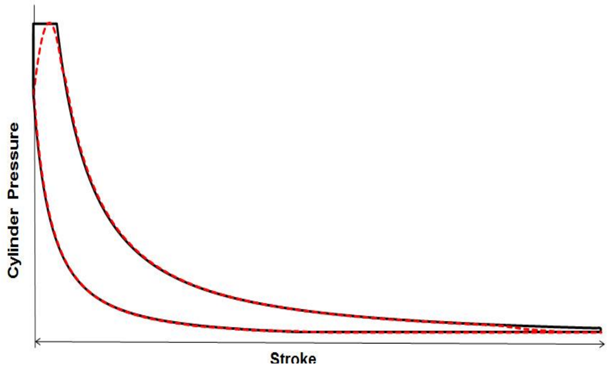
Technical Meeting — 5 February 2020

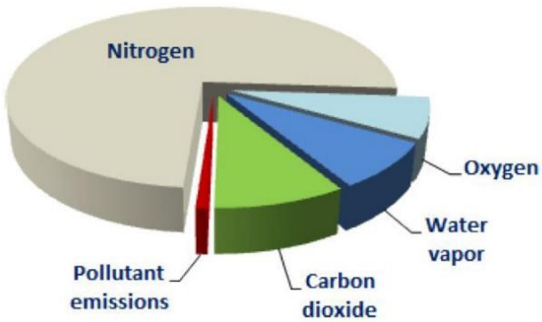
Lachlan Colquhoun, Marine Engine Sales Manager Australia and New Zealand, MAN Energy Solutions, gave a presentation on *Controlling Marine Engine Emissions* to a joint meeting with the IMarEST attended by 42 on 5 February in the Boardroom at Engineers Australia, Chatswood.

Introduction
Lachlan began his presentation by asking, what do we mean by marine engine emissions? The diesel engine was invented by Rudolf Diesel (1815–1913) in the MAN facility in Augsburg, Germany. The principle of the engine is shown in the P-V diagram of the diesel cycle, with the ideal cycle shown in black, and the practical cycle in red.



P-V diagram of the diesel cycle
(Diagram courtesy MAN Energy Solutions)

The diesel cycle has a number of advantages for internal combustion engines, including the highest thermal efficiency, the lowest unburned hydrocarbons, the largest range of available fuel types, and superior combustion control under dynamic and ambient conditions. By increasing the combustion temperature/pressure, we can get more efficiency, but at the expense of more NOx emissions.
Diesel engines, like other internal combustion engines, convert chemical energy contained in the fuel into mechanical power. Diesel fuel is a mixture of hydrocarbons which—during an ideal combustion process—would produce only carbon dioxide (CO_2) and water vapor (H_2O). Indeed, diesel exhaust gases are primarily composed of CO_2, H_2O and the unused portion of engine charge air. The relative concentrations can be shown in a pie chart.



Relative concentration of pollutant emissions in diesel exhaust gas
(Chart from DieselNet website)

GHG Greenhouse gases: substances which trap heat in the atmosphere, including water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3).

The pollutant gases (shown in red) comprise the following:
CO Carbon monoxide
HC Unburnt hydrocarbons
NOx Nitric oxide (NO) and nitrogen dioxide (NO_2) which are formed when N_2 and O_2 react at high temperature
SOx Sulphur oxides emitted when fuels contain sulphur

PM Particulate matter: coarse particles, such as fly ash, condensation of materials vaporised during combustion (visible smoke) and unburnt fuel

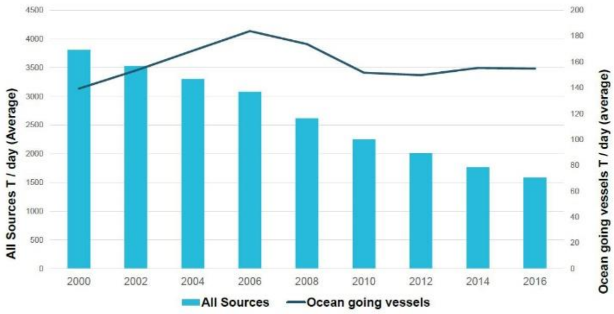
Shipping Emissions

Recent studies indicate that shipping accounts for 94% of all inter-continental transport, 71% of total global trade, 15% of man-made NOX emissions, and 2.2% of man-made CO_2 emissions.

Comparing the transport efficiency of the main modes of goods transport, we see that the fuel needed for the transport of goods is lowest for ships (1.5 g/t-km) and highest for planes (224 g/t-km).

Relative concentration of pollutant emissions in diesel exhaust gas
(Chart courtesy MAN Energy Solutions)

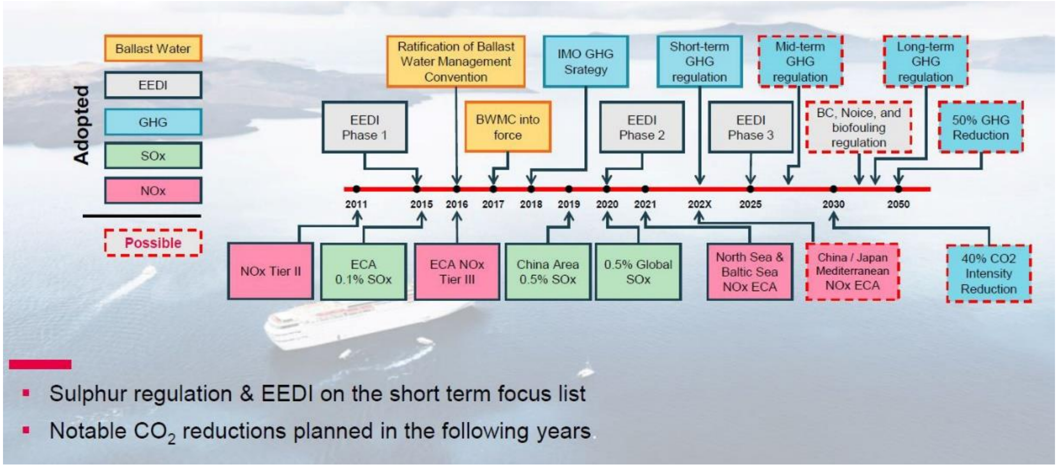
California has been very successful in reducing NOx emissions from land-based transport (truck and rail) over time, but shipping has been lagging behind. However, the current limits placed on shipping emissions should provide reductions in the future as older tonnage is replaced. Regardless of the long-term effect of current marine NOx regulations, the overall trend in California demonstrates that existing NOx reduction technologies can be very effective in reducing NOx emissions.



California NOx emissions trends
(Chart courtesy MAN Energy Solutions)

Current and Future Regulations

Current and future regulations on emissions can be shown in a timeline diagram. The new regulations and the strengthening of the Energy Efficiency Design Index make it more difficult to design inefficient ships. In addition to existing emission control areas (ECAs), the Baltic, North Sea and USA regulations are likely to be expanded to other areas where pollutant emissions like NOx are having a more-pronounced detrimental effect on air quality.



Current and future emission regulations
(Chart courtesy MAN Energy Solutions)

The IMO Resolution MEPC.304(72) shows the IMO strategy on reduction of GHG emissions from ships, aiming for a 50% reduction of GHG emissions by 2050 relative to 2008. Also, the carbon intensity of ships, aiming for a 40% reduction per unit of transport work by 2030 relative to 2008, and 50% reduction by 2050.

Short-term Measures (2018–2023)

- EEDI improvement (Energy Efficiency Design Index)
- SEEMP improvement (Ship Energy Efficiency Management Plan)
- Speed regulation
- Methane slip regulation
- VOC regulation (Volatile Organic Compounds)

Mid-term measures (2023–2030)

- Low-carbon/zero-carbon fuels introduction
- Operational energy efficiency requirements
- Market-based measures

Long-term measures (>2050)

- Zero-carbon/fossil-free fuels for 2050 and later

Alternative Fuels

Alternative fuels include liquefied natural gas (LNG), liquefied petroleum gas (LPG, including propane and butane), ammonia and hydrogen. The fuels and their properties and emission reductions are compared to HFO (heavy fuel oil) Tier II in the accompanying table. Batteries including market leaders Corvus battery rack and Tesla Model 3 battery cells are included for reference purposes.

Alternative fuel properties and emission reductions
(Table courtesy MAN Energy Solutions)

Energy storage type	Specific energy MJ/kg	Energy density MJ/L	Required tank volume m^3 (1)	Estimated PtX efficiency	Emission reduction compared to HFO Tier II			
HFO	40,5	35	1000		SO_x	NO_x	CO2	PM
Liquefied natural gas (LNG -162 °C)	50	22	1590	0,56	90-99%	20-30%	24%	90%
					90-97%	30-50%	15%	90%
LPG (including Propane / Butane)	42	26	1346		90-100%	10-15%	13-18%	90%
Methanol	19.9	15	2333	0,54	90-97%	30-50%	5%	90%
Ammonia (liquid -33 °C)	18,6	12,7	2755	0,65				
Hydrogen (liquid -253 °C)	120	8.5	4117	0,68				
Marine battery market leader, Corvus, battery rack	0,29	0,33	106,060					
Tesla model 3 battery Cell 2170 (2)	0,8	2.5	14,000					

(1) Given a 1000 m^3 tank for HFO. Additional space for insulation is not calculated in above diagram. All pressure values given for high pressure Diesel injection principle.
(2) Values for Tesla battery doesn't contain energy/mass obtained for cooling/safety/classification

Ammonia and hydrogen both have advantages in that there is no CO_2 produced in their combustion.
Batteries have a role to play in short voyages (typically ferries), but the volume required and their endurance mean that they are not in picture for long-haul sea transport anytime soon except as a medium for improving the efficiency of power generation by internal combustion engines.

Significant emissions reductions are possible with alternative fuels. *Lindanger*, the world's first ocean-going vessel capable of running on methanol, is one of nine 50 000 dwt chemical/oil tankers powered by MAN B&W ME-LGI two-stroke dual-fuel engines. The engine is Tier III compliant when run on methanol using HFO, MDO or MGO as pilot fuel. The first of these ships was built in 2016 by Hyundai MIPO Dockyard in Ulsan, South Korea, for Norwegian firm Westfal-Larsen for charter by global marine transportation company Waterfront Shipping.

Lindanger
(Photo from Methanex Corporation website)

Lachlan then discussed the merits and development status of two examples of alternative fuels. The first, LNG has been in use for many decades in the marine sector. Ammonia is a marine fuel in the early stages of its development.

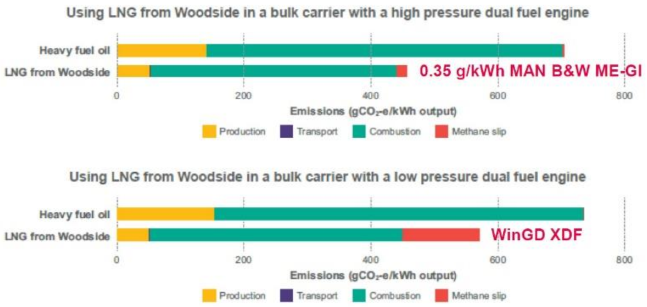
Liquefied Natural Gas

Liquefied natural gas (LNG) is seen by many in the marine industry as a good transition fuel to lower carbon fuels. It produces less CO_2, almost completely eliminates SOx and particulates, and is NOx Tier III complaint without exhaust after-treatment in many applications. There are issues with the quality of the gas in particular the variation in methane number which can cause some engines to de-rate. The four-stroke Otto cycle engines using natural gas are generally less responsive than an equivalent diesel engine. MAN has invested a lot in the development of its four-stroke natural gas engines to minimise these disadvantages. LNG engines and fuel gas supply systems (FGSS) for the marine sector are relatively mature technologies and LNG as marine fuel is growing strongly, particularly in Europe. The main hold-up is the lack of bunkering facilities, but these are increasing. A joint-industry-partnership (JIP) to promote LNG as a fuel for the Pilbara iron-ore trade concluded in 2018. JIP member BHP has recently announced its intention to charter ten LNG-powered Newcastlemax VLOCs for the iron-ore trade, with other miners currently assessing similar plans. A similar JIP has recently been established to promote LNG as a marine fuel on Australia's east coast.

Some of the benefits of a typical marine LNG installation include:

- SOx emissions are largely eliminated (90–99% reduction)
- NOx emissions from four-stroke engines are Tier III compliant without SCR
- 24% reduction in CO_2, which is partially offset by methane slip
- 90% reduction in particulate matter
- Readily accommodates synthetic methane which could be generated by renewable energy

An issue relevant to natural gas engines is 'methane slip' which is the term widely used to describe the release of unburned methane into the atmosphere via the crankcase and exhaust funnel. According to the current IPCC report, methane has twenty-eight times the GHG effect of CO_2. A study by Energetics for Woodside Energy in 2019 compared the methane slip of competing two-stroke engines running on diesel (high-pressure injection) or Otto (low-pressure) heat cycles. The study showed that both technologies reduced equivalent CO_2 (eCO_2) emissions with the high-pressure injection system comparing favourably to the low-pressure system. Four-stroke Otto cycle engines also exhibit higher levels of methane slip compared to the high-pressure two-stroke gas engines. Industry is variously conducting research into ways to remove or 'scrub' methane from exhaust emissions to mitigate this issue.



Life cycle emissions of LNG from Woodside fuelling iron ore shipping from the Pilbara
(Chart courtesy Energetics)

Ammonia

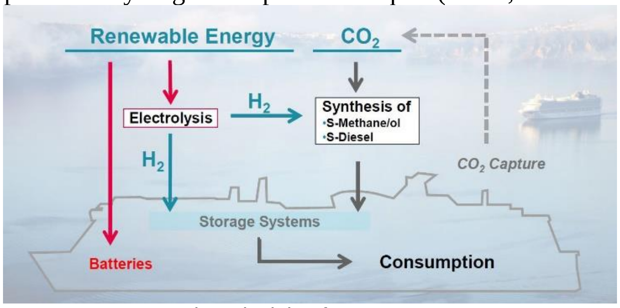
Previous research shows that ammonia works as a fuel in internal combustion engines. MAN Energy Solutions has a programme to adapt our MAN B&W ME-LGI dual-fuel engine to run on ammonia using diesel as a pilot fuel to initiate combustion. Development of this engine is estimated to be 2–3 years. Some of the features and challenges of an ammonia engine include:

- No CO_2 emissions produced when combusted
- Similar engine design and fuel storage systems to LPG
- Ammonia is a widely-traded commodity for fertiliser and pharmaceuticals
- There is a ready market to fuel the global ammonia carrier fleet
- There are IGC Code development issues to overcome
- Ammonia slip (release of unburned ammonia to the atmosphere) is a concern due to odour and toxicity, but it is expected that this can be addressed by after-treatment.

- There is no industrial-scale supply chain for ‘green’ ammonia
- Higher NOx emissions than diesel, but Tier II & III compliance is achieved with existing technology

Power-to-X

Power-to-X refers to a number of electricity conversion, energy storage, and reconversion pathways which use surplus electric power, during periods where fluctuating renewable energy generation exceeds load, or dedicated renewable energy supply. Power-to-X conversion technologies allow for the decoupling of power from the electricity sector for use in other sectors (such as transport). It is suggested that, in the long term, Power-to-X has the potential to replace fossil fuels in the marine sector using pathways such as power-to-ammonia, power-to-gas (synthetic methane), power-to-hydrogen and power-to-liquid (diesel, methanol or ethanol),



The principle of Power-to-X
(Diagram courtesy MAN Energy Solutions)

There is a lot of work under way in the area of electrolysis and synthetic natural gas. For example, Audi has a plant manufacturing synthetic natural gas (SNG) as an e-fuel for Audi customers.

Wes Amelie is a 1036 TEU feeder container ship operated by Unifeeder, which had its four-stroke main engine retrofitted to enable dual-fuel operation. She will become the first vessel in the world to run on SNG generated by wind energy. To demonstrate that SNG can successfully be used as a marine fuel, 20 of the 120 tons of LNG that *Wes Amelie* typically uses per round trip will be replaced by climate-neutral SNG. As a result, CO_2 emissions are expected to decline by 56 tons for the round trip. Automobile manufacturer Audi’s Power-to-Gas facility in Werlte, where a liquefaction plant is currently under construction, will provide the SNG, which will be generated by wind energy and is thus 100% climate-neutral. The first SNG voyage is expected to take place after the completion of the liquefaction plant in Q2 2020. The retrofit is expected to enabled *Wes Amelie* to reduce SOx emissions by >99%, NOx by approximately 90%, and CO_2 by up to 20%. As a result, the vessel now meets both Tier II and Tier III emission requirements set by the International Maritime Organisation (IMO).

Wes Amelie
(Photo from Shipspotting.com website)

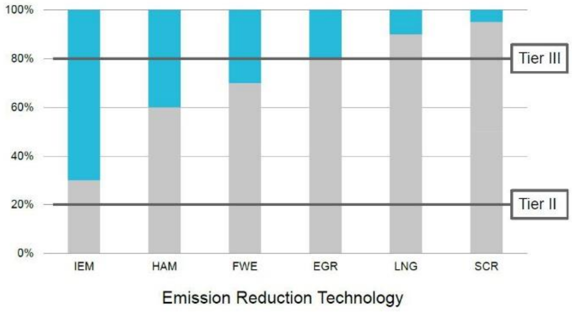
NOx Reduction Technologies

Nitrogen oxides (NOx) are produced in high temperature mixtures of atmospheric nitrogen and oxygen which occur in the combustion cylinder, and this usually occurs at peak cylinder pressure. For this reason, there is a basic trade-off between engine efficiency (specific fuel oil consumption, SFOC) and NOx emissions. As the flame temperature/combustion pressure increases, the efficiency (SFOC) increases, and the NOX emissions increase. Accordingly, we can reduce NOx emissions at the expense of increased SFOC.

Engine OEMs employ a diverse range of technologies to reduce NOx emissions, including:

IEM Internal engine modification
HAM Humid air motor
FEW Fuel-water emulsion
EGR Exhaust gas recirculation

SCR Selective catalytic reduction
LNG Liquefied natural gas



NOx reduction technologies and IMO tier compliance
(Diagram courtesy MAN Energy Solutions)

The table is a generalisation, but shows the relative effectiveness of each of the technologies in reducing NOx.
EGR is a NOx emissions-reduction technique used in diesel engines and works by recirculating a portion of the engine's exhaust gas back to the engine cylinders. This dilutes the O_2 in the incoming air stream and provides gases inert to combustion to act as absorbents of combustion heat to reduce peak in-cylinder temperatures. MAN Energy Solutions utilises EGR in two-stroke applications to achieve Tier III compliance.
SCR is a proven technique and has high NOx-reduction potential (up to 90%). It is the dominant technology used to achieve Tier III compliance in diesel-fuelled engines. However, there are challenges, including the need for an additional consumable (i.e. the urea solution), exhaust-gas temperature control, and the space and mass requirements for the system.

Other Emissions-reduction Technologies
Other technologies being investigated to control emissions from marine diesel engines include:

- Diesel particulate filters: Not currently being used in the marine field, as emission levels of current diesel fuel and LNG don't require, although it may be required in the future as limits become more stringent.
- SOx reduction.
- Catalytic oxidation is used to reduce carbon monoxide but may be applicable as a means of reducing methane slip
- Methane slip scrubbing/capture: There is a lot of effort being put into this area to reduce eCO_2 emission of LNG.

Technology Summary
Lachlan then showed a video of the latest technology from VW showing the technology which they have developed to meet the more stringent Euro 6 emissions requirements for passenger vehicles and their commitment to diesel engines. The animation showed the workings of many of the emissions technologies outlined above and may be a window to what may be ahead in the marine sector.

Conclusion
There are different types of emissions produced by internal combustion engines used in marine applications, and key drivers behind current and future emission limits set by the International Maritime Organisation and local regulators. There are existing and emerging marine fuels and they have relative benefits from the emissions-reduction, shipbuilder's and operator's perspectives. There are existing and emerging technologies employed by engine manufacturers to reduce or scrub emissions, and areas of development.

Questions
Question time was lengthy and elicited some further interesting points.
Slow steaming is an interesting option. If a vessel has to convert to slow steaming, and run at 40% load rather than 80%, then there are usually no problems with these technologies as they are designed to run at lower loads. However, the engine itself is usually less efficient at a lower load, and so you are really better off designing for a slowed steaming speed in the first place as a long-term solution. For existing ships, a permanent de-rating of the engines or optimisation of the engine at lower loads can be implemented for a turbocharger retrofit or changes to fuel-injection equipment may have short payback periods.

Ammonia in a dual-fuel engine requires pilot diesel fuel to initiate combustion. There is a lot of development work going on at the moment into how much diesel is required to ignite the gas.

Hydrogen as a marine fuel is currently limited to small-scale projects. MAN is currently involved in a project for a fjord ferry in Norway. The benefit of using hydrogen is that there are no CO_2 emissions. Limitations of hydrogen in marine applications are that the storage volume required is approximately four times that of diesel fuel, and the boiling point is considerably lower at –253ºC and, accordingly, the energy required for liquefaction is considerably higher than that for LNG. Hydrogen is a very 'tight' gas, meaning that piping and valving requirements are all more stringent. Finally, hydrogen is significantly more flammable than LNG at ambient conditions, meaning that safety considerations are more demanding. Whilst the safety issues can be addressed MAN thinks that implementation in the marine field on the scale required for large ocean-going vessels is a long way off.

The vote of thanks was proposed, and the certificate and "thank you" bottle of wine presented, by Geoffrey Fawcett.

Lachlan Colquhoun (L) accepting his certificate
and "thank you" bottle of wine from Geoffrey Fawcett
(Photo Phil Helmore)