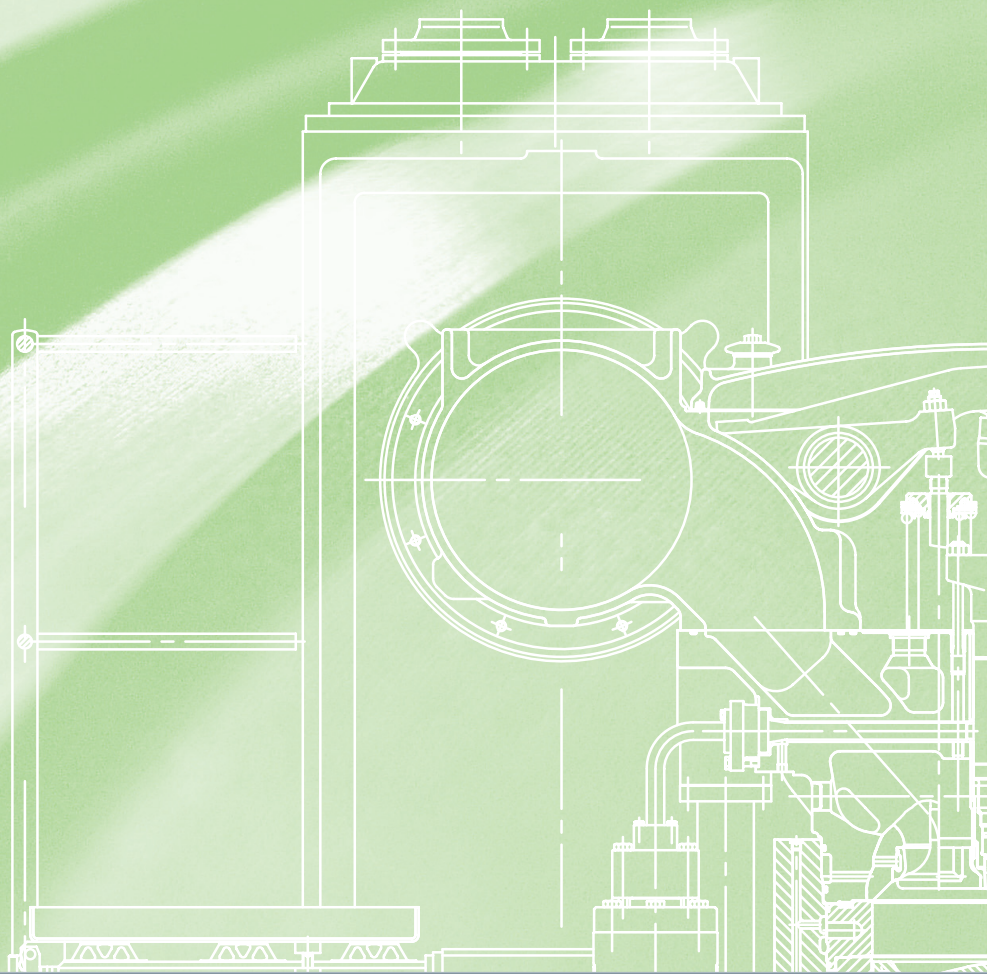


LNG Carrier Power

Total Fuel Flexibility & Maintainability
with 51/60DF Electric Propulsion



MAN Diesel



LNG Carrier Power: Total Fuel Flexibility & Maintainability with 51/60DF Electric Propulsion

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LNG Carrier Power: Total Fuel Flexibility & Maintainability with 51/60DF Electric Propulsion

Dual Fuel Diesel Electric (DFDE) ship propulsion is now widely accepted by the LNG industry. Dual Fuel engines power LNG carriers (LNGC) significantly more efficiently than traditional steam-based propulsion systems. Today, market observers recognise a very broad customer base that considers DFDE propulsion as the new standard technology for their LNGCs.

Besides its economy and outstanding environmental friendliness, the beauty of DFDE propulsion is its built-in flexibility in terms of fuel selection (HFO, MDO, or gas). In times of uncertainty about future fuel price developments, fuel flexibility becomes a definite must for vessels that are designed to operate for many decades.

This paper investigates the DFDE propulsion plant from different angles, discusses the benefits of different engine configurations, and demonstrates that the multi-engine DFDE plant with the right configuration provides full maintainability at any time of the voyage and, in addition, matches traditional steam propulsion systems in terms of fuel flexibility.

LNG Carriers

While the traditional propulsion system has been the steam turbine, today's order book of LNG carriers shows most vessels with non-steam propulsion [1]. Besides steam-based systems, there are two different propulsion concepts presently on order. For the convenience of those who are not very familiar with the non-steam systems, the following chapters provide short portraits.

Diesel propulsion concepts

A major part of these non-steam turbine vessels is the purpose-built fleet that was ordered for Qatar. These LNG carriers range from around 210,000 to 265,000 m³ cargo capacity.

Their main machinery, as illustrated in Fig. 1, comprises two low speed diesel engines for propulsion, four auxiliary gensets for electric power generation, and reliquefaction plants for the treatment of the cargo boil-off gas, the so-called natural boil-off gas (NBOG). For this kind of propulsion concept the abbreviation DRL is very often used for reference.

The main engines as well as the gensets of the DRL system burn heavy fuel oil (HFO). Consequently, those customers who make fuel flexibility a mandatory requirement have to look for other options. MAN Diesel offers two solutions in this respect:

- The ME-GI concept, illustrated in Fig. 2, which is based on dual fuel two-stroke engines with high pressure gas injection (250 to 300 bar). This is described in detail in [2], and shall not be further pursued here
- The 51/60DF-electric propulsion system, with low pressure gas injection (6 bar) and suitably matched engine configuration. This configuration provides not only a level of fuel flexibility comparable to steam turbines, but also full maintainability at any time required by the crew without affecting the vessel's schedule.

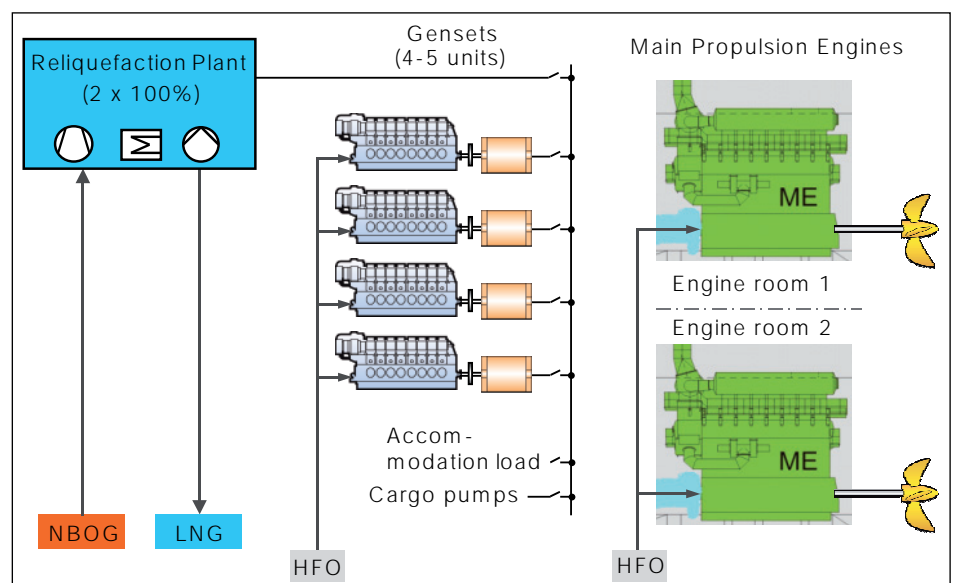


Fig. 1: Schematic main machinery of a two-stroke LNG carrier with reliquefaction plant (DRL), NBOG is fed back to the cargo tanks, and main engines and gensets run on HFO

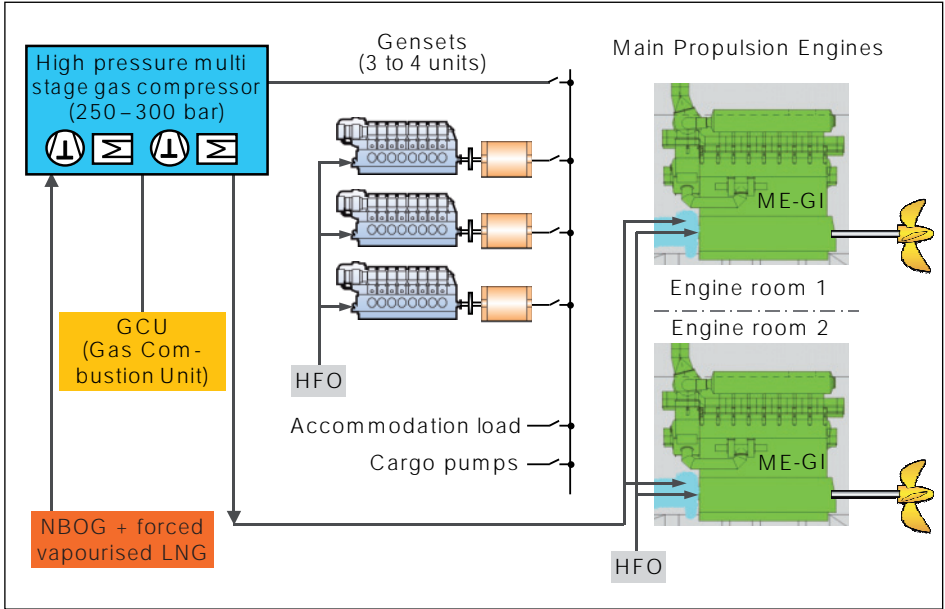


Fig. 2: Schematic main machinery of a ME-GI propulsion plant with high-pressure gas compressor, fuel flexible two-stroke main engines (HFO, gas) and HFO burning gensets

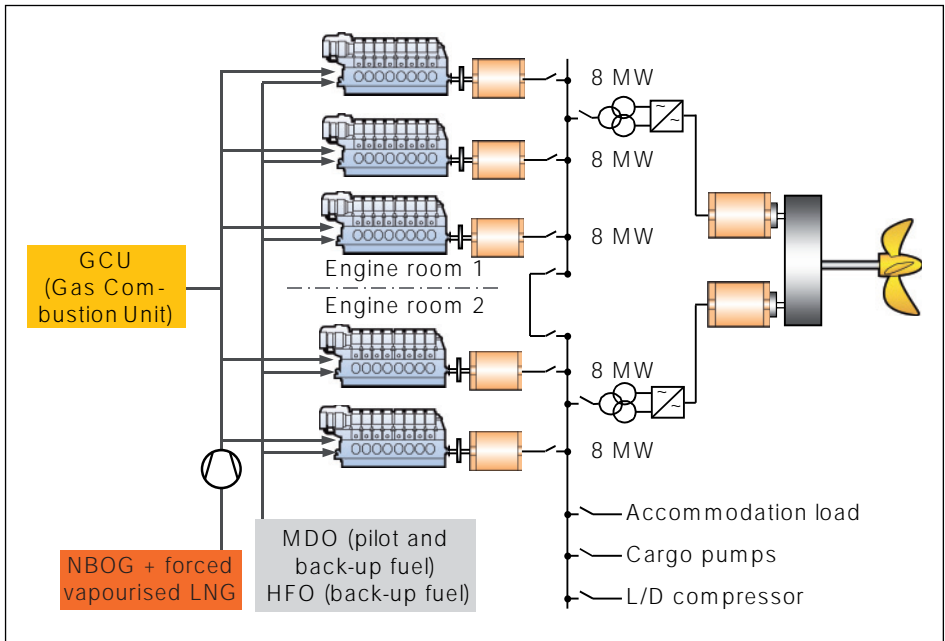


Fig. 3: Schematic main machinery of a four-stroke DFDE plant incorporating total fuel flexibility with any possible ratio of liquid fuel (HFO or MDO) and gas

DFDE propulsion concept

The other big group of vessels with non-steam propulsion features Dual Fuel Diesel Electric plants (DFDE). As shown in Fig. 3, the DFDE concept provides a more straightforward and simple layout of the onboard main machinery park. Four to five main engines, which are all of the same type, drive the alternators that generate the electrical power for all the vessel's consumers, comprising propulsion motors, low-duty compressors, accommodation load, thrusters, cargo pumps, auxiliary systems and other ship equipment.

Being a multi-engine configuration, the DFDE plant provides an excellent level of redundancy and safety, a situation well comparable to the cruise sector, where vessels have operated with four-stroke Diesel-Electric plants for decades. A common feature of both cruise vessels and LNG carriers is their equally stringent demand for safety and engine reliability. It is very noteworthy that millions of passengers per year in the ever-growing cruise marketplace their confidence and trust in the safety and reliability of the cruise vessels and their four-stroke engines. The power plants in cruise vessels are typically equipped with four to six engines of the same type, having similar or equal cylinder numbers. However, based on the example of one of the world's most renowned cruise liners, the *Queen Elizabeth II*, there could be as many as nine engines (9 x 9L58/64).

LNG carrier standard size

The current order book of LNG carriers [1] lists only three vessels with a capacity below 100,000 m³. 45 vessels have been ordered with a cargo capacity above 200,000 m³; this group of vessels is the purpose-built Qatar fleet. 80 vessels, the big majority, range from 138,000 to 174,000 m³, with an average of around 155,000 m³ cargo capacity, and are thus to be considered today's standard size for LNG carriers.

MAN Diesel reference

Most LNG carriers with DFDE propulsion systems that are listed in today's order books have been specified with four main engines. However, owners recently started to consider plants with five DF-engines of equal or similar cylinder numbers, as this configuration provides high levels of operational flexibility, easier plant handling and maintainability as well as additional safety margins.

This will be demonstrated in the following chapters.

In fact, the 174,000 m³ LNG carrier for the Spanish owner EN Elcano, which has become MAN Diesel's first DFDE reference, will be equipped with five equally rated MAN Diesel 8L51/60DF Dual Fuel engines and is scheduled to be delivered by mid 2010, see Fig. 4. With a length of 300 m, a breadth of 45.8 m, and a design draught of 11.5 m, this is the largest LNG carrier ever ordered with DFDE propulsion.



DFDE propulsion puts no limit on the ship size, as the required installed power can be increased simply by adding a few cylinders (e.g. 5 x 9L51/60DF). Hence, in the case of the MAN Diesel 51/60DF engine, the diesel-electric concept can be easily extended to cater for future large vessels in the 200k+ capacity range by adding, say, five cylinders compared to engine configurations in today's standard sized vessels (155k).

Fig. 4: Largest LNG carrier with DFDE propulsion (5 x 8L51/60DF) ordered by Spanish owner EN Elcano at Korean yard STX Shipbuilding

LNG Carrier Power Requirements

Before looking into engine configurations and load scenarios, typical power requirements of the vessel and NBOG quantities, which serve as fuel, will be discussed.

Natural boil-off gas

Since the launch of the first LNG carrier in the 1960s, natural boil-off gas (NBOG) has been used as fuel for power generation on the vessels. Depending on the size and quality of the LNG containment system, boil-off rates are typically in the area 0.11 to 0.15 percent per day of the ship's cargo capacity during laden voyage and approximately half during ballast voyage. For a standard sized LNG carrier (155,000 m³), the evaporating mass of gas would allow the production of around 20 MW of mechanical power at the engine coupling during laden voyage.

While sailing at design speed, which typically ranges from 18.5 to 20 knots [1], the NBOG may not be enough to satisfy the vessel's total power requirements. For additional power, the firing of liquid fuels is required, such as HFO or MDO. Alternatively, the operator, if allowed by the charterer, may produce additional gas from the cargo, the so-called forced boil-off gas (FBOG). Other phases of the voyage, for instance manoeuvring or passage through the Suez Canal, have lower power requirements, and excess boil-off gas is available. If there is more NBOG than consumable by the engines, the cargo containment is designed to accept pressure increases for some time. However, beyond these limits the NBOG would need to be oxidised by the gas combustion unit.

Boundary conditions for LNG carrier operation

For the selection of a propulsion concept and suitable choice of engine configurations, an understanding of the LNG trade is invaluable. The majority of LNG carriers are deployed on fixed trade routes. As shuttle tankers, the vessels are supposed to run continuously without major delays. Harbour times are short, as they are only used for loading and discharging. Thus, the following operational conditions and assumptions apply:

- Maintenance of Dual Fuel engines is done on board during voyage and requires shutdown of the engine concerned. In the worst case, the largest engine will be out of service. For this reason, the Diesel-Electric power plants of cruise vessels are dimensioned in a way that the full power requirement can be satisfied even when one engine is out of service.
- The LNG carrier must maintain schedules and thus service speeds.
- In the worst case, the sea margin is "exhausted" due to fouling of the hull and bad weather conditions.
- Dual Fuel engines run either on gas or on liquid fuel. In both modes, a tiny quantity of liquid pilot fuel, typically around one percent of total fuel consumption, is injected.
- Typical operational profiles and charter contracts allow the powerplant to burn only natural boil-off gas (NBOG). If gas combustion cannot provide enough power to cover the vessel's total needs, the additional power has to be generated by means of liquid

fuel add-up. This means in practice that some engines in a multi-engine plant will operate only on gas, others only on HFO (see chapter "Dedicated engines" below). Due to the different occurrence of NBOG during laden and ballast (return) voyage, at least one of the Dual Fuel engines would need to switch fuels for each leg of the round trip.

Based on these frame conditions, this paper examines the load settings of the individual engines of the multi-engine plant under various scenarios, where the vessels have varying overall power requirements.

Typical power requirements

For a standard LNG carrier as referenced above (155,000 m³), our studies found average power requirements at the engine coupling during various phases of the vessel's voyage to be as set out in Fig. 5. For the purpose of this paper, the values are assumed to illustrate typical power requirements during various phases of the vessel's journey involving various consumers such as propulsion motors, thrusters, cargo pumps, accommodation load, etc.

Sailing (both laden and ballast voyage, including 21% sea margin)	32 MW
Sailing (without sea margin)	27 MW
Manoeuvring	14 MW
Waiting/idling before LNG terminal	1.5 MW
Loading	4 MW
Discharging	7.5 MW
Available engine power through NBOG	
during laden voyage	20 MW
during ballast voyage	11 MW

Fig. 5: Typical average power needs at engine coupling of a 155,000 m³ LNG carrier with DFDE propulsion

The maximum overall power requirement during voyage has been found to be in the area of 32 MW. This value includes a sea margin of 21%, which many ship designers use for the dimensioning of the power plants of LNG carriers. Another widespread dimensioning guideline in the marine sector is that under full power demand, the engines should be running at load levels of around 85%.

Manoeuvring in and out of the harbour may require an average power of 14 MW, while idling and waiting periods before entering the harbour have the lowest power requirement of around 1.5 MW. When loading or unloading the LNG, the cargo pumps are the main consumers of electrical power, and the vessel's overall power needs are then around 4 MW or 7.5 MW respectively.

While the overall power requirements do not vary much between laden and ballast voyages the amount of NBOG is different. As stated, with reference to the vessel's cargo capacity, the typical boil-off rate is 0.12 percent per day during laden voyage and approximately half during ballast voyage. When burnt as fuel in four-stroke Dual Fuel engines, the amount of NBOG is sufficient to produce approximately 20 MW of power at the engine coupling during laden voyage.

Dedicated engines concept

Depending on the fuel – HFO, gas, or other – appropriate lubricating oils have to be selected for the engines. The development of deposits in the combustion chambers and the wear in the engines are linked to the fuel and its assigned lubricant. If the engine burns HFO, lube oil with a base number (BN) of 30 or 40 is the straightforward choice. If the engine burns gas or MDO, the base number should be around 5 to 15 instead.

Configuration type	Power rating per cylinder	Engine configuration	Number of cylinders per plant	Total installed power per plant
Inline configuration	1,000 kW	5 x 8L	40	40.0 MW
Mixed configuration	950 kW	3 x 12V + 1 x 6L	42	39.9 MW

Fig. 6: Typical engine configurations

Practical experience shows that MAN Diesel medium speed engines are very tolerant and robust regarding the use of lube oils. It is acceptable for the 51/60DF Dual Fuel engine to use a single lube oil of BN 30 for both gas burning (during laden voyage) and HFO burning (during ballast voyage).

However, if fuel price development or emissions requirements lead the charterer of the vessel to request operating the engines on gas for several weeks or months, it is advisable to discontinue the use of lube oils which are not optimised for gas operation. Then, the operator should change to a lube oil with a lower base number. As a result, MAN Diesel recommends the installation of a twin lube oil system, as this will ensure the required operational flexibility for all prospective future situations and trade scenarios.

Depending on the engine configuration and the different quantities of NBOG available during laden and ballast voyage, only one or two engines will need to switch fuel. The other engines will stay on the same fuel during both legs of the round trip and are thus dedicated to this fuel. For the convenience of the vessel's operator, the so-called "dedicated engines" will run continuously on the optimum fuel/lube oil combination throughout the round trip without changing lube oil.

Typical Engine Configurations

Given the above dimensioning guidelines, the standard LNG carrier will need an installed engine power total of 40 MW, which is to be split over four or five engines. The power per cylinder of a given engine make determines the total number of cylinders needed. Then, a rational split into individual engines has to be found. With LNG carriers, safety and redundancy considerations as well as regulations require multi-engine plants.

Two typical engine configurations as depicted in Fig. 6 are considered in the majority of projects today. How these plants compare in terms of operational flexibility, loading smoothness, and maintainability is discussed on the following pages.

Inline configuration, 5 x 8L

Nonetheless, in practice some of the engines in the multi-engine plant will burn the NBOG while other engines will provide the power add-up by burning liquid fuel. The following scenarios investigate the fuel flexibility and the maintainability of the plant as well as the loads of individual engines under various overall vessel power requirements.

Scenario 1: inline configuration, calm sea, clean hull

In the early days of the vessel and in calm weather, the overall sailing power requirement is 27 MW, as noted above (see Fig. 5). In the inline configuration consisting of five 8 cylinder engines (see Fig. 6), four engines can provide this power. The operator runs three engines in gas mode to burn the NBOG and one in liquid mode with HFO to provide the required power add-up. The adjacent table shows the resulting loads.

Laden voyage: inline configuration, calm sea, clean hull					
Power demand:	27	Power values in MW at engine coupling			
"NBOG" power:	20				
"Liquid" power add-up:	7				
	Engine 1	Engine 2	Engine 3	Engine 4	Engine 5
Gas mode	x	x	x		out of service
Liquid mode				x	
Power production	6.7	6.7	6.7	7.0	
Engine rating	8.0	8.0	8.0	8.0	8.0
Load setting	83%	83%	83%	88%	0%

With respective load percentages of 83 and 88, all running engines have smooth load settings at levels which are widely practised in the marine sector.

It is of no importance which engine operates on gas and which on liquid fuel as either one has the full flexibility to accept both fuels.

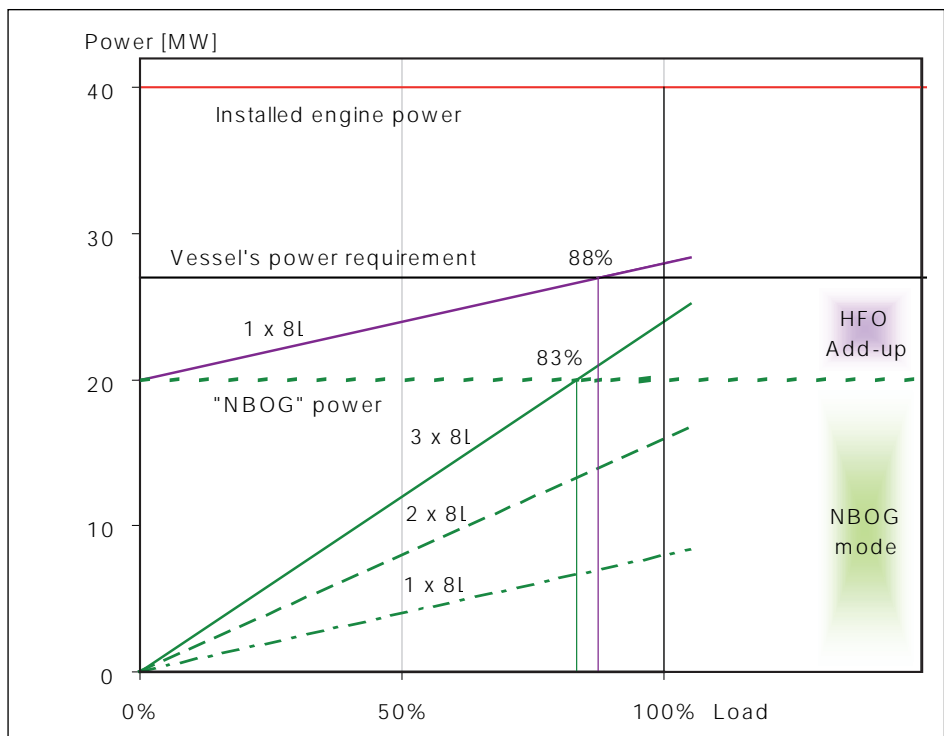


Fig. 7: Engine loads for inline configuration (5 x 8L engines) with 1,000 kW per cylinder rating, three engines in gas mode, one in liquid mode, and one out of service

Scenario 2: inline configuration, increased fouling

With advancing age, increasing fouling of the vessel will dictate more propulsion power to maintain the service speed of the vessel. Unlike the previous scenario, we now assume an increased total power need of 29 MW (use of 8% sea margin). The quantity of NBOG remains unchanged as it depends on the quality of the containment system, which we do not expect to deteriorate significantly with time. Thus, the loads of the gas-burning engines are still the same. However, the engine that is supposed to provide the power add-up is now overloaded. There are various options to deal with the situation.

- Reduce the speed of the vessel and save power.
- Restart the shut down engine.
- Produce FBOG.

The first option is not feasible as trade schedules have to be maintained. The second option is also unacceptable if a major maintenance job is due on this engine. The elegant solution is the third option. With only a small amount of additionally produced FBOG, the load on the gas burning engines is increased slightly and thus the load on the liquid fuel burning engine reduced.

With an additional quantity of less than 10% of the NBOG amount, it is easily possible for the operator to select smooth load factors on all running engines and still keep one engine out of service. Fig. 8 is a graphic representation of the situation. In NBOG + FBOG mode, all engines have smooth and equal load settings.

Laden voyage: inline configuration, increased fouling, NBOG only					
Power demand:	29	Power values in MW at engine coupling			
"NBOG" power:	20				
"Liquid" power add-up:	9				
	Engine 1	Engine 2	Engine 3	Engine 4	Engine 5
Gas mode	x	x	x		out of service
Liquid mode				x	
Power production	6.7	6.7	6.7	9.0	
Engine rating	8.0	8.0	8.0	8.0	8.0
Load setting	83%	83%	83%	113%	0%

Laden voyage: inline configuration, increased fouling, min. FBOG					
Power demand:	29	"FBOG" power 1.8			Power values in MW at engine coupling
"NBOG" power:	20				
"Liquid" power add-up:	7.2				
	Engine 1	Engine 2	Engine 3	Engine 4	Engine 5
Gas mode	x	x	x		out of service
Liquid mode				x	
Power production	7.3	7.3	7.3	7.2	
Engine rating	8.0	8.0	8.0	8.0	8,0
Load setting	91%	91%	91%	90%	0%

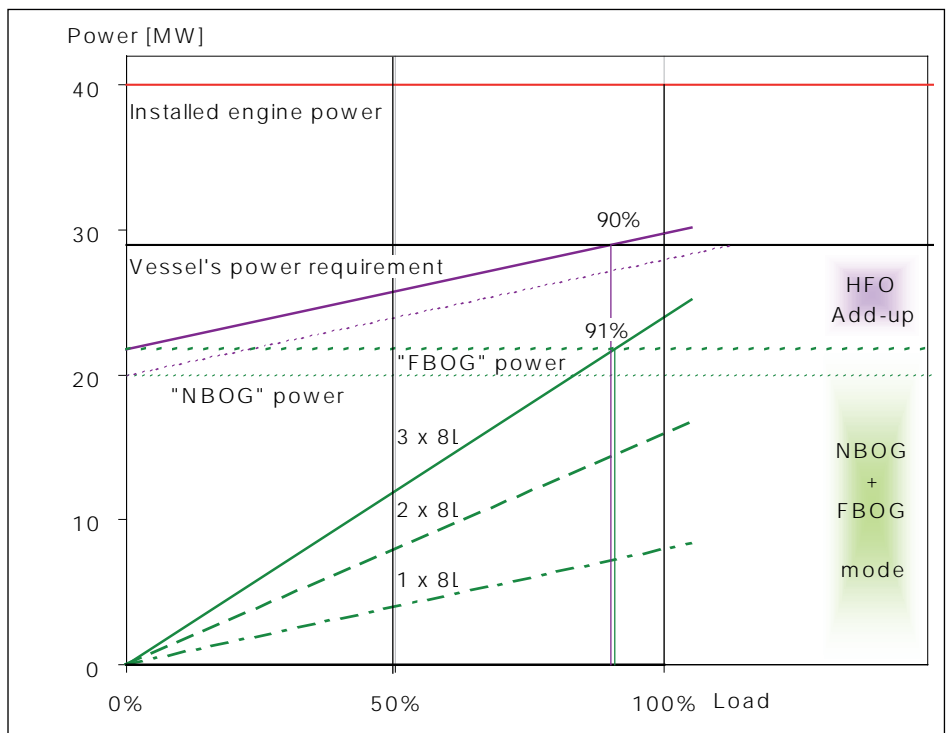


Fig. 8: Engine loads during laden voyage, increased power demand due to increased hull friction (8% sea margin used), three engines in gas mode, one in liquid mode and one out of service

Scenario 3: inline configuration, maximum power requirement

The third scenario looks at a situation where the vessel needs the maximum design power (21% sea margin used). This will be the case with advanced fouling after a couple of years of operation and under bad weather conditions. The latter will also cause an increased boil-off rate and thus an increased quantity of NBOG, as the vessel will vibrate more heavily under swell (assumed boil-off rate 0.15). The resulting loads can be seen in Fig. 9.

When one engine is out of service, the running engines obviously now reach an operational limit, but do not yet exceed it. Unlike conventional diesel engines, Dual Fuel engines in gas mode achieve their optimum efficiency at 100% load, which is also the typical load point for continuous operation in land-based power plant applications. It is left to the discretion of the operator whether to continue engine operation at 100% MCR, whether to start up the remaining engine, if possible, or to take other action e.g. a slight reduction of vessel speed.

In all situations, the inline configuration provides the operator with the maximum level of operational flexibility.

Laden voyage: inline configuration, maximum power requirement					
Power demand:	32	Power values in MW at engine coupling			
"NBOG" power:	24				
"Liquid" power add-up:	8				
	Engine 1	Engine 2	Engine 3	Engine 4	Engine 5
Gas mode	x	x	x		out of service
Liquid mode				x	
Power production	8.0	8.0	8.0	8.0	
Engine rating	8.0	8.0	8.0	8.0	8.0
Load setting	100%	100%	100%	100%	0%

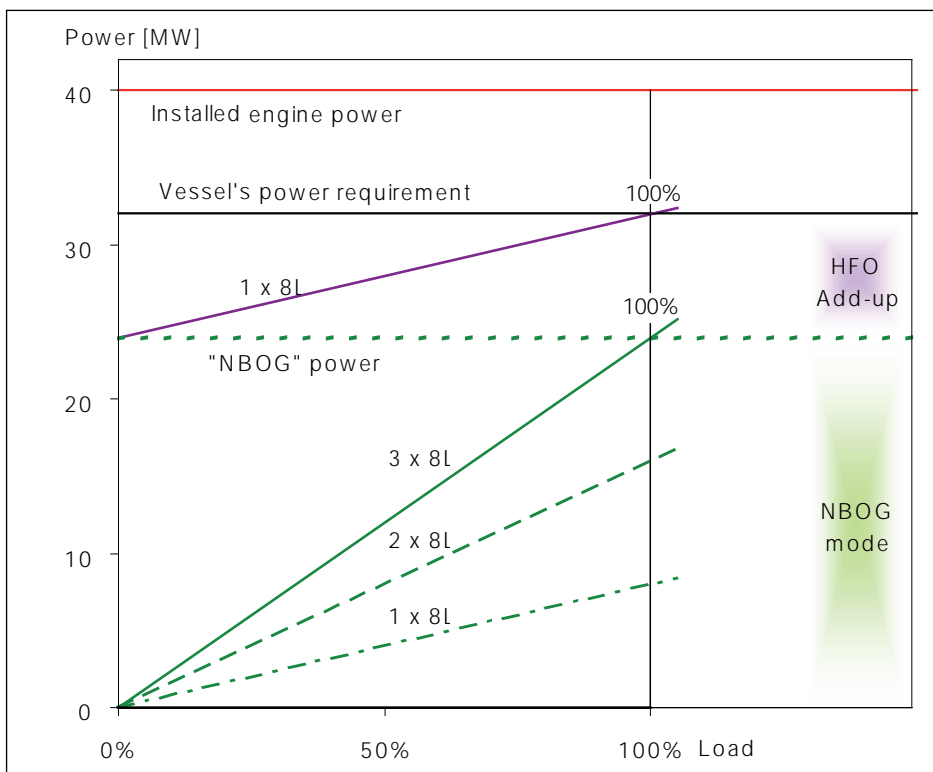


Fig. 9: Engine loads during laden voyage under maximum design power needs (21% sea margin used). Three engines in gas mode, one in liquid mode and one out of service

Laden voyage: inline configuration, maximum power requirement					
Power demand:	32	"FBOG" power 1.5		Power values in MW at engine coupling	
"NBOG" power:	24				
"Liquid" power add-up:	6,5				
	Engine 1	Engine 2	Engine 3	Engine 4	Engine 5
Gas mode	x	x	x		x
Liquid mode				x	
Power production	6.4	6.4	6.4	6.5	
Engine rating	8.0	8.0	8.0	8.0	8.0
Load setting	80%	80%	80%	81%	80%

Mixed configuration 3 x 12V + 1 x 6L

After discussing the load scenarios for the above inline configuration consisting of five L-type engines, this chapter now evaluates the mixed configuration consisting of three V-type and one L-type engine (see Fig. 6). The power requirements of the following scenarios are as in the above case.

Scenario 1: mixed configuration, calm sea, clean hull

In terms of overall power needs, NBOG availability and state of the vessel, the conditions are the same as mentioned above, and one engine is shut down. As the configuration is a mixed configuration, the worst case in terms of power availability is to have one of the large engines out of service, because this creates a serious power drop (compare Fig. 15).

Due to the amount of NBOG, the obvious choice for the operator is to run the two large engines in gas mode and one engine, the remaining smaller one, in liquid mode for power add-up. The situation is then as shown in Fig. 10.

However, this situation is not feasible, as the remaining engine in liquid mode is not powerful enough to supply the necessary power add-up. Obviously, without additional FBOG this plant configuration cannot satisfy the vessel's power and fuel flexibility needs, even at the beginning of the vessel's service life. This configuration will only work if the vessel is allowed to burn more gas than just the NBOG quantity. The operator thus has the following options:

- Reduce the speed of the vessel for lower power requirements.
- Restart the shut down engine.
- Produce forced boil-off gas (FBOG), increase the load on the gas-burning

Laden voyage: mixed configuration, calm sea, clean hull				
Power demand:	27	Power values in MW at engine coupling		
"NBOG" power:	20			
"Liquid" power add-up:	7			
	Engine 1	Engine 2	Engine 3	Engine 4
Gas mode	x	x	out of service	
Liquid mode				x
Power production	10.0	10.0	0.0	7.0
Engine rating	11.4	11.4	11.4	5.7
Load setting	88%	88%	0%	123%

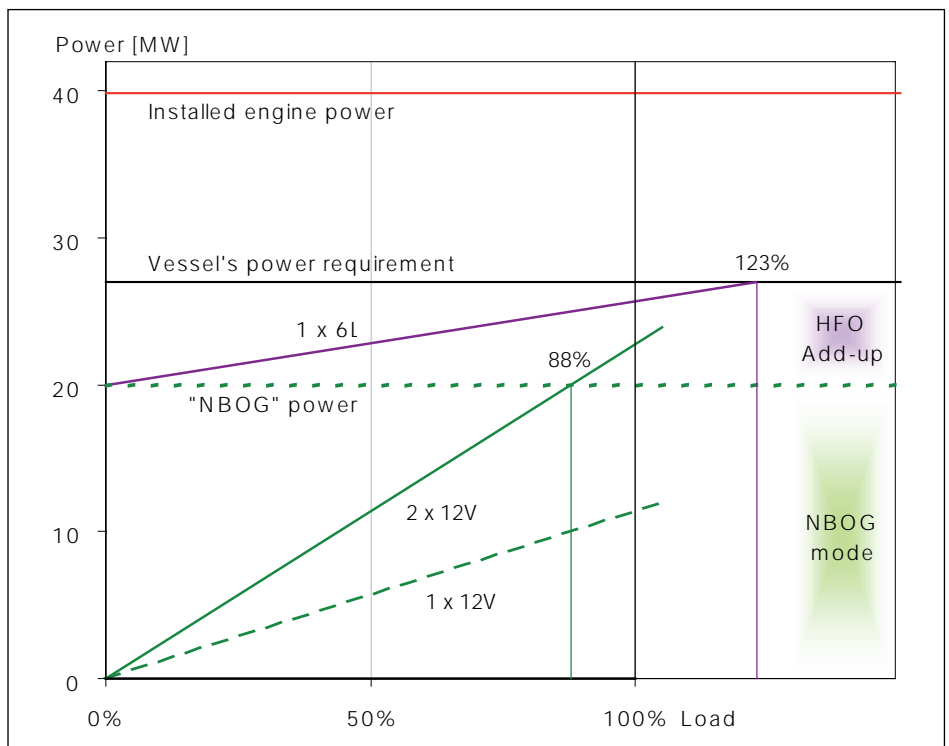


Fig. 10: Engine loads for mixed configuration (3 x 12V + 1 x 6L) with 950 kW per cylinder rating. Two engines in NBOG mode, one in liquid mode for power add-up, and one large engine out of service

engines and thus reduce the load on the engine in liquid mode.

The first two options are not feasible for the same reasons as cited above. The third option would be correct, but this requires a charterer who always allows the use of gas beyond the NBOG quantity. In other words, this configuration

is acceptable for vessels that do not need total fuel flexibility but run mainly on gas.

Scenario 2: mixed configuration, increased fouling

This situation comprises increased power needs, an unchanged quantity of NBOG and one engine out of service. It results in the loads shown in the table.

While the inline configuration could easily cope with this situation and achieve smooth loads by simply adding a minimum amount of FBOG, this is not possible in this configuration. The engine in liquid mode is excessively overloaded.

As Fig. 11 shows, even adding FBOG and loading the gas-burning engines up to 100% does not bring the engine in liquid mode below its operational limit. In order to maintain vessel speed, there is no choice but to start up the large engine not in operation. This, however, may represent a conflict with the chief engineer's maintenance schedule. For reasons clearly illustrated, a four-engine plant of mixed configuration reaches its operational limitations much sooner than the inline configuration with five equal engines.

Laden voyage: mixed configuration, increased fouling				
Power demand:	29	Power values in MW at engine coupling		
"NBOG" power:	20			
"Liquid" power add-up:	9			
	Engine 1	Engine 2	Engine 3	Engine 4
Gas mode	x	x	Out of service	x
Liquid mode				
Power production	10.0	10.0	0.0	9.0
Engine rating	11.4	11.4	11.4	5.7
Load setting	88%	88%	0%	158%

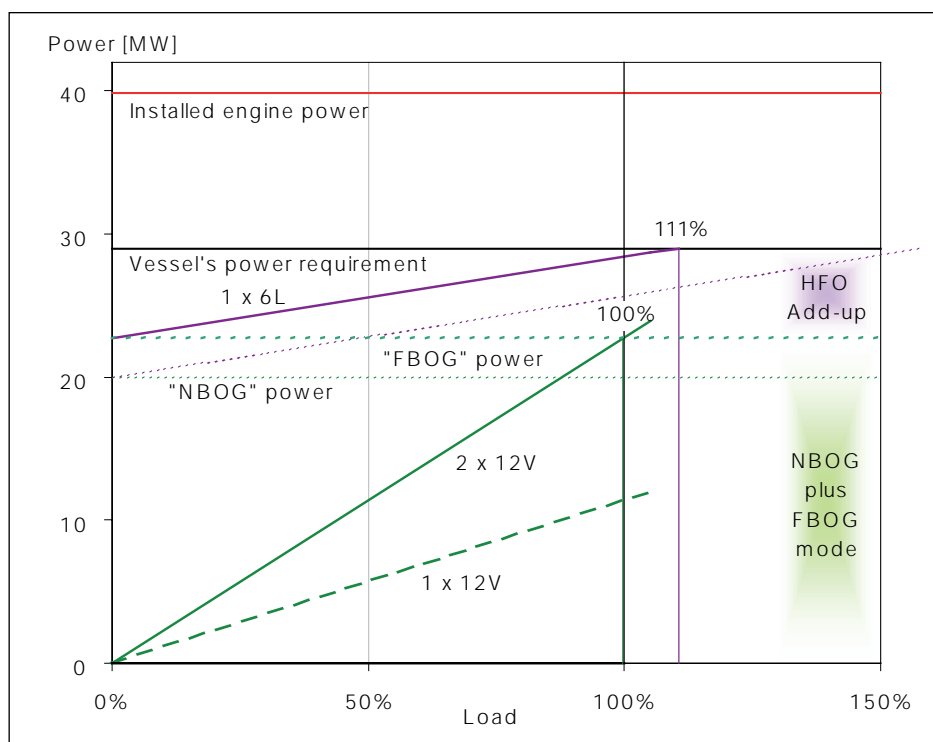


Fig. 11: Engine loads for the mixed configuration under increased power requirements due to increased friction of the hull (8% sea margin used). Two engines in NBOG mode, one in liquid mode for power add-up, and one large engine out of service

Scenario 3: mixed configuration, maximum power requirement

When the vessel requires full design power. The powerplant faces restrictions and deprives the shipowner of operational freedom. Obviously, without all engines running, the plant cannot provide all the power needed. When one engine is out of service, the remaining engines are clearly beyond their operational limits. It is mandatory to restart the large engine, if this is possible at all, since the engine might well be under maintenance.

Secondly, the restarted large engine has to work in liquid mode and the small one has to switch to gas mode so that the propulsion plant can cope with the increased occurrence of NBOG (bad weather conditions) and achieve a reasonable load distribution over all engines as shown in Fig. 12.

Laden voyage: mixed configuration, maximum power requirement				
Power demand:	32	Power values in MW at engine coupling		
"NBOG" power:	24			
"Liquid" power add-up:	8			
	Engine 1	Engine 2	Engine 3	Engine 4
Gas mode	x	x	Out of service	
Liquid mode				x
Power production	12.0	12.0	0.0	8.0
Engine rating	11.4	11.4	11.4	5.7
Load setting	105%	105%	0%	140%

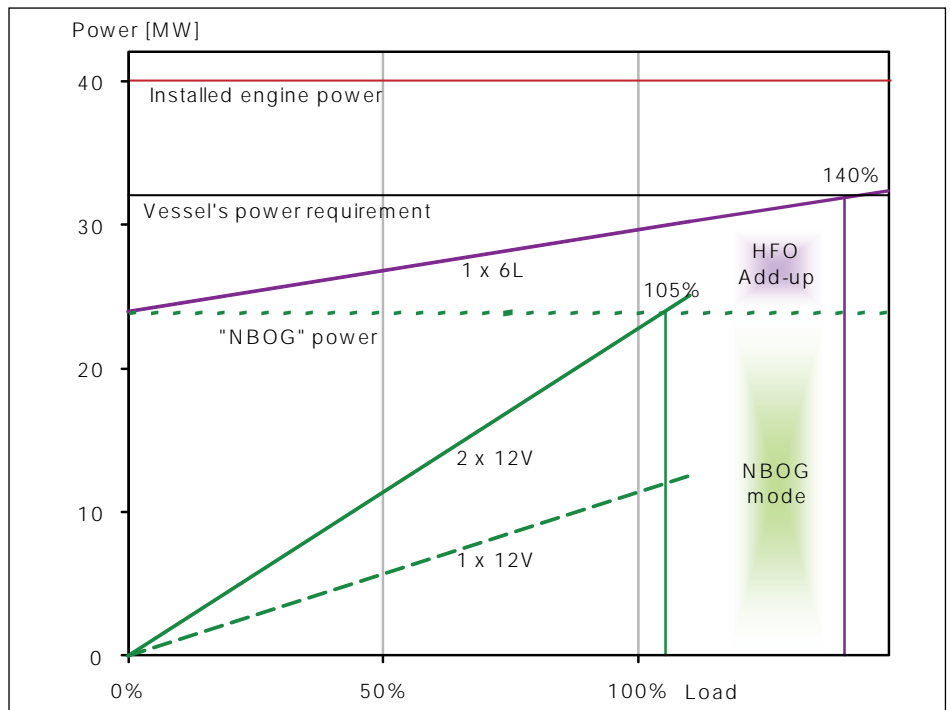


Fig. 12: Engine loads during laden voyage under maximum design power need (21% sea margin used). Two engines in NBOG mode, one in liquid mode for power add-up, and one large engine out of service

Laden voyage: mixed configuration, maximum power requirement all engines running				
Power demand:	32	Power values in MW at engine coupling		
"NBOG" power:	24			
"Liquid" power add-up:	8			
	Engine 1	Engine 2	Engine 3	Engine 4
Gas mode	x	x		x
Liquid mode			x	
Power production	9.6	9.6	8.0	4.8
Engine rating	11.4	11.4	11.4	5.7
Load setting	84%	84%	70%	84%

Low-load consideration

The previous scenarios investigated the high power requirements of the vessel. Waiting periods, for instance, before entering the terminal, represent the other end of the scale, when power requirements are as low as 1.5 MW. The inline engines still work above 15% load, which is the minimum engine load required for gas operation. Thus, even in this extreme low-load situation all the inline engines, regardless of their cylinder number, maintain the flexibility to burn both liquid and gaseous fuels. The resulting load on the large V-type engine, however, is below 15%, which imposes operational restrictions as Fig. 13 indicates.

Segments of the round trip

Based on typical power requirements of the various segments of the round trip of an LNG shuttle tanker, resulting engine loads may be expected as shown in Figs. 14 and 15. The spreadsheets compare the inline configuration with two different mixed configurations.

While the inline configuration is describable and manageable with few cases in a simple and straightforward way, the assessment of the load scenarios of the mixed configurations is much more complex. In practice, this will reduce the convenience and ease of use of the plant, thus increasing the workload on the crew and finally represent a source

of operating errors and mistakes. In other words, the inline configuration has significantly greater user friendliness than the mixed configurations and thus contributes substantially to the safe performance of the vessel.

Not only the number of cases, but also loads beyond the prescribed limits – marked in red in Figs. 14 and 15 – represent restrictions limiting the degree of operational freedom of the plant.

	L-Type		V-Type
Engine type	8L 51/60DF	9L 51/60DF	12V 51/60DF
Resulting load	18.8%	16.7%	12.5%
Operation on gas	possible	possible	not possible
Operation on HFO	possible	possible	not continuously

Fig. 13: Low-load consideration, vessel in “stand-by” (minimum power during waiting periods), average low-load requirements 1,500 kW

Load Scenarios I		Inline Configuration 5 x 8L				Mixed Configuration 2 x 12V + 2 x 8L							
Engine power		1,000 kW / cylinder				1,000 kW / cylinder							
Engines in operation		all engines	all except one	two engines	one engine	all	all except small engines	all except large engines	two large engines	large and small engines	two small engines	large engines	small engines
		Plant	Plant	Plant	8L	Plant	Plant	Plant	Plant	Plant	Plant	12V	8L
	MW	40.0	32.0	16.0	8.0	40.0	32.0	28.0	24.0	20.0	16.0	12.0	8.0
Trip segment	Vessel's power needs	Engine load settings											
	MW												
Sailing (incl. sea margin)	32.0	80%	100%			80%	100%	114%					
Sailing (average value)	29.5		92%				92%	105%					
Sailing (without sea margin)	27.0		84%				84%	96%					
Manoeuvring	14.0			88%					58%	70%			
Idling before LNG terminal	1.5				19%							13%	19%
Load port	4.0			25%	50%				17%	20%	25%	33%	50%
Discharge port	7.5			47%	94%				31%	38%	47%	63%	94%
Sea margin	21%	Continuous operation load limits: 100% upper 15% lower											

Fig. 14 Load settings for typical segments of the vessel's voyage (5 x 8L vs. 2 x 12V + 2 x 8L)

Load Scenarios II		Inline Configuration 5 x 8L				Mixed Configuration 3 x 12V + 1 x 6L						
Engine power		1,000 kW / cylinder				950 kW / cylinder						
Engines in operation		all engines	all except one	two engines	one engine	all	all except small engines	all except large engines	two large engines	large and small engines	large engines	small engines
		Plant	Plant	Plant	8L	Plant	Plant	Plant	Plant	Plant	12V	6L
	MW	40.0	32.0	16.0	8.0	39.9	34.2	28.5	22.8	17.1	11.4	5.7
Trip segment	Vessel's power needs	Engine load settings										
	MW											
Sailing (incl. sea margin)	32.0	80%	100%			80%	94%	112%				
Sailing (average value)	29.5		92%				86%	104%				
Sailing (without sea margin)	27.0		84%				79%	95%				
Manoeuvring	14.0			88%					61%	82%		
Idling before LNG terminal	1.5				19%						13%	26%
Load port	4.0			25%	50%				18%	23%	35%	70%
Discharge port	7.5			47%	94%				33%	44%	66%	132%
Sea margin	21%	Continuous operation load limit 100% upper 15% lower										

Fig. 15: Load settings for typical segments of the vessel's voyage (5 x 8L vs. 3 x 12V + 1 x 6L)

Benefits of the inline configuration

Having worked through the above scenarios, it becomes apparent that for LNG carrier application, an inline configuration consisting of five L-type engines provides an increased and desirable range of benefits compared to mixed configurations with four engines of inline and vee type.

Power reserve

As the maximum power drop is only 20%, if one engine is out of service, the inline configuration confers the greatest power reserves (see Fig. 16). Thus, the inline configuration not only promotes excellent maintainability of the plant (see chapter "Full maintainability" below) but also provides more power reserves than the mixed configurations, and thus the benefit of additional safety margins for the vessel.

As also shown in the above scenarios, mixed configurations are subject to the constraint of bringing all engines into operation in order to satisfy the vessel's power needs.

Smooth engine load factors

The inline configuration with its higher operational flexibility promotes smooth engine load factors, even when one engine is out of service.

Supports dedicated engines

In NBOG mode during the round trip of laden and ballast voyage, a maximum of two engines will need to change between gaseous and liquid fuel. If FBOG mode is permissible during ballast voyage, only one engine needs to change between gaseous and liquid fuel – i.e. the operator can run 4 out of 5 engines continuously on the optimised fuel/lube oil combination without any interventions.

Simplifies plant and engine operation

Under varying operating profiles or weather conditions, the inline configuration maintains its operational flexibility and ease of use. Mixed configurations reach operational limits and restrictions sooner, thus forcing the crew to change engine settings; the question of when to use which engine with which fuel at which load arises more often. The inline configuration facilitates the operation of the plant, reduces the workload on the crew and thus provides additional vessel safety.

Configuration	Inline	Mixed	Mixed	Mixed
Plant	5 x 8L	3 x 12V + 1 x 6L	2 x 12V + 2 x 8L	2 x 12V + 2 x 6L
Cylinders	40	42	40	36
Largest engine out of service	8L	12L	12L	12L
Power drop	20%	29%	30%	33%

Fig. 16: Power drop of total plant power installed when largest engine is out of service

Conclusion

Full maintainability

Due to short harbour times – LNG vessels stay in the terminal usually less than a full day – most maintenance work on a DFDE system has to be done on board while at sea. Maintenance schedules require the regular shutdown of engines. Major maintenance intervals that involve opening the engine, pulling of cylinders, and internal reconditioning cause engine shutdowns which may last for several days.

The previous chapters demonstrated that the 5 x L type configuration allows the shutdown of any engine at any time while keeping the loads of the remaining engines within permissible limits. On the other hand, the mixed V/L-type configurations with four engines face restrictions. In fact, a vessel equipped with such a plant will experience a serious power drop, down to 67-70% of the installed engine power, if one of the large engines is out of service (see Fig.15). The analysis shows that the mixed configuration of a four-engine plant runs much sooner into operational limitations than the inline configuration with five equal (or similar) engines. In many cases, the vessel with a mixed configuration would not be able to maintain service speed. In other words, maintenance would have an impact on the vessel's schedule, and possibly on the contractual commitments of the owner towards the charterer.

As this is not the case with the inline configuration, vessels with such plants enjoy maximum maintainability.

Furthermore, the average maintenance time per inline engine is lower compared to V-type engines. Simplified maintenance – which reduces the workload on the crew – combined with shorter downtime – which increases the availability of the engine – are a useful addition to the overall safe and smooth operation of the vessel.

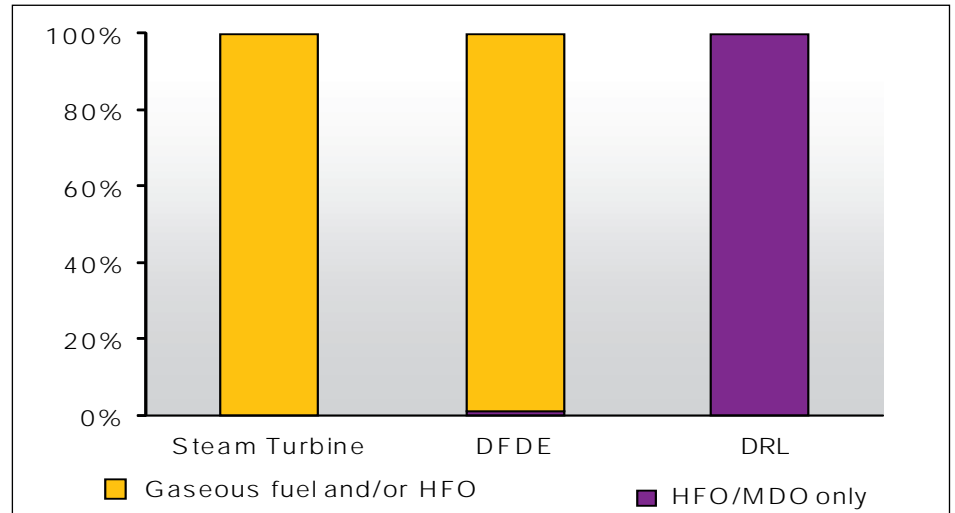


Fig. 17: Fuel flexibility potential of diesel propulsion concepts vs. steam turbine based on percent of consumed energy during a typical round trip (6,500 nm port-to-port distance)

Total fuel flexibility

The cost of fuel is by far the major component in an LNGC's operational expenditure. The development of fuel prices has become a matter of great uncertainty. Crude oil prices that nearly doubled during the course of 2007 make it difficult to forecast fuel pricing in the short term and perhaps impossible in the long term. Thus, the fuel flexibility of the vessel power plants becomes desirable if not a must for shipowners and charterers.

As every Dual Fuel engine can burn a range of fuels at different load levels, the Dual Fuel plant in total has the capability to burn any permutation of the liquid and gaseous fuels available. Moreover, fuel flexibility refers not only to fuel types (HFO, MDO or gas), but also to the varying quantities of liquid fuel and gas burnt at the same time. Hence, in terms of fuel flexibility, the Dual Fuel plant matches steam turbine systems (see Fig. 17), but at much higher efficiencies. This flexibility is considered to be one of the most convenient features of DFDE propulsion.

In fact, with a 5 x L-type configuration, total fuel flexibility can be maintained

even when one engine is out of service. This is an important advantage and a very distinctive feature compared to a mixed V/L-type configuration with four engines.

Fig. 17 shows the fuel flexibility potential of various propulsion systems. Obviously, the steam turbine (column 1) provides 100% fuel flexibility, as the boilers are insensitive to which fuel is fired and can cope with either liquid or gaseous fuels or mixtures thereof.

At the other end of the scale are vessels built according to the DRL concept (column 3), which comprises two-stroke diesel propulsion engines, gensets and reliquefaction plants. These vessels have no fuel flexibility, as they are designed to use liquid fuels only, which is HFO at present (column 3). Anticipated environmental regulations and requirements are likely to cause the refinery industry to change to higher quality products (reduction of sulphur content) and thus higher priced marine fuels.

The conversion of vessels with the DRL concept to Dual Fuel capability is under consideration. One solution could be the conversion of the HFO burning

propulsion engines into a two-stroke Dual Fuel version (ME-GI). A vessel with such engines would need to be equipped with auxiliary gensets for the generation of electric power. Additionally, two redundant compressors for the provision of high pressures of 250 to 300 bar for the injection of the gas into the cylinders would need to be installed. In maximum gas mode, two-stroke Dual Fuel engines require about five to eight percent liquid pilot fuel.

Summarising the above, it can be stated that a suitably configured DFDE system provides the LNGC operator with an extremely high level of fuel flexibility, matching that of the steam turbine without imposing restrictions on engine maintenance schedules.

Low energy consumption and emissions

Fig. 18 explains the recent trend away from the traditional steam turbine towards diesel propulsion systems for LNG carriers. While the major driver for the change has to be seen in the fuel economy of the diesel systems, an increasingly important by-product is a reduction in CO₂ emissions which are directly linked to the overall efficiency of the vessel's machinery. In terms of the vessel's total energy consumption, and thus its greenhouse gas emissions, there is a very substantial reduction from the 100 percent reference point for steam systems down to the 65 percent level of diesel-based systems. Recently, steam systems in enhanced versions have claimed a 10-15 percent improvement of efficiency. However, at the end of the day this improvement would bring them only to the 85 to 90 percent level seen in Fig. 18, which is still significantly above that of the diesel engine based systems.

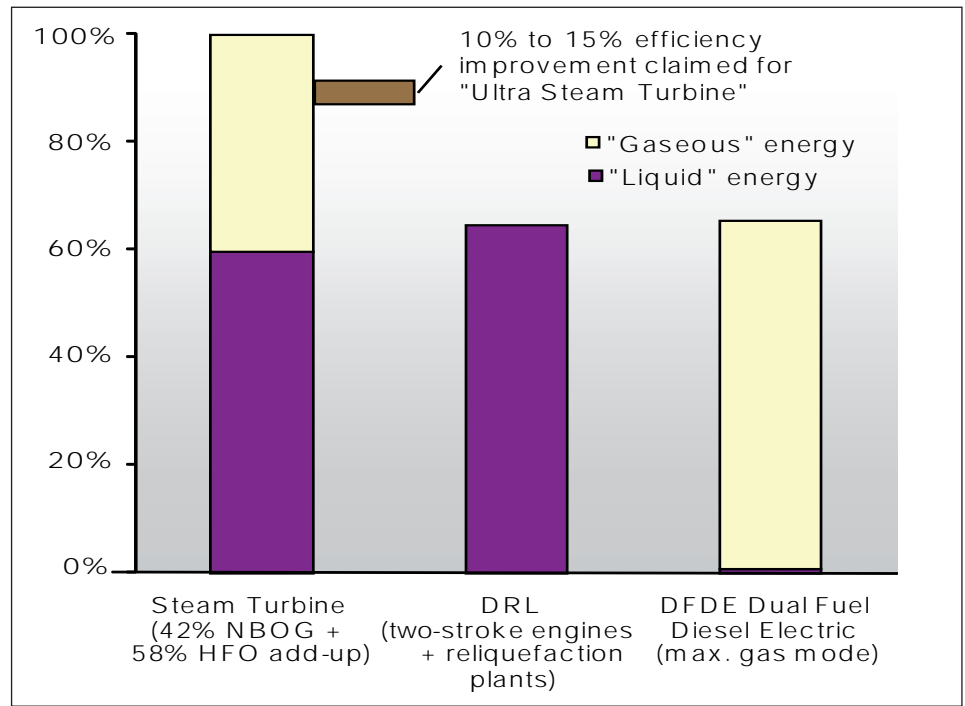


Fig. 18: Vessel's total energy consumption per round trip for various propulsion systems based on 200k class LNGCs of constant displacement, port-to-port distance 10,000 nm, service speed 19.5 kn, according to [3]

Aside from CO₂, SO₂ and NO_x, a major focus is also emission reduction. Fig. 19 compares vessel emissions for different propulsion concepts. The comparison looks not only at the main propulsion engines, but is based on the complete energy consumption of the vessel.

The peak values for CO₂ emissions are with the steam turbine system due to its low efficiency. DRL is certainly better than the steam system. However, it has the peak values for SO₂ and NO_x emissions. DFDE is unrivalled as the most environmentally friendly solution of all the LNGC propulsion concepts discussed today. In gas mode, DFDE requires only around one percent of liquid pilot fuel (MDO) to ignite a very lean and homogeneous air-gas mixture in the combustion chamber.

This makes DFDE the most environmentally friendly propulsion concept with the lowest emissions in terms of CO₂, NO_x, SO₂, particulates and smoke.

Due to environmental concerns, a range of emission fees are well established today. Examples are not only the restrictions in the United States, but also the SECA regulations in the Baltic Sea, and the NO_x fee introduced by Norway in 2007. It is expected that the future will see more emission fees and these will contribute significantly to the operational costs of vessels.

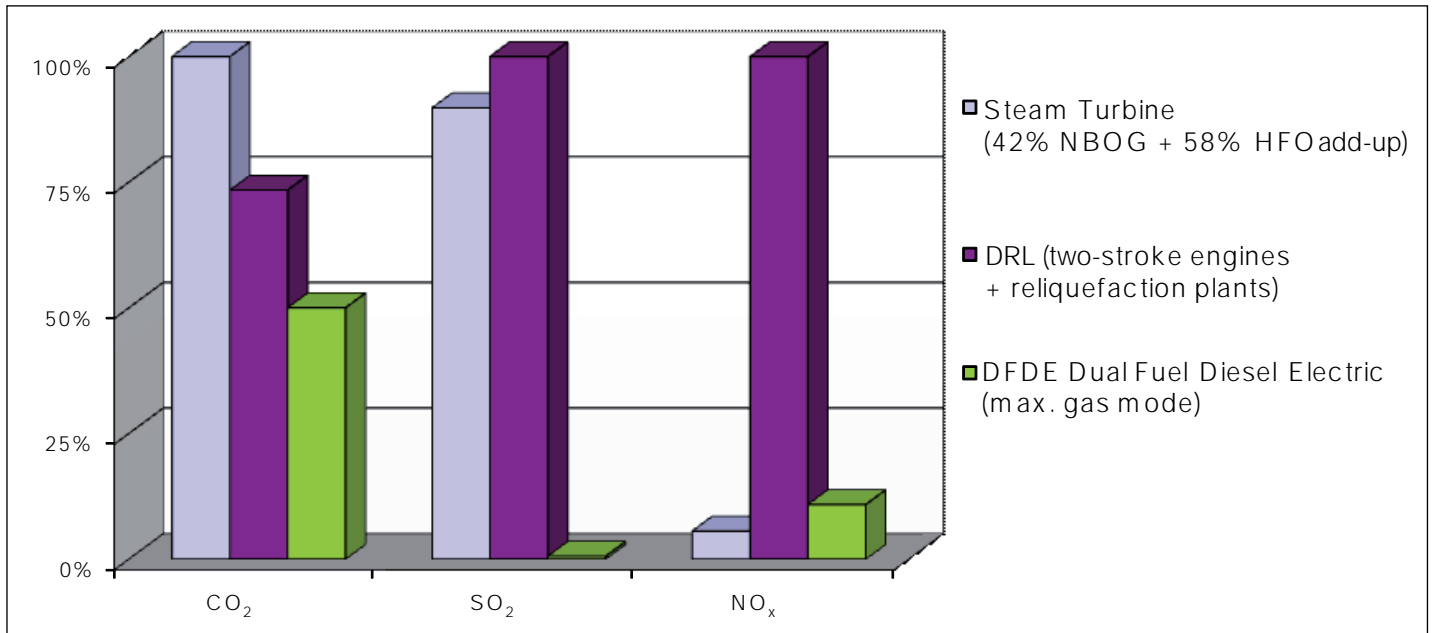


Fig. 19: Vessel emissions for various propulsion systems based on 200k class LNGCs of constant displacement, round trip with port-to-port distance of 10,000 nm, service speed 19.5 kn, according to [3]

Fig. 20 gives an indication of what this additional cost could be in the future. It is anticipated that CO₂ emissions fees will be payable in all waters around the globe, while SO₂ and NO_x fees may only be applicable in selected areas. The example assumes that only 20% of the vessel's voyage will be in restricted areas. It is clear that the columns would be much taller if all waters become restricted areas for SO₂ and NO_x. Being the "greenest" propulsion alternative for LNG carriers, the economic attractions of DFDE will be further extended, once emissions fees are introduced on a wider scale.

Even if emissions fees are only partially established at present, shipowners still have to design their LNGCs for decades of operation and thus already need to take these environmental aspects into consideration.

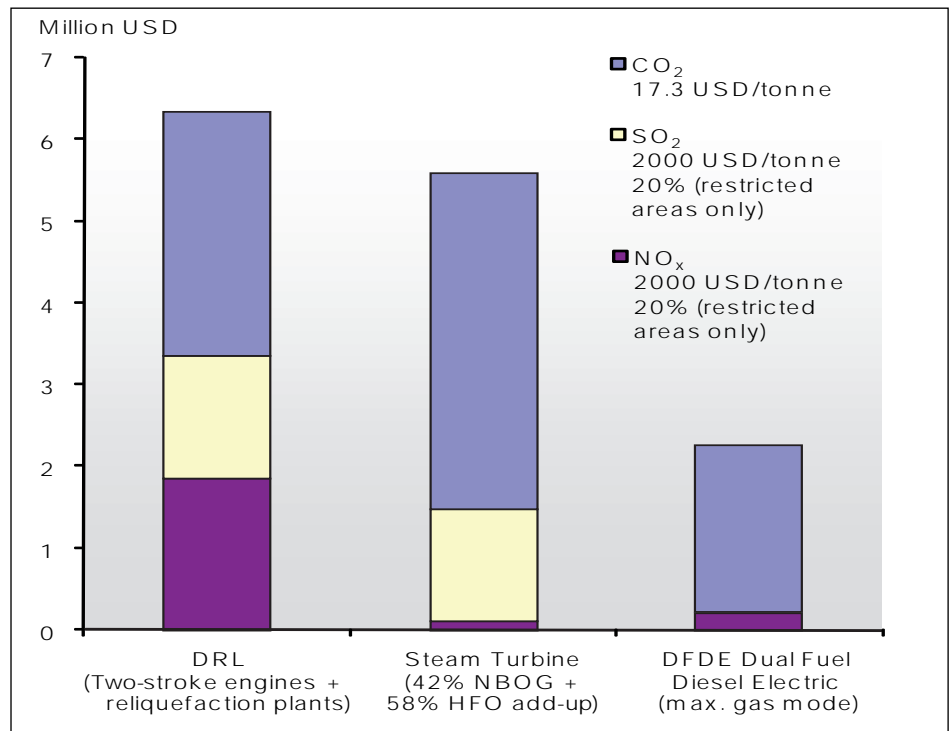


Fig. 20: Annual emission fees for various propulsion systems based on 200k LNGCs of constant displacement, round trip with port-to-port distance of 10,000 nm, service speed 19.5 kn according to [3]

Summary and Outlook

With a well-selected multi-engine configuration, the 51/60DF plant features fuel flexibility to an extent that matches the boilers of a steam turbine propulsion system without compromising the vessel's maintainability. Any engine can be serviced at any time without affecting the ship's sailing schedule and the level of the vessel's fuel flexibility.

Environmental aspects and considerations are becoming more prevalent, not only in the public's perception, but also in legislation. As a result, increasing or new emissions fees will add significantly to the operational costs of vessels, especially in the long term over the vessel's complete service life. Hence, it is a further benefit of the 51/60DF multi-engine plant that it represents the most environmentally friendly propulsion system available today. Moreover, the authors are also convinced that diesel-gas propulsion will not only acquire a leading role in the LNG carrier business, but will also become a major factor in other shipping segments as well.

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Abbreviations

BN	Base Number	LNGC	LNG Carrier
CNG	Compressed Natural Gas	MDO	Marine Diesel Oil
CO ₂	Carbon Dioxide	nm	Nautical Mile
DF	Dual Fuel	MW	Mega Watt
DFDE	Dual Fuel Diesel Electric	NBOG	Natural Boil-Off Gas
DRL	Diesel (low speed) and Reliquefaction	NO _x	Nitrogen Oxides
FBOG	Forced Boil-Off Gas	SECA	Sulphur Emission Controlled Area
HFO	Heavy Fuel Oil	SO ₂	Sulphur Dioxide
LNG	Liquefied Natural Gas	ST	Steam Turbine

