia-fueled-four-stroke-engine/8033121.article

  - **Ammonia: MAN B&W 2-stroke engine (ready for 2024?)**
  - **WinGD**

Ammonia Energy Association: Butting, MAN ES unveil new SCR unit for marine ammonia engines
Jan 16, 2024

- **Ammonia**
  - High Pressure Direct Injection
  - Two-stroke operation (MAN) gives enough time for low reactivity ammonia to react
  - Pilot oil (support fuel) used to control combustion process/ignition
  - Fuel bound nitrogen (NH_3) poses a challenge from NO_x perspective
  - Lack of carbon indicates inherent soot mitigation (pilot oil?)
  - Double walled fuel lines, extra sensors, tank location above deck
  - Significant changes in the engine room
  - Water not effective as a fire fighting measure
  - Bunkering faced with safety considerations

Summary

- **Numbers of Tier 4 engines available are steadily increasing since 2019**
  - Recent growth in availability of <600 kW engines
  - Wabtec engines use EGR vs SCR to attain low NOx performance
    - No SCR or DEF, but requires additional cooling subsystems

- **Retrofit of a DPF onto a Tier 4 engine with OEM SCR adds physical volume and weight that needs to be assessed for feasibility in the vessel on a case-by-case basis**
  - Engine duty cycle determines requirement for active vs passive regeneration
    - Active regeneration yields DPF temperatures of ~1000 F
  - Majority of OEM aftertreatment systems feature DPFs located upstream of the SCR
    - Higher temperature enables less fuel use for active regeneration
    - Some examples of post SCR DPF exist for on-road
    - SCR catalyst integrated onto DPF is under development

Summary

- **Alternatives to DPFs are not commercial yet for marine applications**
  - ESP/WESP—large physical volume, high voltages
  - Catalyzed DPFs may allow SCR/DPF as single integrated module

- **Alternative fuels for combustion technologies**
  - Several options are being considered
    - Each has pros/cons vs traditional fuel: No "obvious" best choice at this point
    - Several OEMs offer engine technology for some (LNG, methanol, ammonia)
    - Bunkering has open questions for both on-shore and vessel infrastructure