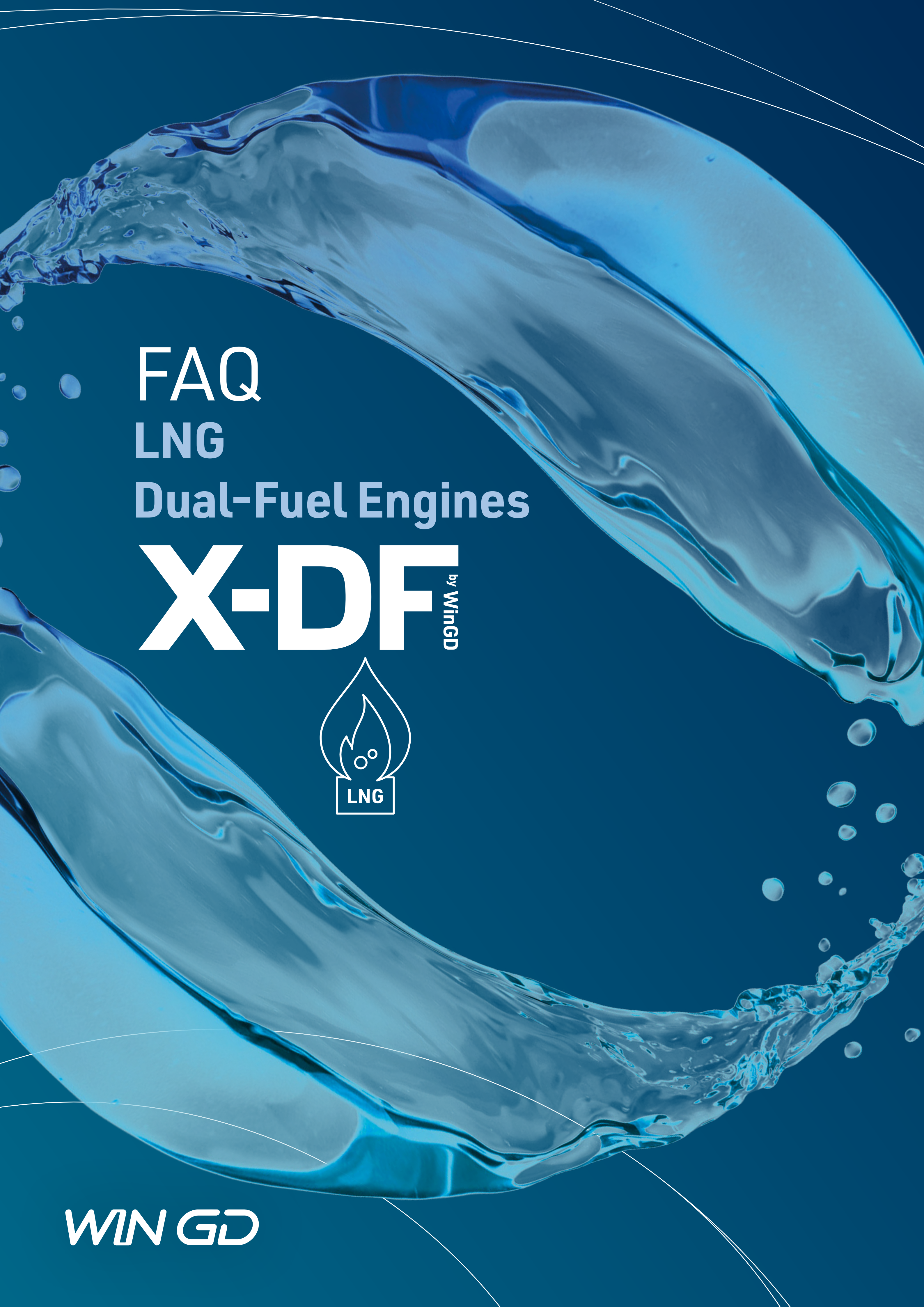


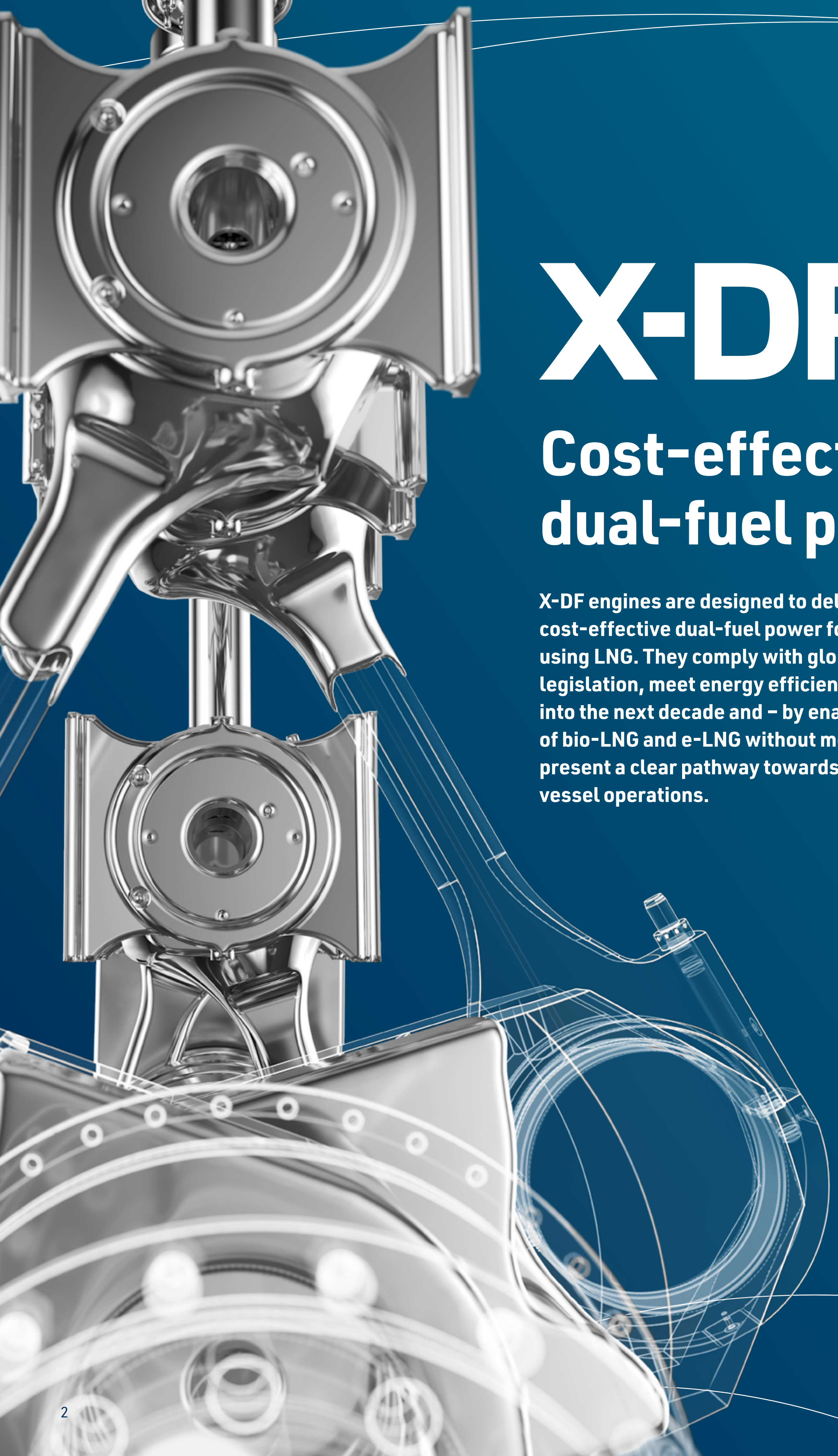
FAQ

LNG Dual-Fuel Engines

X-DF by WinGD

LNG

WIN GD



X-DF by WinGD

Cost-effective dual-fuel power

X-DF engines are designed to deliver reliable, cost-effective dual-fuel power for vessels using LNG. They comply with global air pollution legislation, meet energy efficiency targets well into the next decade and – by enabling the use of bio-LNG and e-LNG without modification – present a clear pathway towards decarbonised vessel operations.

X-DF engines for LNG employ low-cost, high efficiency and reliable low-pressure technology that requires lower investment in auxiliary systems than high-pressure engines. And with X-DF2.0 technologies iCER and VCR making them competitive on overall emissions while retaining a system cost advantage, X-DF LNG engines represent a cost-effective and future-ready solution to LNG-fuelled vessel power.

Today, X-DF is the only low-pressure dual-fuel two-stroke engine being promoted for newbuild vessels, achieving close to 100% market share among LNG carrier new builds in 2024 while extending its references across several other merchant sectors.

With almost 900 engines in service and on order, and a track record of more than 10 million running hours, the pioneering X-DF concept continues to evolve and win repeat orders.

For up-to-date details on the running experience of WinGD X-DF engines please visit our website at www.wingd.com

Key milestones

- **2016**
  The first X-DF engines enter commercial operation on Terntank vessel Ternsund. Today, close to 900 in service or on order.
- **2017**
  The first LNG carrier powered by two X-DF engines sets sail. Today X-DF is the market leader in the segment.
- **June 2020**
  The first X-DF2.0 technology, iCER (intelligent Control by Exhaust Recycling) is launched. By delivering enhanced combustion control through the introduction of inert gas, iCER reduces fuel consumption in both LNG and diesel modes, as well as reducing methane slip. X-DF engines are now available with either off- or on-engine iCER, to accommodate engine room design and shipyard commissioning.
- **June 2023**
  The next generation of X-DF2.0 technology, Variable Compression Ratio (VCR) technology, is launched. Dynamically adjusting compression ratio – for the first time in any marine engine – enables X-DF engines to further reduce fuel consumption and emissions when using either diesel or LNG, for further operational flexibility and enhanced environmental compliance.

FAQ Contents

1 What are low-pressure and high-pressure dual-fuel LNG engines?

Dual-fuel engines are designed to one of two combustion concepts:

Diesel Cycle: Also known as high-pressure injection. These engines use the standard combustion process common to all conventional low-speed engines, with LNG fuel injected into the combustion chamber at high pressure, alongside a simultaneous injection of pilot fuel that ignites combustion.

Otto Cycle: Also known as low-pressure admission. These engines deploy a lean-burn combustion process whereby LNG is admitted to the combustion chamber under low pressure before compression in the cylinder. The LNG fuel is then ignited by the injection of pilot fuel under high pressure.

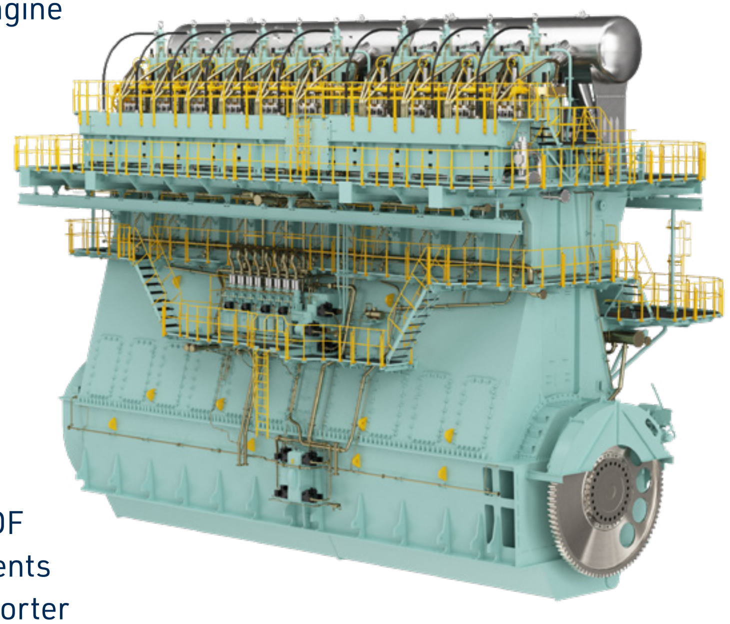
The distinguishing feature of X-DF engines for LNG is that they work on the lean-burn Otto cycle when operated in gas mode. The gas enters the combustion chamber before piston compression occurs via a low-pressure feed ranging from 6 bar(g) to 15 bar(g) depending on engine size, rating and the fuel's lower heating value.

2 What are the advantages of low-pressure X-DF engines?

The X-DF concept provides several benefits compared to high-pressure engines. As a result, X-DF technology has been widely adopted by the marine market.

Low-pressure X-DF engines	High-pressure gas engines
Low-pressure gas supply means low investment costs for the Fuel Gas Supply System (FGSS), low electrical power consumption, low maintenance costs and simple operation	High-pressure gas supply means more expensive Fuel Gas Supply System (compressors and/or pumps, components etc.), higher electrical energy consumption and higher maintenance costs
Low pilot fuel quantity, ranging from 0.5 - 1% of total energy consumption over engine power	Higher pilot fuel quantity, ranging from 0.5 - 8% of total energy consumption over engine power
X-DF engines can be operated on gas down to 10% power. Start/stop is requested in diesel mode. Manoeuvring for vessels with CPP is available in gas mode at this power	High-pressure gas engines may operate in gas mode at relatively low loads, but in practice run primarily on liquid fuel due to the high percentage of pilot fuel required
Low NO$_X$ emissions, Tier III compliant without exhaust gas treatment system	Tier II compliant only and an exhaust gas treatment system like EGR or SCR is needed to meet Tier III
Particulate matter emissions are significantly reduced compared to diesel engines	Particulate matter emissions still significant

3 What size and type of X-DF engines are available?

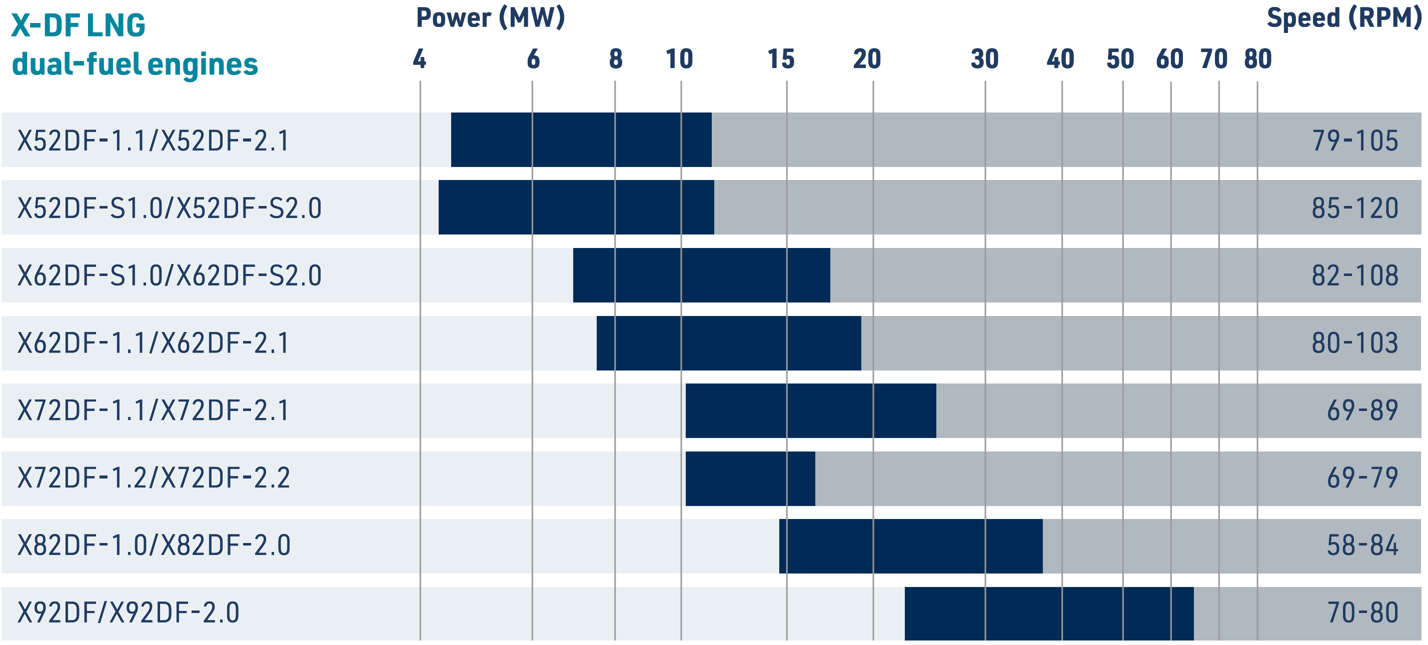


X-DF engines are available in the engine sizes listed in the table below. For more details on individual engine versions, including cylinder numbers, please consult the latest WinGD Engines Booklet.

Worth highlighting are the S1.0 and S2.0 variants, designating short-stroke engines designed for applications where compact engines are required.

The 1.2 and 2.2 versions of the X72DF engine are tailored to the requirements of the LNG carrier market, with a shorter bedplate and engine rating fields optimised for the segment's typical operating demands.

As well as X-DF-1.0 engines, WinGD also offers X-DF-2.0 engines featuring intelligent Control by Exhaust Recycling (iCER) and, optionally, Variable Compression Ratio (VCR) technology, both of which deliver further improvements in fuel consumption and emissions performance.



4 Which vessel segments is X-DF used in?

X-DF engines are applicable to all merchant vessels that would typically be powered by two-stroke engines. Of the close to 900 engines in service and on order, the majority are deployed on twin-engine LNG carriers, with significant references in the containership, tanker and pure car/truck carrier fleets, as well as on Ro-Ro vessels and bulk carriers.

5 Why is X-DF the leading engine technology in the LNG carrier segment?

X-DF has been the dominant engine technology amongst LNG carrier new builds since its introduction, achieving close to 100% market share in 2024.

The main reasons for its popularity in this segment are:

System cost: Because X-DF low-pressure engines only require the use of low-pressure compressors or pumps as part of the fuel gas supply system, they offer a significant CAPEX discount compared to high-pressure dual-fuel engines.

System OPEX: The low-pressure technology required across the fuel chain means that power demand for fuel handling and maintenance demands are reduced substantially compared to the system needed around high-pressure engines. Combined with the inherent fuel efficiency and reliability of the X-DF engine, this presents a compelling OPEX case for LNG carrier operators.

Tailored approach: WinGD has introduced X-DF features specifically designed for the LNG carrier market. One example is the X-DF-2.2, which features a shorter bedplate than base models due to the traditional segment requirement for only five-cylinder engines. The engine rating field has also been adjusted for the typical LNG carrier operating profile.

Continuous improvement: As well as being the only mature low-pressure dual-fuel two-stroke engine technology, X-DF also benefits from WinGD's continuous investment in both improving the core design and introducing technology upgrades. Engines featuring both X-DF-2.0 technologies, iCER and VCR, have been widely ordered by LNG carriers.

6 How do X-DF engines and high-pressure engines compare on fuel consumption?

The engine, fuel gas supply system, auxiliary systems, emissions abatement technologies and other factors have a significant influence on the overall energy requirement for the ship propulsion system and must be calculated when making consumption comparisons. In most cases, low-pressure systems have an advantage.

X-DF-2.0 technologies further improve the fuel consumption comparison. See Operating Expenses for a detailed comparison.

Owners should take care to consider fuel performance tolerance margins when forecasting fuel costs. WinGD has maintained the same performance data and tolerances since X-DF and subsequent X-DF2.0 technologies were introduced; other designers have periodically changed tolerance margins, making them wider for some engines and operating modes.

7 What is the impact of X-DF's lower power output compared to standard low-speed engines?

X-DF LNG engines have been designed to avoid pre-ignition and knocking risks – where the air-fuel mix is either too lean or too rich for stable combustion – so the maximum rating has been reduced compared to single-fuel engines.

The X-DF engine rating field covers most of the applications that typically apply derated output, meaning that for most applications no additional cylinders are required compared to standard low-speed engines.

However, even in cases with an additional cylinder, the additional costs are more than covered by the cost savings of the low-pressure fuel gas system.

8 Why do X-DF engines require less pilot fuel than high-pressure engines?

X-DF engines require less pilot fuel due to unique pre-chamber technology, a clear advantage over the high-pressure gas engine injection concept.

	Low-pressure X-DF engines	Competing high-pressure engines
Pilot fuel consumption	**0.6 – 1.5** g/kWh @ 100% power **1.3 – 3.3** g/kWh @ 30% power	**2.9 – 10.2** g/kWh @ 100% power* **6.5 – 22.7** g/kWh @ 30% power*

* Depending on selected pilot oil energy fraction

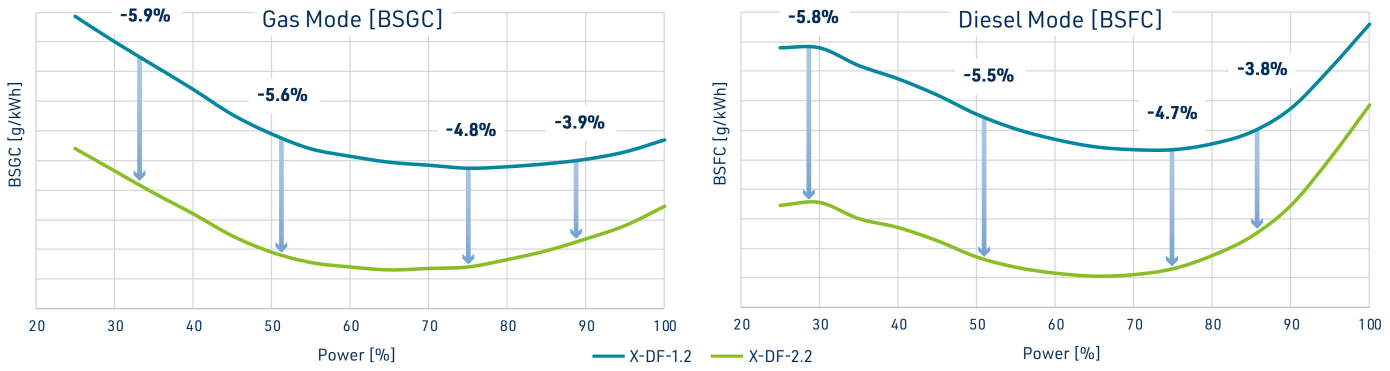
9 What is iCER?

Intelligent Control by Exhaust Recycling (iCER) is an enhancement available to all newbuild X-DF LNG dual-fuel engines, signified by the engine designation X-DF-2.0. It offers better control of combustion, enabling an increase of compression ratio and ultimately an increase in thermal efficiency – reducing fuel consumption, emissions and the release of unburned methane. The technology is available in both off-engine and on-engine variants, with the on-engine arrangement providing a reduced engine room footprint as well as additional flexibility for installation and commissioning.

10 How does iCER enhance X-DF performance?

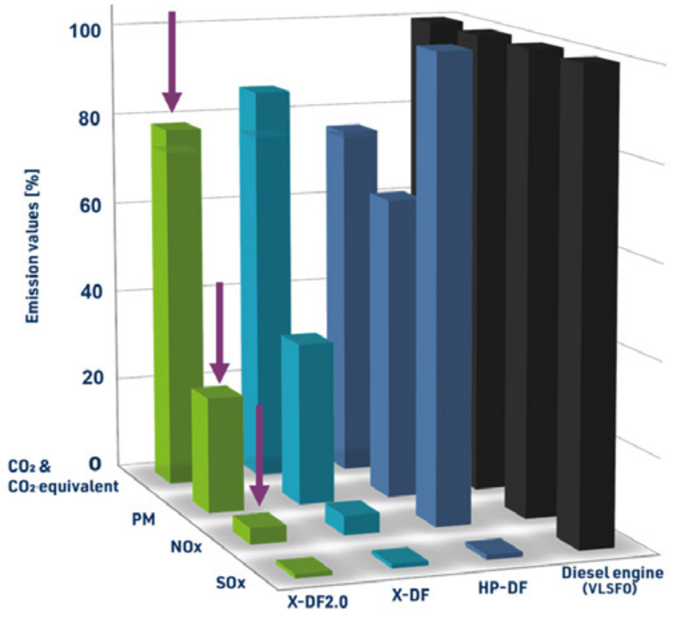
The impact of iCER is a 5.5% improvement in both gas and diesel consumption for an X72DF-2.0 engine compared to an X72DF, with a further emissions benefit in gas mode due to the separate reduction of unburned methane emissions (see Emissions for more on 'methane slip').

Fuel consumption improvements using iCER in gas and diesel modes



By substituting part of the oxygen used for combustion with cooled exhaust gas, iCER reduces reactivity, therefore improving thermodynamic behaviour. The result is lower firing pressure fluctuations, resulting in better fuel consumption and lower emissions. The emissions reductions are illustrated in the following chart.

Comparative emissions for diesel and LNG low-speed engines



All X-DF LNG-fuelled engines meet Tier III NO_X limits in gas mode. As a result of iCER, X-DF-2.0 can also achieve Tier III NO_X emissions compliance in diesel mode without using Selective Catalytic Reduction (SCR).

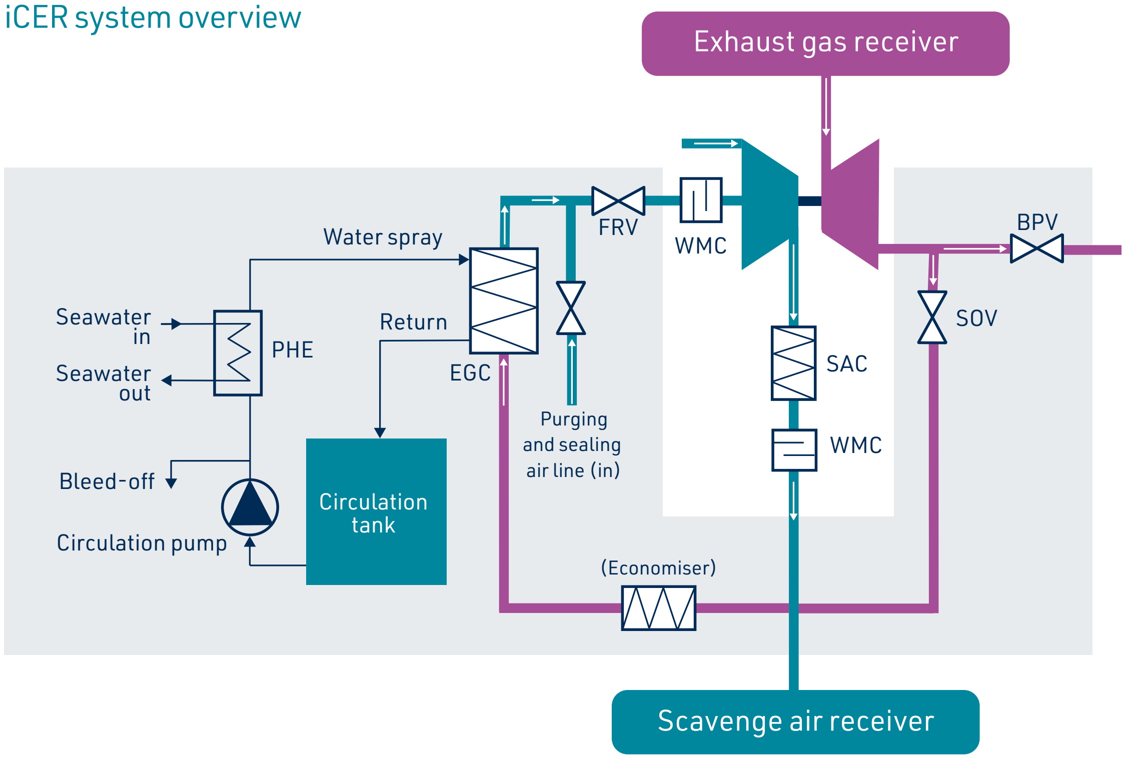
The low-pressure exhaust recirculation deployed by iCER also offers several benefits over high-pressure Exhaust Gas Recirculation (EGR) when used to improve the performance of low-pressure engines. These include:

- No additional electric blower required
- Higher exhaust gas bypass ratio (up to 50% vs. 25-32% at full engine load)
- Full exhaust gas flow through turbochargers at all loads, no compromise in turbocharger matching
- No risk of pre-ignition or unstable combustion
- Higher compression ratios supported
- Lower brake specific gas consumption
- Simpler control with no requirement for a cylinder bypass valve

11 What are the features and installation requirements of iCER?

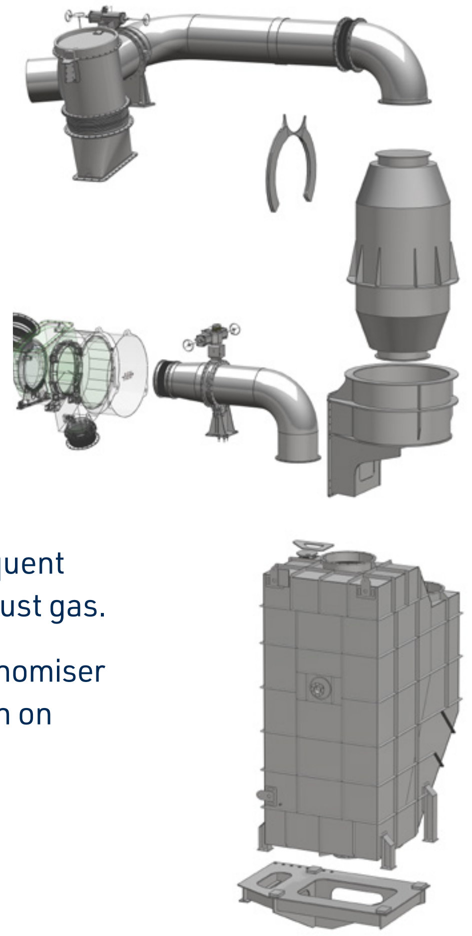
iCER cools and recirculates part of the exhaust gas through a low-pressure path. The recirculation is handled by a system next to the engine that circulates part of the exhaust gas after the turbine through an Exhaust Gas Cooler (EGC) to the compressor inlet. The exhaust gas and fresh air are mixed before entering the compressor wheel of the turbocharger.

iCER system overview



Abbreviation:

FRV	Flow Regulating Valve	**WMC**	Water Mist Catcher
SOV	Shut Off Valve	**EGC**	Exhaust Gas Cooler
SAC	Scavenge Air Cooler	**PHE**	Plate Heat Exchanger
BPV	Back Pressure Valve		

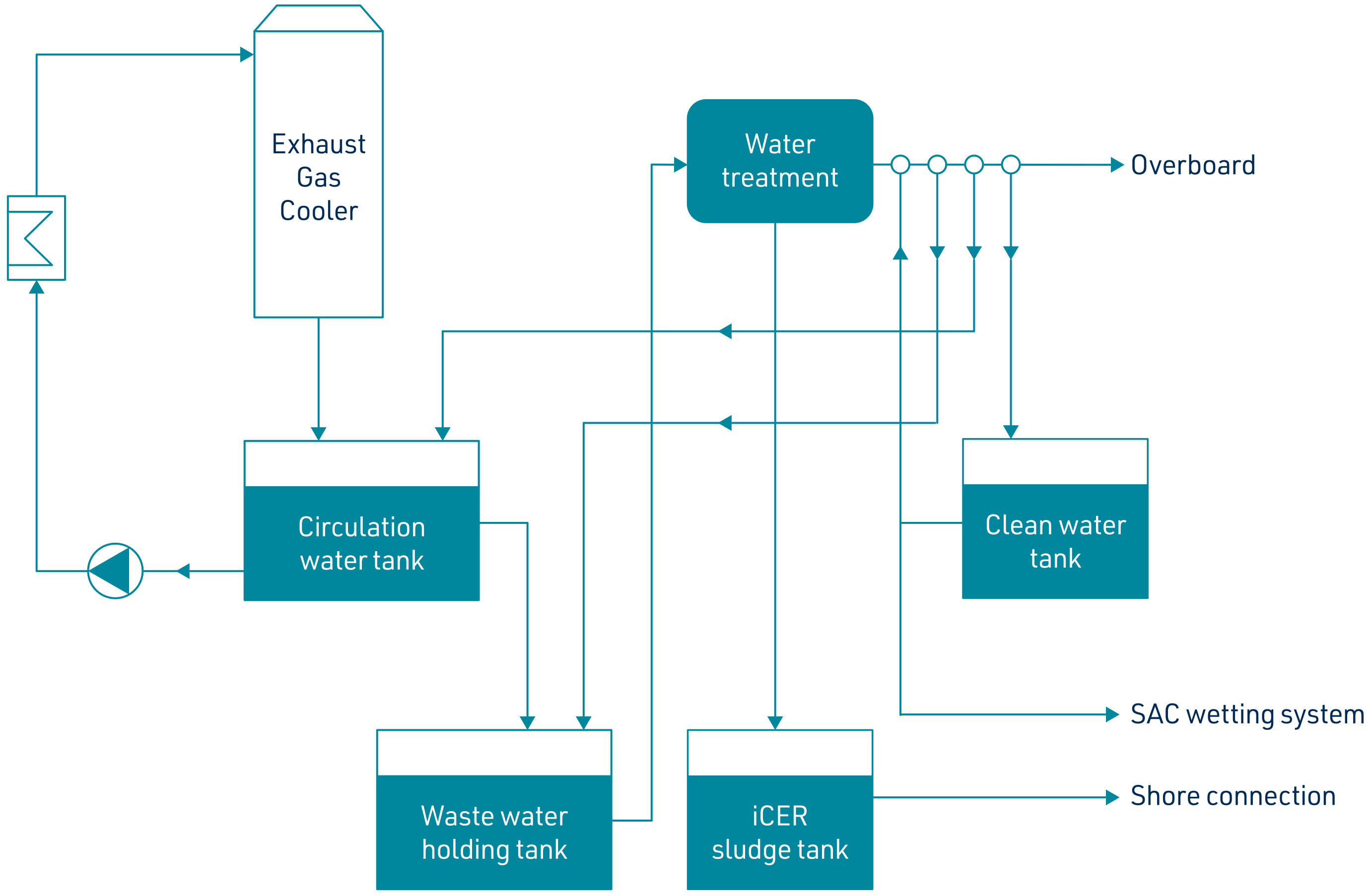


In its off-engine configuration, the iCER system is placed close to the engine as a stand-alone arrangement, including an EGC with a demister. The cooler tower contains a quench section and an absorber section. Hot exhaust gas enters at the top of the quench section, where spray nozzles introduce water cooling.

The gas then flows to the bottom of the absorber section which handles the main cooling. The absorber contains filler which enlarges the cooling surface with water introduced from the top. A subsequent demister removes water droplets in the exhaust gas.

For off-engine configurations an optional economiser can be installed to increase steam production on board using the recirculated exhaust gases.

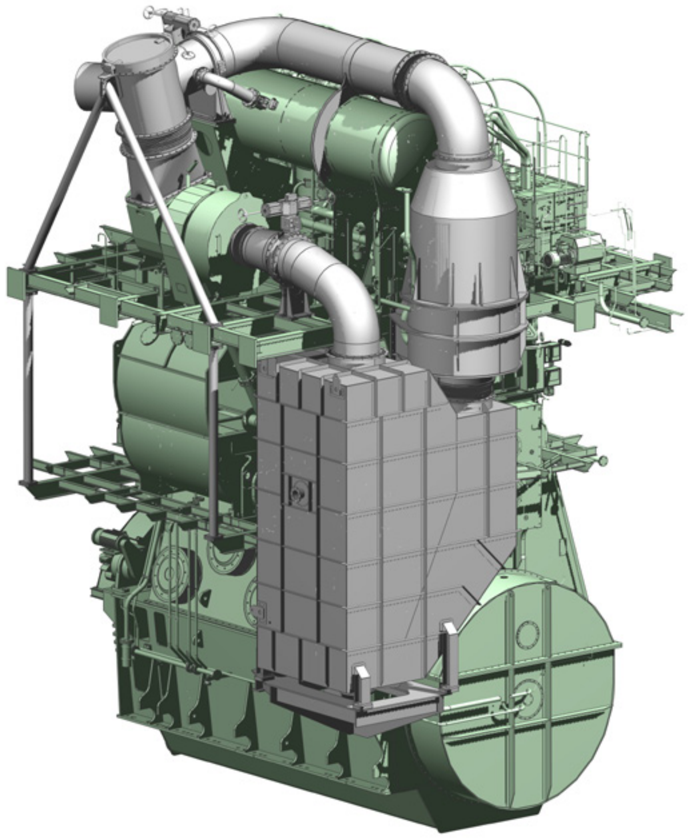
iCER water cooling system applicable for both on- and off-engine iCER



11 What are the features and installation requirements of iCER? continued...

The on-engine configuration of iCER reduces the engine room space needed as well as offering simpler installation and commissioning. It is currently available for X72DF-2.1/2.2 engines and will be rolled out across further engines depending on market demand.

X72DF-2.1/2.2
iCER on-engine



12 What is Variable Compression Ratio (VCR) technology?

An engine's Compression Ratio (CR) directly influences thermal efficiency. On a pre-mixed gas engine, CR is limited by combustion behaviour under most challenging conditions (100% engine load, tropical conditions). This implies a compromise in diesel efficiency.

With Variable Compression Ratio technology, the latest X-DF-2.0 technology released by WinGD, CR is dynamically optimised to reach best possible performance under any operating condition in both gas and diesel modes. In diesel mode, the CR can be increased to a similar level as on a conventional diesel engine.

In gas mode, the CR can be increased in part load to use 'combustion margin' – the wider range of air-to-gas ratios under which stable combustion occurs – and therefore achieve higher efficiency where the engines are operated most of the time.

VCR is particularly effective at reducing methane slip when combined with iCER in gas mode. While running higher CR at part load, the exhaust recirculation rate can be increased. Test results confirm a further reduction of methane slip of up to 30% compared to operation without VCR at part load operation.

Variable Compression Ratio (VCR) technology is available as an option for new X62DF-2.1, X62DF-S2.0 and X72DF-2.1/2.2 engine orders. Availability for other engines will follow based on market demand.

13 How does VCR improve X-DF performance?

In full scale engine tests, VCR has been shown to reduce fuel consumption and CO_2 emissions by up to 7.7% in diesel mode. In gas mode, fuel consumption can be reduced by up to 3.1%, with total greenhouse gas emissions (including methane) reduced by up to 4.6%.

VCR delivers operational flexibility by reducing any penalty associated with switching between LNG and fuel oil. Fuel and emissions reductions are greater with VCR at part loads, where engines are most often operated. And with the possibility to adjust compression ratios, power availability can be improved at any engine load, for example by using larger shaft generators in a wider speed range.

And as the VCR system operates automatically, all the above benefits are achieved without operator intervention.

13 How does VCR improve X-DF performance? continued…

The table highlights potential annual fuel consumption, emissions, GHG price and OPEX savings, assuming typical vessel operating profiles.

Vessel type	Engine type	Engine rating [kW]	Consumption savings [tons/yr]	Consumption savings [%]	GHG reduction [tons/yr]	GHG reduction [%]	OPEX savings: Fuel [US$/yr]	OPEX savings: GHG [US$/yr]*	OPEX savings: Sum [US$/yr]*
174k cum LNGC	2x 5X72DF 2.2 VCR	2x 12,129 75 RPM	GM: 361	GM:-2.4	GM: 993	GM:-2.4	GM:-307,000	GM:-148,985	GM:-455,985
			DM: 1,036	DM:-5.6	DM: 3,260	DM:-5.6	DM:-549,000	DM:-293,800	DM:-842,800
7000 CEU PCTC	7X62DF S2.0 VCR	11,920 104.8 RPM	GM: 163	GM:-2.3	GM: 449	GM:-2.3	GM:-138,700	GM:-64,490	GM:-203,190
			DM: 494	DM:-5.7	DM: 1,555	DM:-5.7	DM:-261,600	DM:-139,950	DM:-401,550
1900 TEU Feeder	6X62DF S2.0 VCR	11,500 105 RPM	GM: 146	GM:-3.1	GM: 401	GM:-3.1	GM:-124,000	GM:-54,990	GM:-178,990
			DM: 440	DM:-7.7	DM: 1,385	DM:-7.7	DM:-233,000	DM:-124,650	DM:-357,650
115k dwt BC	6X62DF 2.1 VCR	10,450 82 RPM	GM: 121	GM:-2.3	GM: 333	GM:-2.3	GM:-103,000	GM:-54,900	GM:-157,900
			DM: 424	DM:-6.5	DM: 1,336	DM:-6.5	DM:-233,250	DM:-139,950	DM:-373,200

Fuel Prices: LNG = $850; VLSFO = 530
Typical operation profile used per vessel segment

DM: Continuous Diesel Mode operation
GM: Continuous Gas Mode operation

*Based on carbon tax price = $90

14 What are the features and installation requirements of the VCR system?

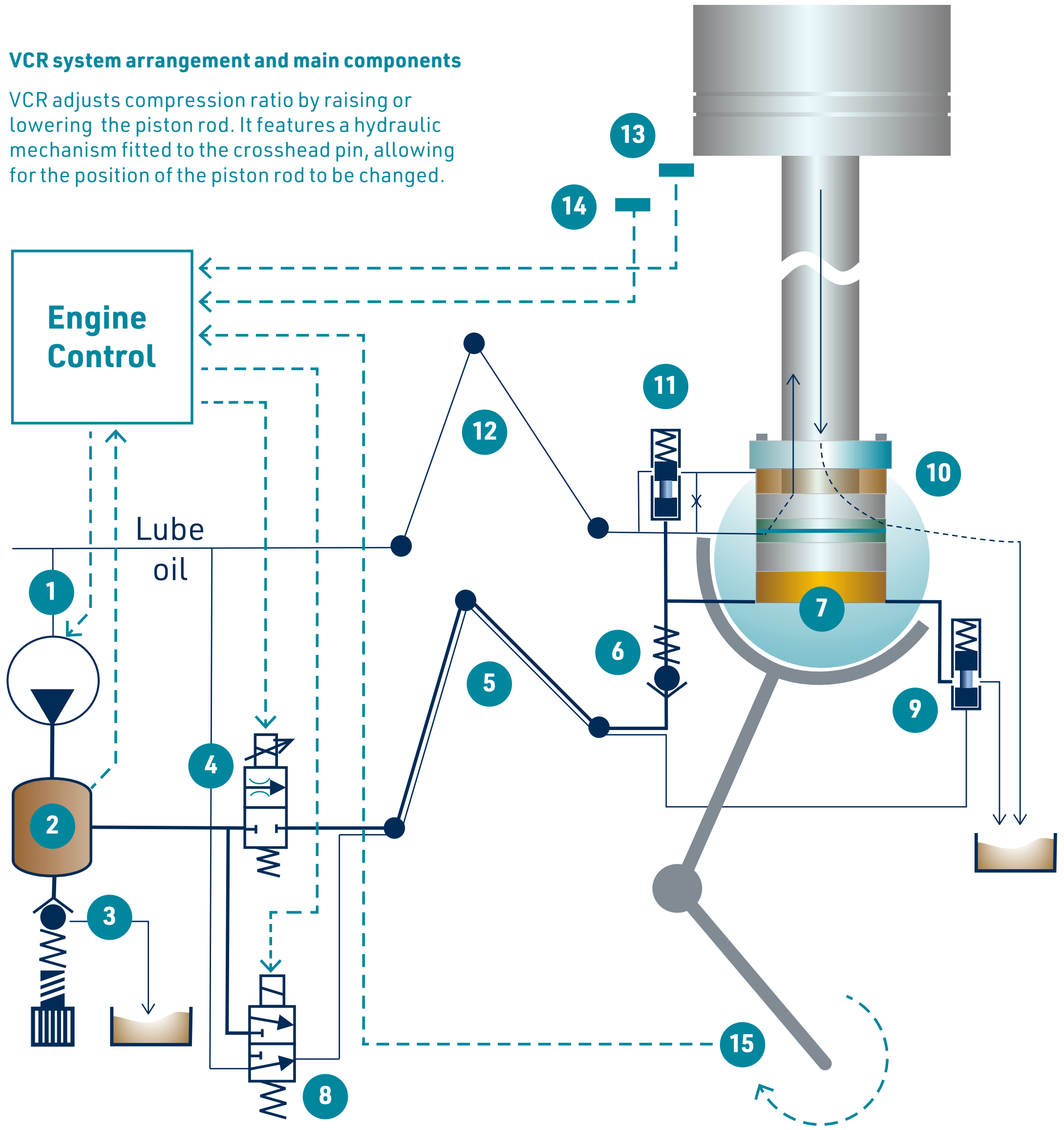
The VCR adjusts compression ratio by raising or lifting the piston rod. It features a hydraulic mechanism fitted to the crosshead pin, allowing for the position of the piston rod to be changed. The piston position is controlled by the amount of lube oil in the lower chamber located below the piston rod. The oil amount is controlled by filling pressurised lube oil through a knee lever and by draining the lube oil from the lower chamber. The filling is controlled by a solenoid proportional valve located between the inlet of the knee lever and the lube oil feed manifold.

The subsystems include an oil feed system that allows oil to be supplied to the unit on each cylinder, drawing oil from the bearing oil supply via a small variable speed pump. The pump requires electrical power of around 5kW in normal operation and up to 15kW for periods of increasing compression ratio. The pump feeds the oil to a distributor rail and into each crosshead at a low pressure of around 40-50 bar, again keeping power demands low.

This simple, sturdy design is very similar to other hydraulic systems already on the engine, including exhaust valve drives. It is designed to require no specific maintenance between drydocking periods.

VCR system arrangement and main components

VCR adjusts compression ratio by raising or lowering the piston rod. It features a hydraulic mechanism fitted to the crosshead pin, allowing for the position of the piston rod to be changed.



- **① Feed pump** Electrically driven, it increases the engine lube oil pressure (4…5bar) to the feed pressure of 40…50bar. Variable motor speed to minimise power consumption.
- **② Feed manifold** Distributes the lube oil to all cylinders.
- **③ Pressure control valve** Limits the pressure in the feed manifold.
- **④ Solenoid proportional valve** (Inlet) Controls the flow of oil to the lower chamber of each cylinder.
- **⑤ Knee lever of VCR** Connects the proportional valve with the lower hydraulic chamber.
- **⑥ Delivery valve** Spring loaded non-return valve.
- **⑦ Lower chamber** Lifts the piston rod depending on amount of oil in it.
- **⑧ Solenoid relief valve** Controls opening and closing of outlet valve (9).
- **⑨ Outlet valve** (Spring-loaded) Releases oil from the lower hydraulic chamber to lower the position of the piston rod.
- **⑩ Upper chamber** Holds the piston down under any situation (e.g. engine start or malfunction of exhaust valve).
- **⑪ Lift-off v/v with filling orifice** Retains oil volume in upper chamber in case of low oil pressure in lower chamber to avoid lift-off of piston.
- **⑫ Knee lever for piston cooling** Existing knee lever for usual piston cooling.
- **⑬ Sensor for piston position** Measures piston timing and enables control of piston rod position.
- **⑭ Sensor for air temperature** In piston underside, measures scavenge air temperature close to the scavenging ports of each cylinder.
- **⑮ Crank angle signal** Existing engine crank angle signal used also for the VCR control.

14 What are the features and installation requirements of the VCR system? continued...

The position of the piston is controlled through WinGD's standard WiCE engine control system, without the need for hardware modifications. Simple software allows for the piston position in each cylinder to be controlled via a closed loop. A position feedback sensor monitors the piston position at every revolution and the solenoid valve adjusts the amount of oil in the lower chamber to keep the piston at the set compression ratio for the defined operating mode.

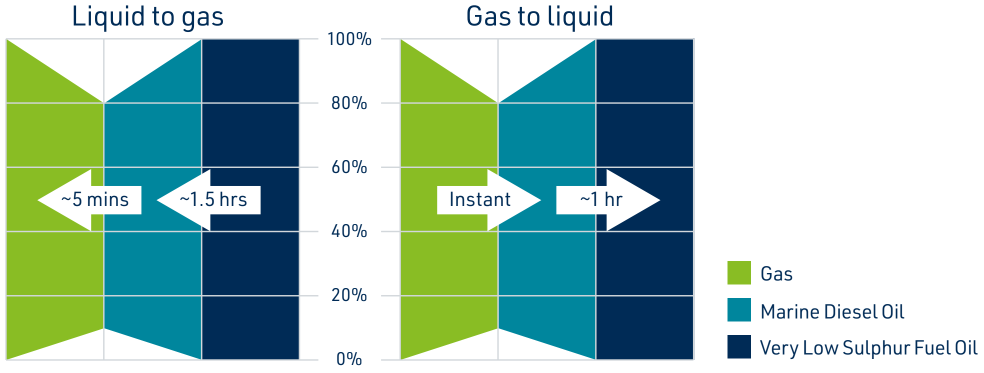
VCR requires minimal changes to installation arrangements. Outline dimensions, engine seating and connections remain unchanged and no additional shipyard pipe connections are required. The increased oil demand (around 2%) can be covered by the existing pump layout. However, the oil supply pump's variable frequency drive will need to be installed on the ship side instead of on the engine.

B Engine operation

15 How does the fuel change work: from gas to diesel and vice versa?

When an X-DF engine runs in gas mode, a trip to diesel mode is available on request at any engine power; it is instantaneous and without any loss of engine power or speed. The trip to diesel mode happens automatically if required by the engine control or safety system.

When an X-DF engine runs in diesel mode, transfer to gas mode is available upon request, at engine power in the range of 10% to 80% without any loss of power or speed.



Changeover procedure between different fuels: Gas, MDO and VLSFO

During the changeover procedure from gas to diesel, the cylinder lubricating oil does not need to be changed and can remain on low-BN (Base Number) oil as specified for X-DF engines.

16 Which engine power range is available in gas mode?

While the engine is operating in gas mode the engine power can be varied in the range of 10% to 100%. This means from "Slow" up to "Full Speed", independent of driving a Fixed Pitch Propeller (FPP) or a Controllable Pitch Propeller (CPP). For "starting/stopping" the class rules require the engine to run in diesel mode only. This is also required for "reversing" when driving an FPP.

In principle, once an engine operating a CPP has switched to gas mode there is no need to return to diesel mode until the engine operation is finished in the next port. Given that the engine load remains above 10%, manoeuvring including reverse-pitching of the propeller can be done with the engine operating in gas mode.

17 How do X-DF engines and conventional low-speed diesel engines differ in load acceptance?

While theoretically the load acceptance capability of X-DF engines is somewhat lower compared to that of conventional low-speed diesel engines, operating experience of many engines in service has shown that this is not of any limitation in practice.

18 How do X-DF engines handle load fluctuations compared to conventional low-speed diesel engines?

Similar to the previous question, operational experience of vessels in service has shown that load fluctuations caused by heavy sea conditions are within the design limits and consequently no changeover to diesel mode is required.

B Engine operation

19 Does gas quality in terms of Lower Heating Value (LHV) or Methane Number (MN) have an impact on low-pressure X-DF engines?

The Lower Heating Value (LHV) has no impact on engine performance and output in the range of 28 MJ/Nm3 to 36 MJ/Nm3 (volumetric LHV).

X-DF LNG engines can operate on fuel with a Methane Number (MN) as low as 65 with full power output, which is a MN lower than the globally available LNG for bunkering. Accordingly, in practice, there is no impact of MN to the available power output of the engine and there have been no MN-related engine issues throughout the millions of running hours accumulated on X-DF engines.

In tropical conditions, full power output is available with fuels of MN≥65 on X-DF-2.0 engines as a result of iCER's exhaust recycling. On first-generation X-DF, full power is achieved through automatic activation of Dynamic Combustion Control (DCC) – see question below. Lower MN might influence DCC activation to be triggered earlier, i.e. at lower engine load and at higher rates. DCC allows full engine power output independent of ambient conditions and engine ratings.

20 What is Dynamic Combustion Control (DCC)?

On X-DF engines without iCER, DCC ensures efficient gas combustion and full power output under any operating conditions. The specific engine control feature is automatically activated by an algorithm that continuously monitors cylinder pressures.

At high engine power, hot and humid ambient conditions, or when operating with low MN fuel, cylinder pressure could exceed the normal operation range. In this case, DCC injects a small quantity of diesel (between 3% and 15% of energy input) from the main fuel injectors – to rectify the air-fuel gas ratio (lambda) – and increases air supply from the turbocharger.

The Brake Specific Energy Consumption (BSEC) of the engine remains similar with DCC active. The gas consumption decreases at the same rate as the liquid fuel consumption increases. DCC is included in the engine control system software of all X-DF engines without iCER and is IMO Tier III certified. On engines with iCER, combustion is controlled via the exhaust gas recirculation rate and DCC is not required, therefore DCC has been eliminated.

C Capital expenditure

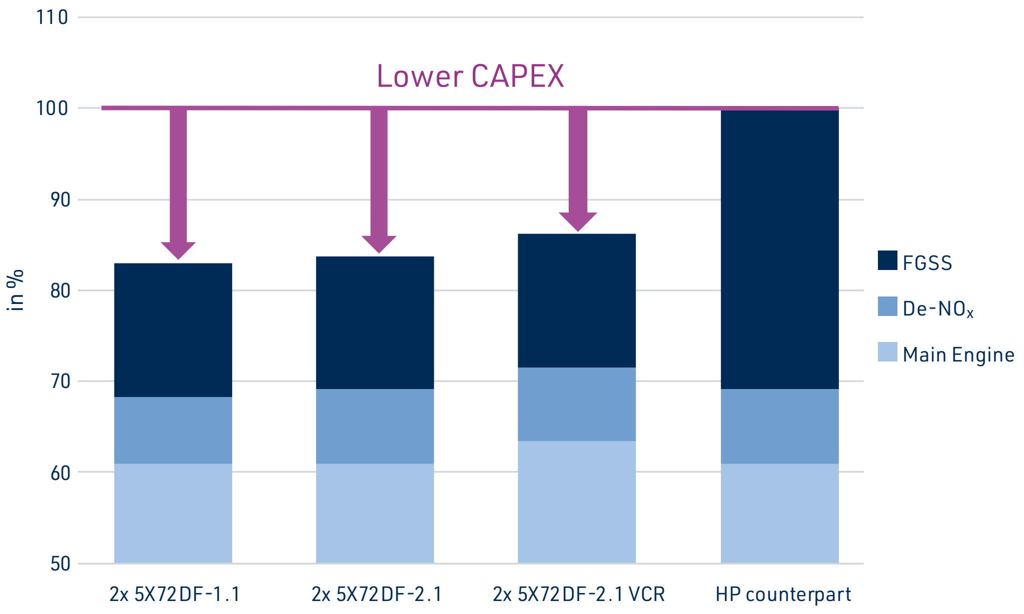
21 Why does the X-DF solution have lower CAPEX than the high-pressure gas engine solution?

Though the prices of the engines are relatively similar, the cost of the Fuel Gas Supply System (FGSS), such as compressors, pumps, evaporators, heat exchangers, piping system, sensors, valves, etc. is significantly lower for an X-DF engine than for a high-pressure gas engine installation. Furthermore, the X-DF solution is Tier III compliant without any exhaust gas treatment - this is needed to achieve Tier III compliance with a high-pressure gas engine.

In the comparison below, the investment cost for the full gas supply system, engine and aftertreatment plant for a typical 174,000cbm LNG carrier is presented, with a comparison between twin X-DF engines with iCER (X-DF-2.1), iCER plus VCR (X-DF-2.1_VCR) and a similar high-pressure engine installation.

The significant impact of the fuel gas supply system requirements for high-pressure engine configurations is evident.

Engine, fuel system and aftertreatment costs, 174k LNG carrier



C Capital expenditure

22 What impact do iCER and VCR have on CAPEX and how does this compare to high-pressure engines?

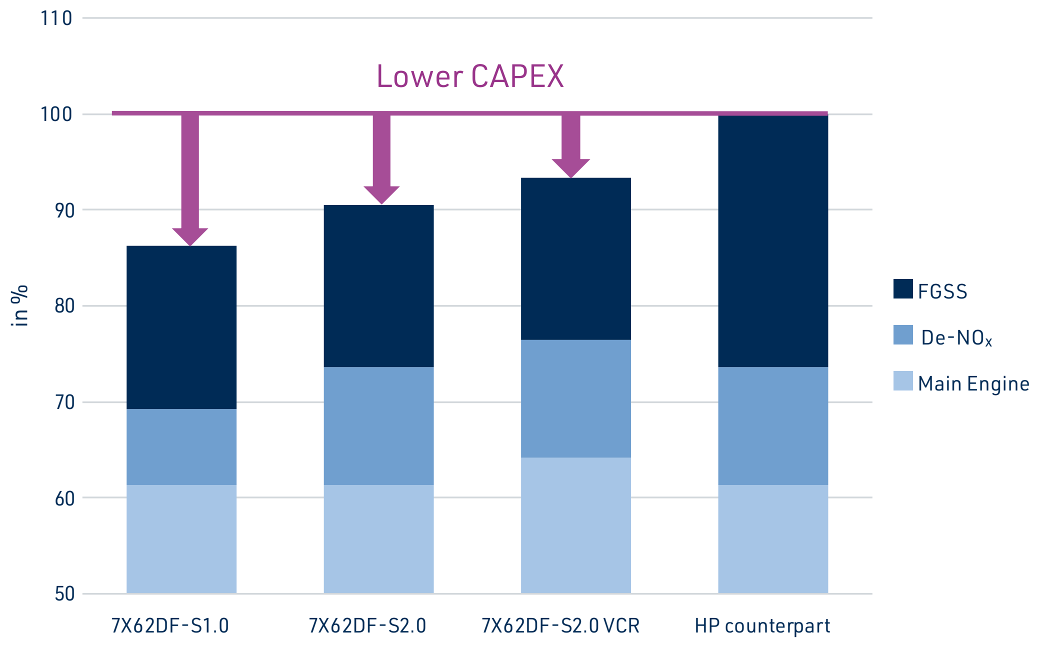
The chart below shows the system investment cost for a typical 7,000 CEU pure car/truck carrier (PCTC), highlighting the differences in engine and auxiliary equipment costs.

For the X-DF-2.0, engine cost is similar to the base X-DF model but with a higher investment in emissions abatement system – with the result of lower fuel consumption and emissions in both modes as well as Tier III NO_X compliance in diesel mode as well as on gas.

For VCR, engine cost is increased fractionally compared to the X-DF and X-DF-2.0 configurations, although still well below the total CAPEX of a high-pressure engine and fuel system. The result is further reduced fuel consumption in both diesel and gas modes, as well a reduction in methane slip.

The small additional investment costs for X-DF-2.0 and VCR have a significant impact on operating costs and emissions. The X-DF-2.0 with VCR operates in diesel mode without a fuel penalty compared to single-fuel engines, and with lower fuel consumption and equivalent overall greenhouse gas emissions compared to high-pressure dual-fuel engines.

Engine, fuel system and aftertreatment costs, 7,000 CEU PCTC



D Operating expenditure

23 Why does the X-DF solution have lower OPEX than the high-pressure gas engine solution?

OPEX consists of consumables and maintenance costs.

Consumables

The OPEX comparison between a low-pressure X-DF propulsion solution and a high-pressure gas engine propulsion solution requires a detailed analysis taking the following aspects into consideration:

- Main engine consumption
- The ship's operational profile
- Energy consumption of the fuel gas supply system (compressors, pumps, etc.)
- Additional generator engine load (parasitic load)
- Running hours in ECA areas (Tier III mode)
- Fuel penalty for Tier III mode (high-pressure gas engines only)
- Costs of LNG, MDO, MGO, HFO, NaOH or UREA

When operating in Tier III areas, the low-pressure X-DF propulsion solution results in lower consumable costs than the high-pressure gas engine solution as no exhaust gas treatment is needed for compliance.

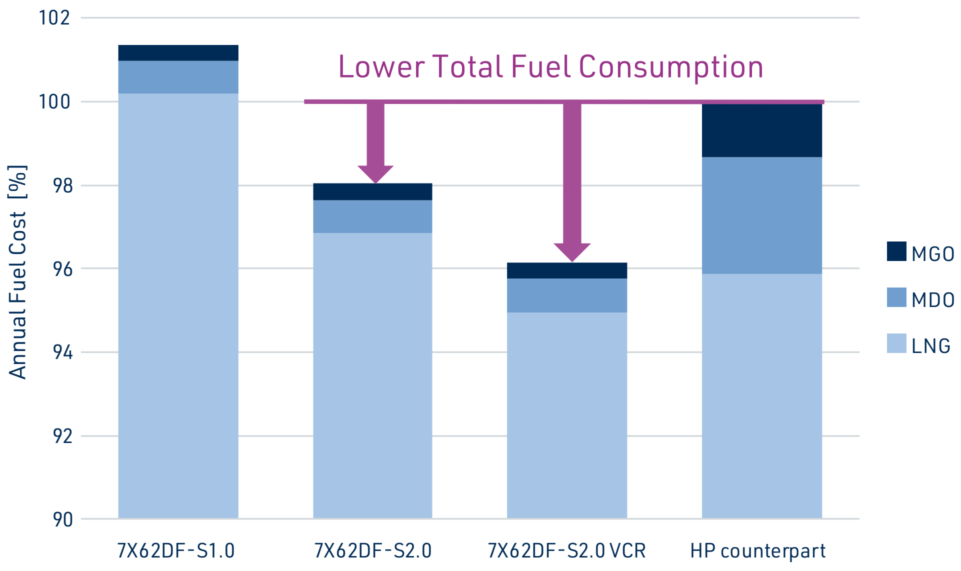
X-DF always features ultra-low NO_X and particulate emissions without generating any extra costs, while high-pressure gas engines require EGR or SCR, increasing the energy consumption on the engine significantly and requiring additional consumables.

The energy consumed by the gas supply system (such as the compressors and/or pumps) is less for a system operated at low pressure. This benefit is particularly pronounced on LNG carriers where the engines are primarily fuelled by boil-off gas which needs to be compressed to be delivered to the main engines.

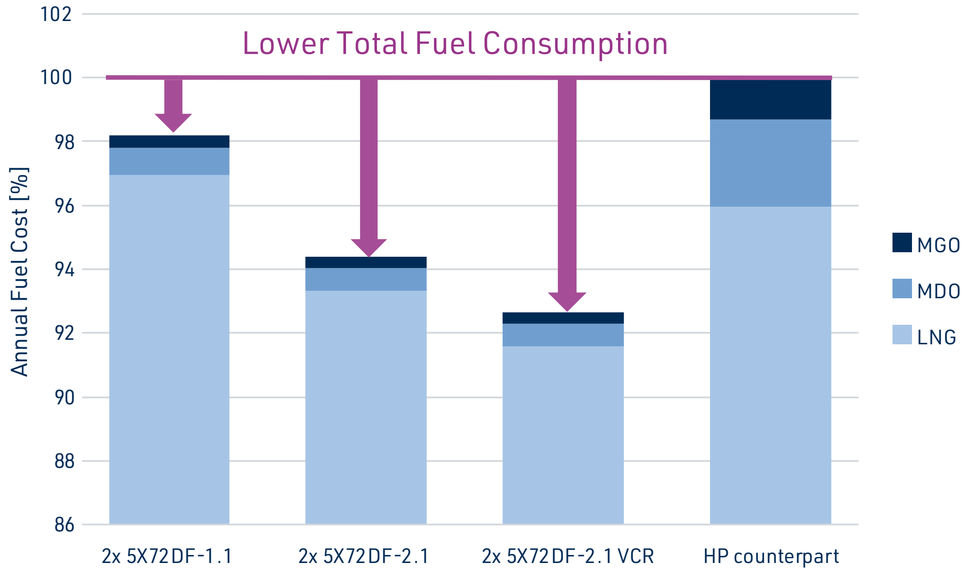
As a result of the above factors, a low-pressure X-DF engine propulsion solution often has similar accumulated daily consumable costs to a high-pressure gas engine propulsion solution even if the gas consumption of the main engine is higher. The chart overleaf illustrates this using the 7,000 PCTC case from Question 22.

D Operating expenditure

Annual fuel costs, 7,000 CEU PCTC



Investment costs, 7,000 CEU PCTC



Maintenance

Fuel gas supply system related components are designed for low-pressure only (e.g. pipe class PN16 or similar is selected). As with initial CAPEX costs, this reduces the required spare parts costs. It allows simple and safe maintenance procedures compared to a high-pressure system.

The crew can safely and independently perform most maintenance tasks during normal port stays. A simple gas system pressure test takes only a few minutes compared to hours on a high-pressure supply system.

D Operating expenditure

24 What impact do iCER and VCR have on OPEX and how does this compare to high-pressure engines?

The iCER system requires very limited additional electrical power to operate the circulation pump, sea water pump and water treatment system. For VCR, the small variable-speed pump that actuates the hydraulic control requires electrical power of around 5kW in normal operation and up to 15kW for periods of increasing compression ratio.

No other consumables are required for either system. In each case, the electrical demand is fulfilled by the auxiliary engines. This extra auxiliary load is factored into the annual fuel consumption calculations shown in Question 23.

E Engine safety

25 What is knocking? And does it limit engine operation in any way?

The combustion in an engine chamber aims to burn the air-fuel mixture progressively and smoothly from the point of ignition outwards. However, at high pressures, spontaneous ignition can occur within the air-fuel mixture without the ignition of this flame front.

These instantaneous and uncontrolled releases of energy cause pressure waves to propagate through the combustion chamber. These pressure waves can cause the combustion chamber to resonate at a natural frequency, resulting in a typical audible noise known as “knock”, giving rise to the name “knocking”.

In contrast to medium and high-speed Otto-cycle engines, knocking has not been seen to affect X-DF engines, therefore having no effect on performance.

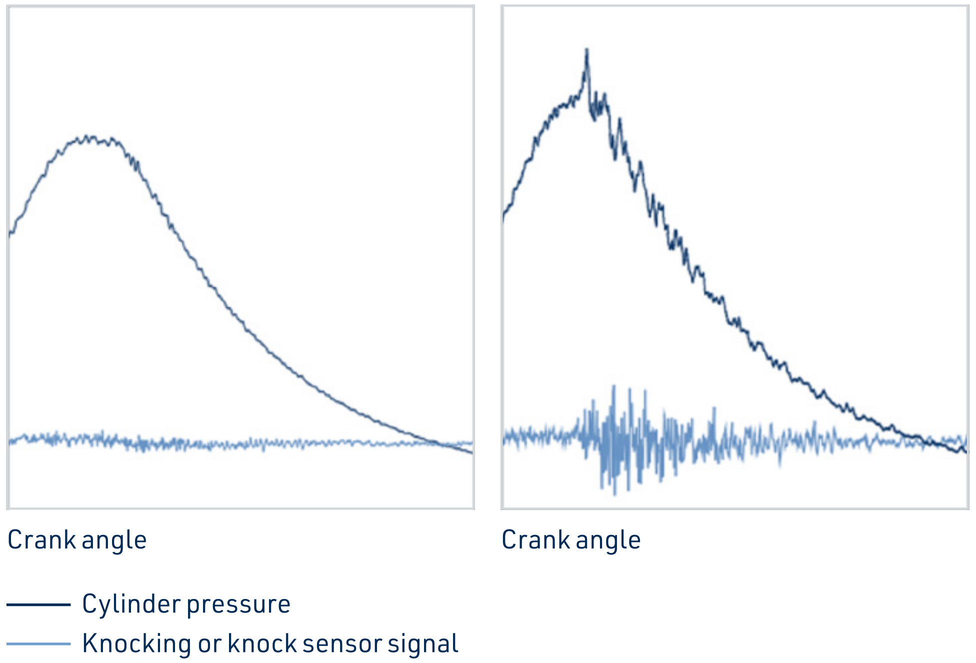
Operating the engine with a very lean gas mixture, i.e. a high air-gas ratio (lambda), combined with low scavenge air temperatures, limit the possibility of knocking.

25 What is knocking? And does it limit engine operation in any way? continued...

The dominant limiting factor for X-DF is early ignition and fast combustion and the resulting maximum cylinder pressure, which is controlled by the exhaust gas recirculation rates on iCER engines, and with DCC on engines without iCER.

The control system of the X-DF engine monitors the combustion and is capable of taking corrective actions without the need of an operator.

Cylinder pressure and knocking sensor signals for normal and knocking conditions



26 How are potential gas leakages detected and managed on the X-DF piston underside?

X-DF engines have various engine control and safety functions designed to detect gas leakage and to control abnormal engine behaviour. Leakage of gas fuel into the piston underside could occur due to a Gas Admission Valve (GAV) remaining stuck open (will not close) or a blow-by on the piston rings. Both cases are monitored and detected by the engine control system.

Severe leakage results in high firing pressure of the affected cylinder from early ignition and fast combustion of the excessive gas amount. It will be detected by the cylinder balancing and exhaust gas temperature monitoring systems. Severe leakages could even trigger the knocking sensor.

The rail valve actuated GAV is monitored constantly by the valve stroke sensor. Should the GAV for unknown reasons stay open for a prolonged period of time, the safety system triggers a gas trip (i.e. trip to diesel) immediately.

A gas detection sensor is mounted in the piston underside compartment, constantly monitoring the composition of the scavenging air. Should it detect an increase in the gas concentration, the safety system will first sound an alarm, and in the case of continued increasing amounts of gas, a gas trip.

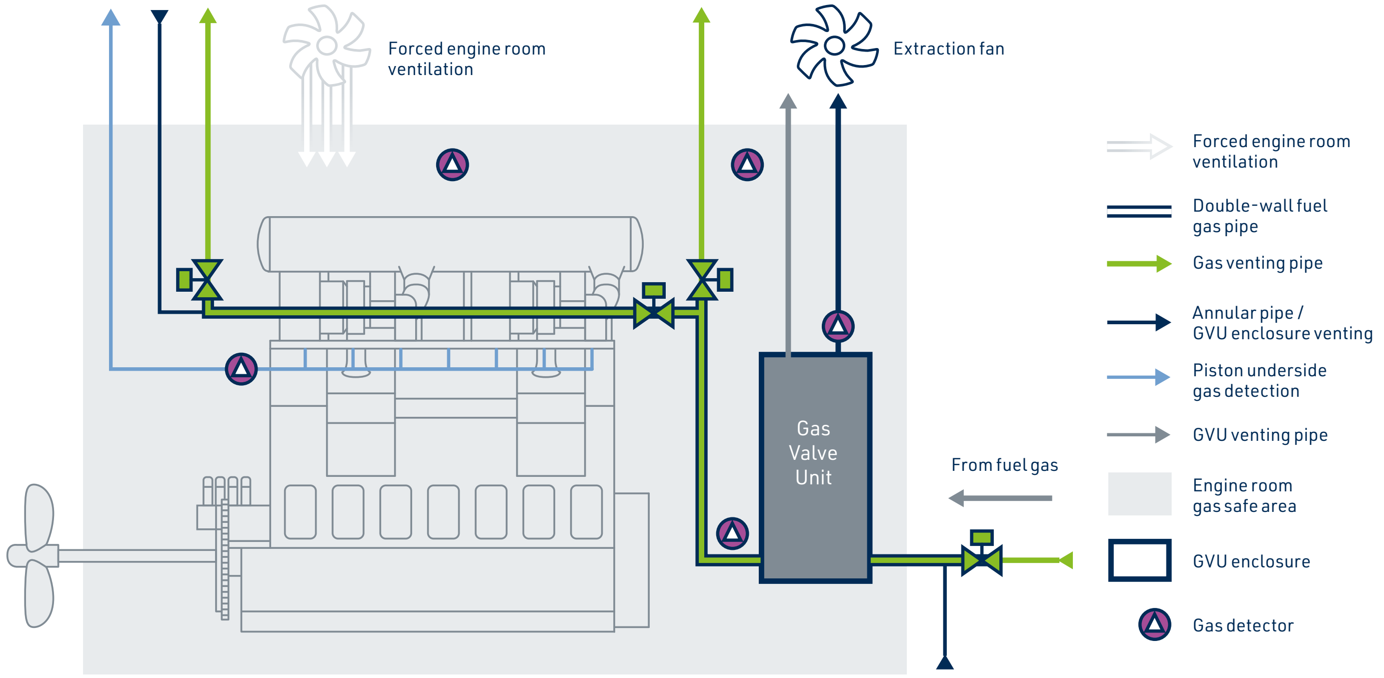
The sensor monitoring the cylinder pressure also acts as a detection feature. Should the cylinder pressure deviate beyond a certain preset threshold on one cylinder, an alarm (i.e. offset reached) will be triggered.

The gas piping in the engine room and on the engine are constantly monitored to detect leakages. The gas piping is double-walled and the annular space is constantly ventilated. Two gas concentration sensors detect any possible gas leakage and activates an alarm that trips the engine to diesel mode (see chart on previous page).

The above-described principles are described in the Dual-Fuel Engine Safety Concept which is available online.

X-DF field experience has demonstrated excellent results and flawless operation of the system, resulting in very stable gas mode operation.

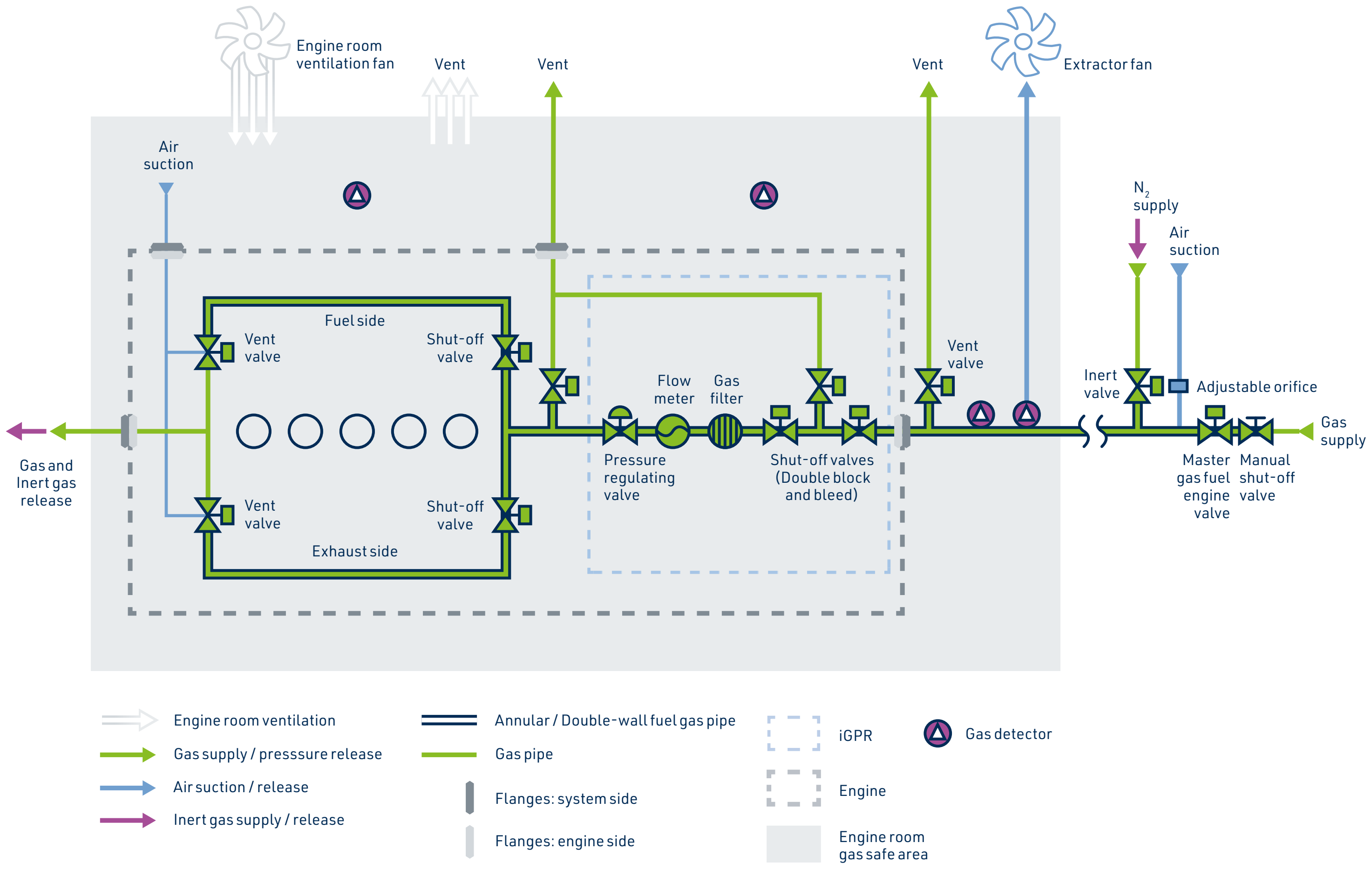
Gas safe engine room arrangement for engines with external Gas Valve Unit (GVU)



E Engine safety

26 How are potential gas leakages detected and managed... continued...

Gas safe engine room arrangement for engines with integrated Gas Pressure Regulation (iGPR)



27 What fail-safe measures are included in the VCR system?

A VCR fallback mode is intended to be used in case of an unexpected failure of the system and that means the engine can go back to regular diesel operation, ensuring availability of propulsion. Additionally, in case of VCR failure, engines with iCER can also operate in fuel sharing mode or combustion stability mode, allowing them to still burn high ratios of gas.

This is desirable especially on LNG carriers to continue burning boil-off gas from the cargo tanks.

F Emissions

28 What are methane emissions?

Methane is a greenhouse gas that contributes to global warming. Compared to $C0_2$, its impact is considerably more severe, especially in the short term. Therefore, losses of methane to the atmosphere during fuel production, transportation and during the combustion process should be kept at a minimum.

Proper gas extraction and handling throughout the transportation and utilisation chain is a key contributor to LNG achieving overall reductions in greenhouse gas emissions.

29 How are methane emissions regulated?

Discussions at the IMO are currently focused on measures towards achieving the targets set forth in their revised strategy on reduction of GHG emissions from ships and methane emissions are to be taken into consideration in this context. These will include a technical measure – potentially a fuel standard – as well as an economic measure that could use the IMO Guidelines on Lifecycle Assessment for Marine Fuels as a basis for calculating a pricing measure.

The IMO guidelines currently include a default emission factor for methane using low-speed Otto DF engines of 1.7% of the consumed gas. However, this reflects only the first generation of X-DF engines, without either iCER or VCR technology. As an example, the X72DF-2.0 VCR engine features IMO averaged slip levels corresponding to approximately 0.8% of consumed fuel, less than half the default factors.

The European Union included shipping in the EU Emissions Trading System from January 2024, requiring shipping companies to buy rights to emit greenhouse gas (GHG) emissions on voyages to, from and between European Economic Area (EEA) ports. From 2025, vessels using EEA ports will be required to meet stepped reductions in the GHG intensity of all energy used onboard or face financial penalties, under FuelEU Maritime. The European regulations use a very similar emissions calculation method as in the IMO's guidelines – and currently with the same default emission factors for methane.

All regulations allow for values other than the default emissions factors to be certified. As part of EUROMOT, WinGD is involved in developing such a certification scheme. Currently there are varying proposals for this certification scheme.

30 How are methane emissions regulated? continued...

As these regulations are revised, it is expected that a different default emission factor for the more recent X-DF-2.0 engines with lower methane slip can be included. Until then, WinGD proposes the option of certifying a lower emission value based on actual measurements from the factory acceptance test of the parent engine.

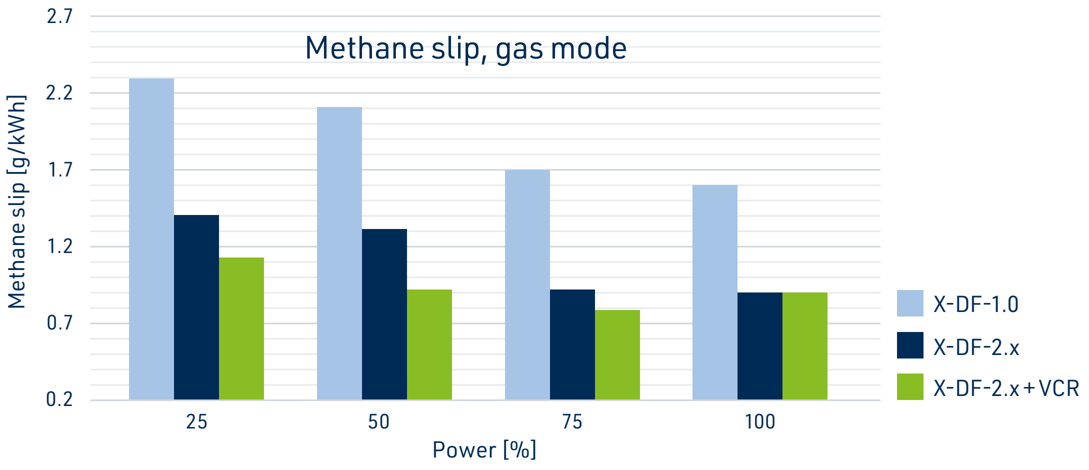
WinGD expects that an additional default factor for the latest X-DF technology will be established in advance of upcoming strengthening of regulations. For example, FuelEU Maritime, starts with moderate reduction rates and X-DF will achieve compliance until 2035 even with the current default factor of 1.7 %. A new default factor will be added long before then.

30 How much methane is emitted by X-DF engines?

Every combustion engine emits unburned hydrocarbon regardless of the process and the size of the engine. Eventually unburned methane (CH_4) forms part of the Total Hydrocarbon (THC) emissions present in the exhaust of these engines.

As a matter of principle, low-pressure X-DF engines have considerably lower THC and hence also methane emissions (commonly also designated as "methane slip") compared to four-stroke medium- and high-speed dual-fuel engines. This low methane emission level is inherent to low-speed two-stroke engine physics and is achieved by optimising the engine's internal combustion process as well as the combustion chamber design.

Methane slip emissions for X72DF type engines



The figure graph (on previous page) shows the range of methane emission results from measurements on variants of the X72DF engine. Methane emissions are engine-size dependent, with higher values for the smaller bore size engines. Relative emissions are also higher at lower power levels.

31 What else is WinGD doing to reduce methane slip?

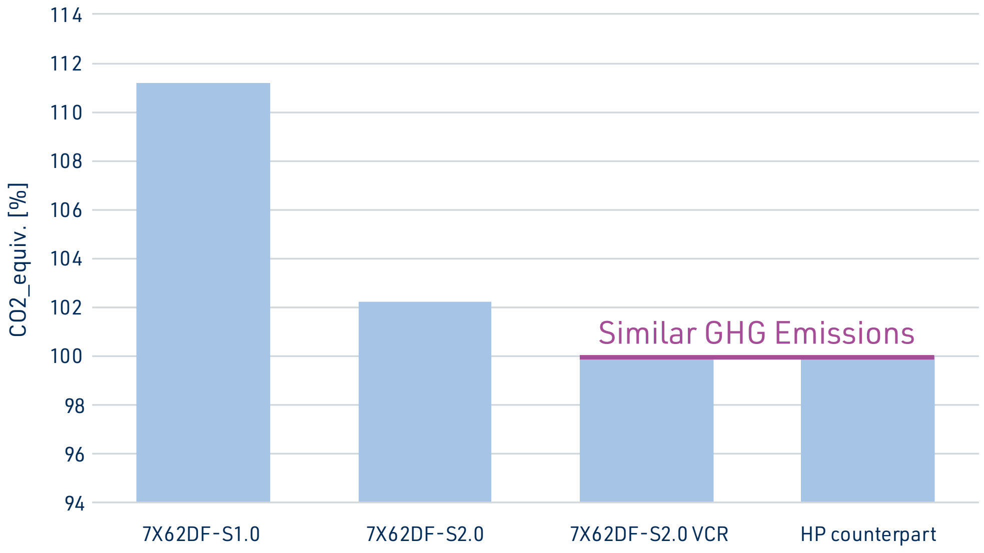
The iCER technology introduced as the first solution under X-DF-2.0 reduces methane slip by up to 50%. VCR also delivers incremental benefits in methane emissions, as detailed earlier.

WinGD's R&D efforts continue to focus on further reducing the engine's overall impact on the environment. Working together with ship owners, partners and other industry experts, there is a strong commitment to further improvements in this area.

32 How is X-DF LNG technology beneficial in terms of Greenhouse Gas emissions?

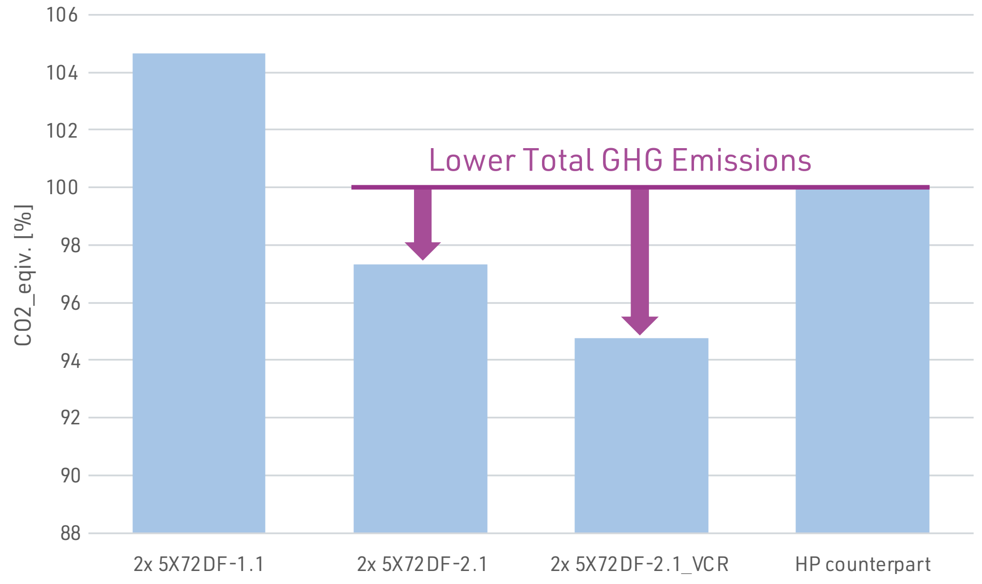
When comparing the Greenhouse Gas performance of X-DF engines running on LNG with propulsion systems running on residual fuels, two factors must be considered: The use of LNG is associated with 25-30% lower CO_2 emissions during combustion, even though this benefit is reduced due to the emission of unburnt methane.

: Annual total GHG emissions, 7,000 CEU PCTC



32 How is X-DF LNG technology beneficial in terms of GHG emissions? continued...

Annual total GHG emissions, 174k LNG carrier



However, even when applying the above-mentioned conversion factor of 30, the total GHG balance is still reduced by about 16-23%, a clear improvement over conventional diesel engines. The balance is improved further when the fuel efficiency and methane slip reductions achieved by iCER and VCR are added. As shown in the charts, highlighting two common applications of dual-fuel LNG technology, the latest X-DF technology achieves similar overall GHG emissions to high-pressure low-speed dual-fuel engines.

33 How do X-DF engines comply with IMO Tier III NO$_X$ emission limits in gas mode?

In gas mode, low-pressure dual-fuel engines operate according to the Otto-cycle, i.e. the fuel-gas and air are homogeneously pre-mixed in the combustion chamber before ignition.

Together with the high amounts of air, this results in lean premixed combustion with a much more uniform temperature distribution throughout the combustion chamber than on engines that operate according to the Diesel cycle. In those engines, gas or liquid fuel is injected into the combustion chamber close to the end of or after compression. Consequently, the combustion occurs in a mixing-controlled or diffusion regime at conditions close to stoichiometry and the formation of NO$_X$ is promoted due to the existence of high-temperature regions close to the flame.

The lower peak temperatures of the X-DF engines reduce NO$_X$ emissions below the respective IMO Tier III limit. X-DF engines do not require any further NO$_X$ reduction systems, such as Exhaust Gas Recirculation (EGR) or Selective Catalytic Reduction (SCR), which are applied to high-pressure engines in order to achieve compliance with Tier III NO$_X$ emissions limits.

As mentioned in previous answers, when using iCER technology, X-DF-2.0 engines comply with Tier III NO$_X$ emission limits even when using fuel oils.

34 Are low-pressure X-DF engines IMO Tier III compliant during manoeuvring, starting and stopping?

Yes. The compliance of X-DF engines with IMO Tier III is not affected by any procedures applicable during manoeuvring, starting and stopping.

For safety reasons, the IGF code and IACS rules require that engine starting, stopping and reversing for manoeuvring must be carried out in diesel operating mode.

Therefore, corresponding control strategies are defined and clearly documented as Auxiliary Control Devices (ACD), in accordance with the “IMO Guidance on the application of Regulation 13 of MARPOL Annex VI Tier III requirements to dual-fuel and gas-fuelled engines”.

35 How is X-DF compliance affected by changes to the NO$_X$ Technical Code and associated sections of MARPOL Annex VI, scheduled to enter force in 2027?

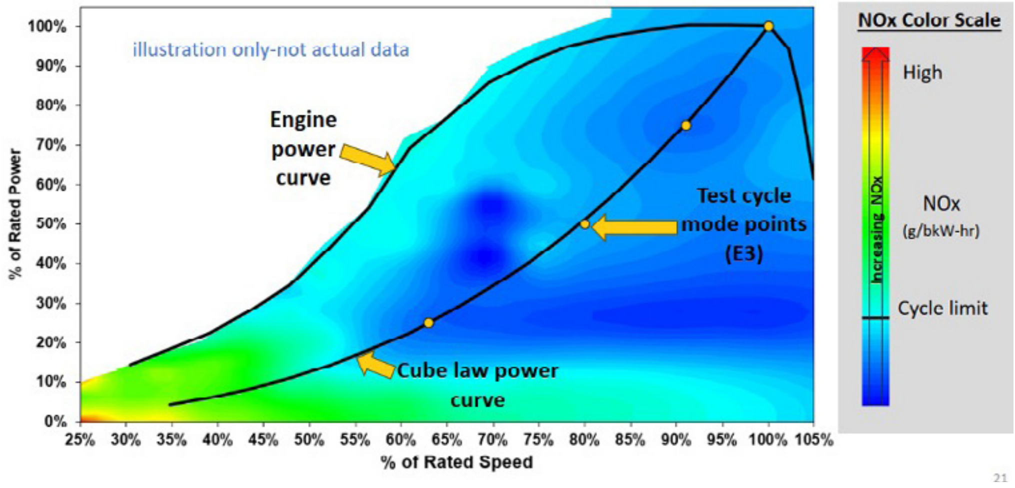
At IMO’s Marine Environment Protection Committee meeting MEPC 82, the committee made important advances on the regulatory measures on nitrogen oxides (NO$_X$) from marine engines. These changes will not present any concerns for operators of X DF engines.

MEPC 82 agreed draft revisions to the NO$_X$ Technical Code and related parts of MARPOL Annex VI that aim to codify existing best practice around NO$_X$ certification. In particular, the amendments place new certification requirements on engines with Multiple Engine

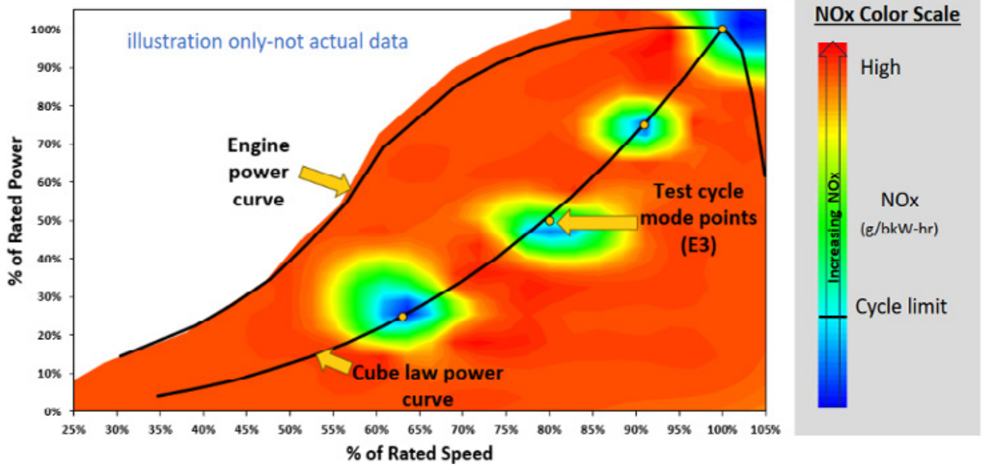
35 How is X-DF compliance affected by changes to the NOx Technical Code... continued...

Operating Profiles (MEOPs) and those using auxiliary control devices. Furthermore, these revisions include a screening mechanism for emissions between and beyond the test cycle mode points (“off-cycle emissions”) to verify that the emission control strategy is “rational”, as requested by MARPOL Annex VI.

Rational emission control strategy example



Irrational emission control strategy example



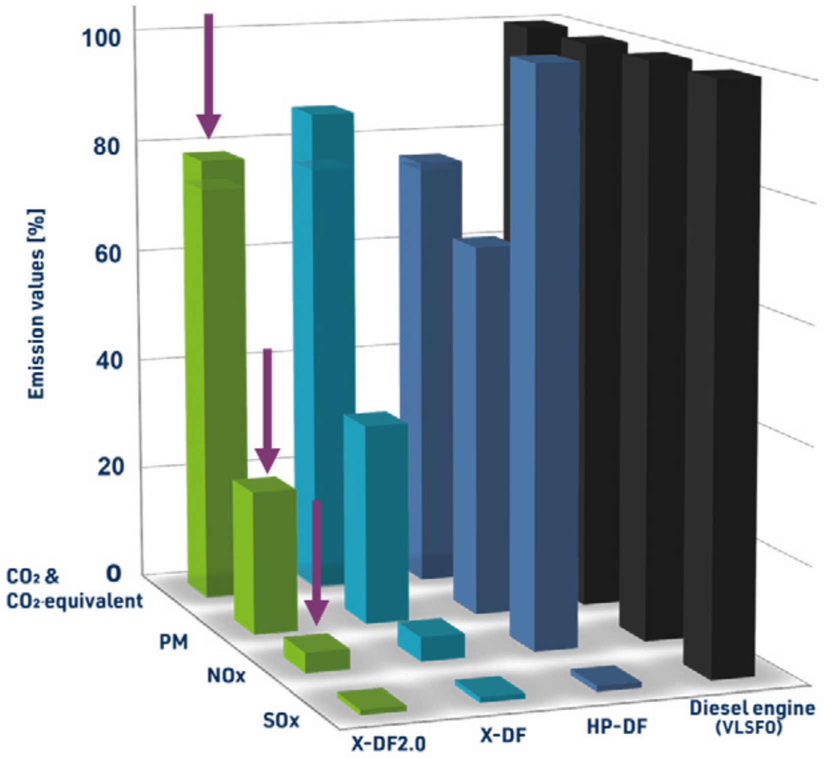
WinGD confirms that our NO_X emission control strategy has always been in line with these requirements and that the amendments pose no challenges for certifying X-DF and X-DF-2.x engines, which will remain fully compliant with all NO_X regulations. As the lean-burn Otto-cycle concept inherently results in the lowest possible NO_X formation of all available engine concepts, operators can rest assured that X-DF engines will retain the NO_X tier required for their operation, in all operational modes.

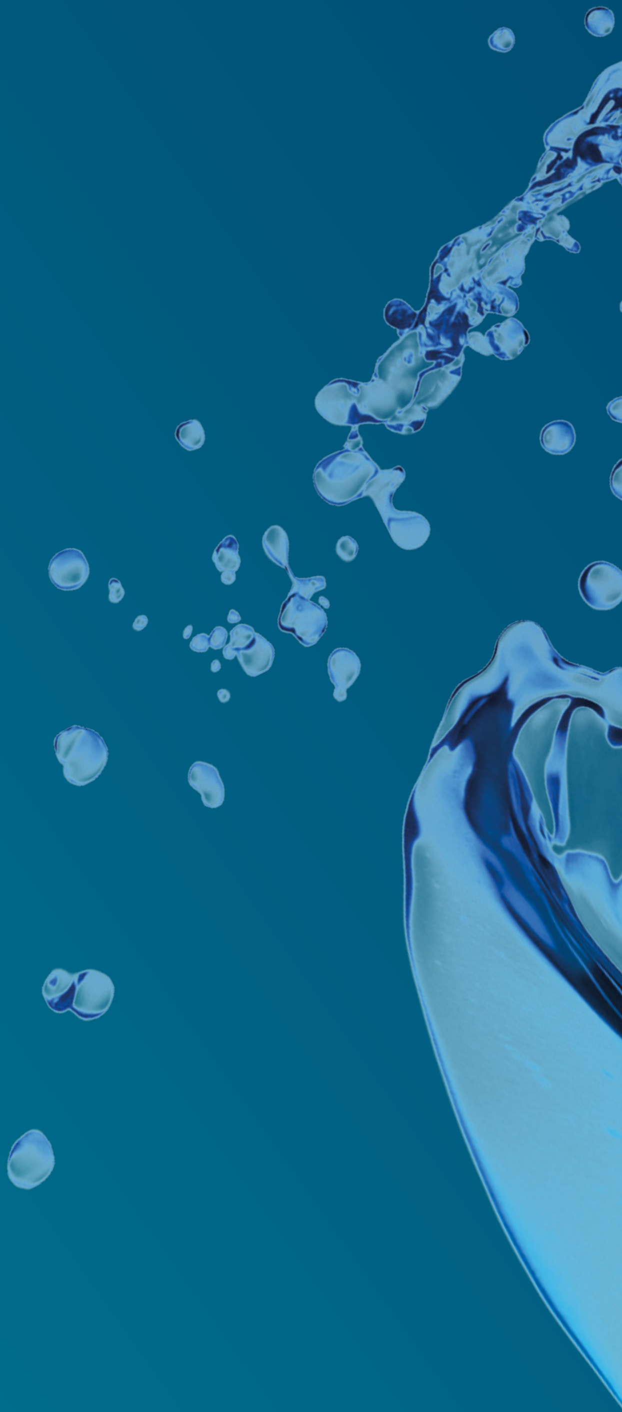
36 What is the overall environmental footprint of X-DF engines?

The total greenhouse gas balance is clearly positive compared to conventional diesel engines. At the same time, all emissions that are directly harmful to health and the environment, such as SO_X, NO_X and particulate matter, are also considerably reduced. X-DF engines are inherently compliant with all existing environmental standards.

This is specifically important when comparing with other DF technologies (as seen in illustrations on page 12). Propulsion systems with X-DF engines are currently the most environmentally sustainable solutions using fossil fuels.

Emissions profile, X-DF, high-pressure dual-fuel and single-fuel engines





Committed to the decarbonisation of marine transportation through sustainable energy systems.

WinGD designs marine power ecosystems utilising the most advanced technology in emissions reduction, fuel efficiency, digitalisation, service and support. With their two-stroke low-speed engines at the heart of the power equation, WinGD sets the industry standard for reliability, safety, efficiency and environmental design.

Headquartered in Winterthur, Switzerland, since its inception as the Sulzer Diesel Engine business in 1893, it is powering the transformation to a sustainable future.

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