ENERGY USE ONBOARD LNG DFDE SHIPS

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ABSTRACT

Dual Fuel Diesel Electric (DFDE) is becoming the choice propulsion system for LNG carriers. At the time the first DFDE vessels came into service in 2008, the LNG carrier fleet predominantly employed steam turbine propulsion with a few vessels employing diesel direct drive propulsion. Today DFDE propulsion is employed in around 20% of LNG carriers whilst around 80% of carriers on order have chosen DFDE. This paper aims to address three important issues: (a) to review the energy usage of current DFDE LNG carriers over a 12 month period and compare their performance with steam propulsion; (b) undertake an in-depth analysis of a modern DFDE LNG carriers during sea trials and relate the findings with actual vessel operations, and (c) analyse the relationship between efficiency and emissions that is peculiar to DFDE LNG carriers so as to identify the areas for improvement such as considering regulation amendments that would improve reductions in atmospheric emissions. The analysis in this paper has shown that in terms of operational efficiency, calculated using the Energy Efficiency Operational Indicator (EEOI), the performance of DFDE propulsion is on average 45% better than steam propulsion when using the periods and voyages analysed. However, when methane slip is considered then the DFDE configuration actually performs worse than steam propulsion with its detrimental impact depending upon the lifetime of atmospheric methane i.e. 20 or 100 years. Furthermore, it has also been found that the operational profile and regulatory requirements for DFDE LNG carriers are predominantly based upon the use of natural gas whereas the performance evaluation of new DFDE vessels is being carried out when using HFO. This discrepancy does not provide confidence in providing a reliable benchmark for the future performance evaluation of LNG carriers. The paper concludes with recommendation that methane slip should also be considered when establishing the impact of ship emissions and that for DFDE LNG carriers there should be an updating of sea trial procedures.

Keywords: *DFDE, LNG, EEOI, EEDI, Methane Slip, Efficiency, Ship Emissions.*

Abbreviation	Definition
BOG	Boil off Gas
CO_2	Carbon dioxide
DFDE	Dual Fuel Diesel Electric
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
FSRU	Floating Storage and Regasification Unit
GCU	Gas Combustion Unit
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
HHI	Hyundai Heavy Industries
IMO	International Maritime Organisation
ISO	International Standards Organisation
MDO	Marine Diesel Oil
OPL	Off-Port Limits
SFC	Specific Fuel Consumption

1. INTRODUCTION

Natural gas (NG) is the cleanest fossil fuel, it is relatively cheap and available in abundance and for these reasons the use of natural gas as a primary energy source has been gathering momentum over recent decades. NG is transported in ships in its liquefied form in specially designed liquefied natural gas carriers (LNGCs) to markets where the LNG is re-gasified before distribution into grids, etc. The use of LNGCs is a cost effective way of transporting large quantities of NG over long distances where pipelines do not exist. In 2014, there were 335 of these vessels types in service [1] utilising three different propulsion systems, with the predominant type being steam-turbine propulsion. However steam-propulsion is slowly being replaced with dual fuel-diesel electric propulsion and to a lesser extent the direct drive diesel-propulsion systems.

Boil off gas (BOG) is generated during transportation of LNG and it is the need to utilize this BOG that has determined LNGC propulsion system design. Initially, steam boilers were the most cost effective method of burning BOG as they could accommodate both the burning of NG as well as fuel oil, although in practise early tank insulation was such that the BOG generated during voyages was sufficient to provide 100% of the fuel requirement [2]. Modern tank design has benefited from a paradigm shift in materials technology leading to more efficient insulation technologies meaning a significantly lower BOG rate. The operator now has the choice on whether to supplement the BOG with forced boil off gas (FBOG) or fuel oil. This, together with the fact that a steam plant has a lower efficiency than a diesel-engine, has led to the development of gas burning diesel engines, known as dual fuel engines, for LNGCs.

The dual fuel diesel electric propulsion (DFDE) system features modified diesel engines that have been designed to burn BOG or fuel oil to drive a generator. The design employs multiple diesel generators, typically four are needed, to provide all the vessel's power requirements (service and propulsion), a system termed the "power station principle" [2]. The diesel engine operates using BOG and a small quantity of pilot fuel oil for ignition or else it can operate on fuel oil alone. It cannot burn the two main fuel types at once i.e. various proportions of the gas and liquid fuel cannot be burnt. The provision of multiple diesel generator sets provides redundancy and protection against total loss of power. The handling of BOG in instances where the main propulsion system is not in use e.g. at anchor or drifting, necessitates the use of a gas combustion unit (GCU). Figure 1 shows a typical DFDE configuration.

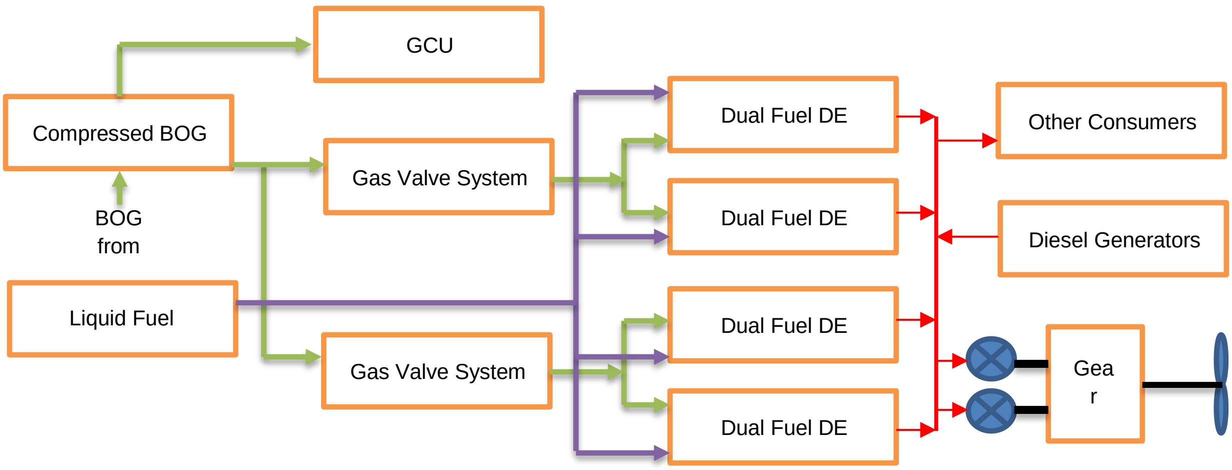


Figure 1: Schematic of a DFDE configuration. Source: [3]

A majority of the LNGC industry are turning towards DFDE as the preferred propulsion system to replace steam propulsion. This is seen when analysing the data from Clarkson's World Fleet register, where it is apparent that steam propulsion was installed on all new LNGCs from the 1960s to the 1990s. By the 2000s the proportion of new LNGs with steam had dropped to 69% while today it has fallen to 21% with the future order book indicating that this will fall to12%. Conversely, DFDE LNG carriers first came into service in 2008 and now make up 20% of the current LNGC fleet, while for LNGCs on order, the figure stands at 79% [1].

This paper aims to consider three important aspects: (a) Review the current energy usage of current DFDE LNGCs over a 12 month period and compare their performance with steam LNGCs by way of a case study (b) Perform an in-depth analysis of a modern DFDE LNGC during sea trials to evaluate performance and relate performance to likely vessel operations (c) Analyse the relationship between efficiency and atmospheric emissions when considering the regulatory framework so as to suggest potential improvements. It is expected that the results obtained from this study would contribute to the understanding of how DFDE vessels operate, and also identify options that may be available to improve energy and to reduce their impact on the environment.

2. RESEARCH APPROACH

A qualitative research method involving the use of case studies is employed. This method is chosen because it provides an in-depth understanding of the DFDE technology during specific operational periods ensuring genuine experiences are captured. The focus is on individual cases and not the larger population, to seek an in-depth holistic understanding of DFDE propulsion technology [4]. The data collection and analysis process is neither linear nor straightforward but is iterative as the data is collected and analysed simultaneously.

Case Study A: Involves the analysis of an existing DFDE vessel currently in service. It analyses the energy flows and usage during different modes of operations including ballast, laden, port (loading and discharging), off port limit operations (OPL), vessel manoeuvring, and maintenance. The analysis covers a 12 month period and includes voyages from Africa to Europe, Asia and South America. This analysis has ascertained how energy is used, and how the vessel's operational profile impacts upon energy distribution.

Case Study B: Involves the performance analysis of a newly constructed DFDE LNG carrier during sea trials to determine ship performance in terms of speed, power and propeller revolutions, under specifically prescribed conditions, to verify the satisfactory attainment of the contractually stipulated speed [5]. The data from the sea trial becomes the standard/benchmark within which the performance of the ship is evaluated during her lifetime, and is used to provide guidance on planning future voyages, dockings, hull scrubs, etc. [6].

The results from the two case studies provides an opportunity to improve understanding of how the design operational conditions vary from actual operational conditions and also how this disparity affects how DFDE LNGC efficiency is analysed over her lifetime.

3. CASE STUDY A

DFDE vessels in service have a similar power and propulsion system design topology and operational arrangements. They all utilise multiple diesel-generator set configurations and can use a choice of primary fuels MGO, HFO or BOG (with MGO pilot fuel). Additionally they are fitted with an auxiliary boiler to produce low-pressure steam for auxiliary needs. Principal characteristics of the DFDE LNG carrier case study is summarised in the Table 1:

Table 1: Case Study A: Vessel Principal Characteristics

Characteristics	Value	Comments
1. Ship Principal Characteristics		
Characteristics	**Value**	**Comments**
Ship Type	LNG Carrier	
Date of Delivery	2010	
Summer Draught	12.32 m	
Draught, Ballast	9.78 m (Normal & Heavy Weather)	
Cargo Tank Capacity	173,400 m^3	At 100%
Deadweight, Summer Draught	79,541 t	
Displacement, Summer Draught	113,567 t	
Service Speed	20.4 knots	@ Design Draught 11.95 m
2. Propulsion System		
Descriptive Notes: Electric Propulsion Driver Via Gearbox		
Make and Model	Converteam N3HXC 1120LL	
Output	32,400 kW	Shaft: 16,000KW x 83.3rpm each Motor: 16,500KW x 610 rpm each
Specific Fuel Consumption at rated power	191 g/kWh (MGO) 7410 kJ/kWh (Gas)	
Propeller (2 sets)	5 Bladed 8.6m diameter	Fixed Pitch
3. Generators		
Diesel Generators:		
Engine Make and Model	Wartsila 12V50DF x 3 Wartsila 9L46 x 1	
Generator	11400 kW at 514rpm 10395 kW at 514rpm	
Fuel	Methane/HFO/MGO	
4. Auxiliary boiler		
Make and Model	Kangrim PA0403P38	
Rating	6500 kg/h at 7 Bar saturated steam	Max pressure 10 bar
Rated Fuel Consumption	491 kg/h	
Fuel	HFO/MGO	

The Energy Efficiency Operational Indicator (EEOI) is used in this paper to analyse vessel efficiency. The EEOI provides a representative value of the ship's efficiency over a given period or voyage and can be used to investigate trading patterns of the vessel. The EEOI describes transport efficiency expressed in CO_2 emitted per unit of cargo and nautical mile for a specified voyage. The formula is expressed below [7]:

$$EEOI = \frac{Fuel\ Consumption\ \times Carbon\ Factor}{Mass\ of\ Cargo\ \times Distance\ Covered}$$

The trading period of the DFDE LNG carriers investigated in this paper is between 16 May 2012 and 26 May 2013 during which time the vessel delivered ten cargoes, all originating from Nigeria. Three of these cargoes were delivered to France, two cargoes were delivered to Brazil, Korea and Portugal and one cargo was delivered to Japan. The calculated EEOI for these voyages are shown in Table 2; all input values for the calculation were obtained from on-board vessel's records. These routes are typical trading routes for vessels loading LNG from Nigeria with the vessels operating at service speed for the majority of the time.

Table 2: Calculated EEOI for case DFDE Vessel

Voyage	Distance (nm)	LNG Delivered(m^3)	LSDO Consumed(t)	LNG Consumed(t)	HFO Consumed(t)	EEOI (CO_2/t.nm)
1- NG-FRA	7,960	140,683	18	2,666	44	29.7
2- NG-SKR	19,050	146,480	33.7	5314	103.3	23.9
3- NG-SKR	19,050	145,579	49.8	5100	61.2	23.0
4- NG-PGL	7,306	163,959	18.3	1635	21.1	17.0
5- NG-FRA	7,960	161,999	32.3	2173	30.7	21.2
6- NG-FRA	7,960	161,947	29.7	2233	22.7	21.6
7- NG-JPN	25,260	153,939	64	6425	50.8	20.5
8- NG-PGL	7,306	162,612	24	1833	20.8	19.3
9- NG-BRA	6,784	160,734	32.7	2992	16.6	34.0
10- NG-BRA	6,784	159,323	34.3	3408	40.7	39.3

The figures obtained for DFDE LNG carriers can be compared against steam LNG carriers which also traded over this period (the trading period actually covered is between 19 June 2012 and 26 May 2013). These vessels delivered six cargoes again all originating from Nigeria. Two cargoes each were delivered to Japan and Korea and one each to Spain and India. The results of the EEOI for these voyages are shown in the table 3; again all data was obtained from on-board vessel's records [8].

Table 3: Calculated EEOI for comparative steam vessel. Source: [8]

Voyage	Distance (nm)	LNG Delivered(t)	LSDO Consumed(t)	LNG Consumed(t)	HFO Consumed(t)	EEOI (CO_2/t.nm)
1- NG-JPN	22,559.3	129,683	12	4,694	2,676	32.37
2- NG-IND	16,242.8	128,887	33	4,649	637	31.74
3- NG-SPA	7,179.5	134,445	39.2	2,039	247	29.65
4- NG-JPN	22,406.1	128,848	4	4,861	2,505	32.65
5- NG-SKR	22,289.7	128,596	14	5,261	2,438	34.35
6- NG-SKR	22,249.6	128,480	7	5,304	2,568	35.26

4. CASE STUDY B

The speed trials of a new LNG carrier are carried out to settle the relationship between the vessel's speed and the different loading conditions with fuel consumption also being recorded. The speed test is carried out at power settings of 30%, 50%, 75% 90% and 100% with a minimum of two runs, one run with the ship heading in one direction and the second run with the vessel heading in the opposite direction. The ship speed is measured three times at one mile intervals across a minimum of eight minutes per run are recorded and the average of the three values per run. In accordance with ISO 15016, [9] some corrections for wind, wave and swell from acceptable sea trial conditions are applied if required. For a new LNG DFDE carrier specified in Table 4, the following were recorded [10]: 1) Sea-state and depth 2) Atmospheric pressure and temperature 3) Time of test and course 4) Relative wind direction and velocity 5) Wave height and relative direction 6) Swell height, relative direction 7) Mean rudder angle movement 8) Mean drift angle 9) Ship's speed, power and shaft rpm 10) Fuel consumption. The results are given Table 5.

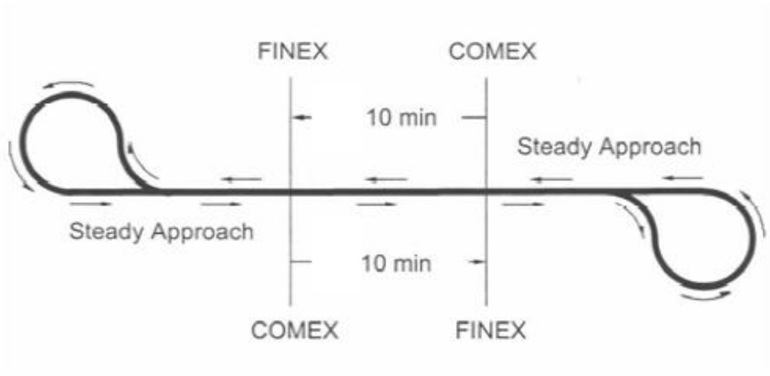
Table 4: Case Study B- Vessel Principal Characteristics.

1. Ship Principal Characteristics		
Characteristics	**Value**	**Comments**
Ship Type	LNG Carrier	
Date of Delivery	2015	
Summer Draught	11.65 m	
Draught, Ballast	9.78 m (Normal & Heavy Weather)	
Cargo Tank Capacity	175,000 m^3	At 100%
Deadweight, Summer Draught	87,000 t	
Displacement, Summer Draught	113,567 t	
Service Speed	19.75 knots	Design Draught 11.65 m
2. Propulsion System		
Descriptive Notes: Electric Propulsion Driver Via Gearbox		
Make and Model	Converteam N3HXC 1120LL	
Output	24000 kW x 77.8 rpm	
Specific Fuel Consumption at rated power	189 g/kWh	To be determined during sea trials
Propeller (2 sets)	4 Bladed 8.2 m / 8.37 m	Fixed Pitch
3. Generators		
Diesel Generators:		
Engine Make and Model	Wartsila 8L50DF x 5	
Generator	78000 kW at 514 rpm	
Fuel	Methane/HFO/MGO	
4. Auxiliary boiler		
Make and Model	Kangrim PA0403P38	
Rating	5000 kg/h at 10Bar saturated steam	Max pressure 10 bar
Rated Fuel Consumption	491 kg/h	
Fuel	HFO/MGO	

Table 5: Case Study B- Speed Trial results.

Principal Diamensions LBP x Bmld x Dmld : 280 m x 47.8 m x 26.2 m					
Place			Off Goeje Island		
Beaufort Number			4		
Anemometer Position (Above W.L)					
Projected Area (m^2)		Long	6368.1		
		Trans	1637.6		
Distance From Shore			14 NM		
Ship Conditn.	Max. Ballast	Sea and Weather			
Draft Ext. (m)	dF	9.60 m	Weather		Fine
	dM	9.50 m	Sea Water	Temperature	25^{o}C
	dA	9.60 m		S. Gravity	1.020
	dcorr	9.52 m	Atmosphere	Temperature	24.2^{o}C
Trim by stern	0.0 m			Pressure	1020 mbar
Displacement	97636.2 MT		Sea Depth		125 m

Path of Ship during Double Run



Load	Run	Dir (deg)	Time	Dur. (NM)	Speed	RPM (Port)	KW (Port)	RPM (stbd)	KW (stbd)	Rudd. Angle	Drift Angle	Rel. Wind		Wave		Swell		Fuel Flow	SFC (Test)	SFC (ISO)
												Dir.()	m/s	Dir.	H.(m)	Dir.	H.(m)			
30%		200	00:00	3	11.75	50.5	3669	50.4	3991	0.4	1.4	P62	21.24	S180	1.0	P150	0.3	4826	219	204
50%	1	20	03:45	3	15.49	58.7	6303	58.7	6141	0.25	2.0	P18	14.55	P135	0.8	S165	0.4			
	2	200	07:25	3	14.61	58.8	6064	60.0	6423	0.20	1.4	P129	1.99	S180	0.6	P170	0.4			
	Mean				15.05	58.8	6184	59.4	6282									6865	207	197
75%	1	20	10:25	3	17.54	68.3	9696	68.4	9393	0.7	2.0	S17	22.20	S25	2.5	S10	0.3			
	2	200	13:45	3	18.05	69.4	9465	69.4	8922	0.4	0.5	P68	2.12	S180	2.0	P170	0.4			
	Mean				17.79	69.9	9431	68.9	9158									9341	203	189
90%	1	20	20:40	3	20.33	73.6	11423	73.6	11181	0.9	0.9	S20	19.50	S5.1	1.5	P9.9	0.4			
	2	200	23:05	3	18.78	73.6	10877	73.6	10539	0.4	0.3	P38	8.14	P175	1.5	S180	0.4			
	Mean				19.56	73.6	11150	73.6	10860									10644	202	189
100 %	1	20	06:00	3	21.05	76.0	12346	76.3	12193	0.7	0.1	S16	22.60	P0.2	1.5	P165	0.4			
	2	200	11:15	3	20.75	77.2	12266	77.1	11953	0.5	0.3	P25	4.27	P175	1.0	S14.8	0.4			
	3	200	18:15	3	20.11	77.8	12550	78.1	12345	0.7	1	P28	11.18	P175	1.0	S170	0.4			
	4	20	22:10	3	20.88	76.3	12523	76.4	12245	0.7	1	S19	24.02	S10.0	1.0	P5.0	0.4			
	Mean				20.69	76.8	12421	77.0	12184									12246	202	189

5. ANALYSIS OF RESULTS

5.1 CASE STUDY A

Of the 10 voyages analysed, it can be seen that those with the lowest EEOI are the voyages to Portugal which have EEOI's of 17 gCO_2/ton.NM and 19.3 gCO_2/ton.NM respectively. The voyage to Japan was next best with a calculated EEOI of 20.5 gCO_2/ton.NM followed by two of the voyages to France having values of 21.2gCO_2/ton.NM and 21.6gCO_2/ton.NM. The two Korean Voyages have similar EEOI values of 23.0 gCO_2/ton.NM and 23.9 gCO_2/ton.NM whilst another voyage to France has a higher EEOI value of 29.7 gCO_2/ton.NM but the two voyages with the highest EEOI's are those to Brazil with index values of 34 gCO_2/ton.NM and 39.3 gCO_2/ton.NM respectively.

It is important to note is that whilst the voyages to Brazil are the shortest in terms of distance travelled, they had the most inefficient voyages. On closer analysis, it was seen that the source of these inefficiencies was due to the relatively high amount of LNG utilized during the voyage. These high values are due to the peculiarities of the discharge operations that were undertaken in Brazil as the discharge terminal is a Floating Storage and re-gasification unit (FSRU), and quite large amounts of natural gas are consumed during discharge operations for tank stabilisation needs. Another issue of note is the disparity between the voyages to France, with one of the voyages being considerably (40%) higher than the other two when the EEODI's values are considered. This disparity was traced to the fact that on the one voyage, the full cargo capacity of the vessel was not utilized with vessel only delivering 140,683m^3 of LNG compared to the 161,999m^3 and 161,947m^3 delivered on the other two voyages respectively.

When the values obtained are compared with values obtained by a steam LNG carrier operating the similar routes, it is seen that the figures for the DFDE vessel is generally better. When the voyages to Japan are analysed, the EEOI of the steam vessel is 32.5 gCO_2/ton.NM which is 61% higher than the EEOI for the DFDE vessel. For the voyages to Korea the EEOI of the steam vessel is 31.9 gCO_2/ton.NM which is 36% higher than a similar voyage to Korea by the DFDE LNG carrier. The voyages to Europe also have a similar trend with the average EEOI of the steam vessel being 29.65gCO_2/ton.NM which is still 64% higher the similar voyage to Europe by the DFDE vessels. The EEOI's values for voyages to Brazil are comparatively high for the DFDE vessels and comparable to steam vessels but as mentioned earlier this is due to the fact that they discharge to FSRUs. Overall though when comparing the EEOI values of the DFDE vessels with those of the steam vessels, then the DFDE offers on average a 45% improvement in efficiency.

5.1 (a) The impact of Methane Slip

The DFDE vessels despite having a better average EEOI than the steam vessels system suffer one major disadvantage: Methane slip. This term refers to unburned methane emitted into the exhaust ports of the diesel engine and hence into the atmosphere. As methane is a highly potent greenhouse gas, it potentially counters gains in reducing CO_2 emissions through improved efficiency [11]. The effect is of concern because methane has 20-25 times the global warming potential of CO_2 over a 100 year cycle, while over a 20 year interval the effect is 72 times [12]. Therefore, when calculating the effect of emissions from LNGCs on global warming then methane slip ought to be considered in addition to the CO_2 emissions.

The lowest level of methane slip for the Wartsila 50DF engine fitted on many DFDE vessels (including the vessels considered here) is 8 g/kWh [13]. Given that the average SFC_{ME} of these engines is 175 g/kWh, the following calculations can be used to determine the CO_2 equivalent emissions of methane slip:

$$Methane\ Slip = 8\ g/kWh$$

$$SFC_{\boldsymbol{ME}} = 175\ g/kWh$$

$$Methane\ equivalent\ of\ SFC_{ME} = \frac{8}{175} = 4.57\%$$

Assuming 1 Tonne of methane gas is burnt in the DFDE engines;

$$1\ Tonne\ of\ CH_{4\ gas}\ fuel\ burnt\ in\ DFDE\ Engines = 2.75\ Tonnes\ of\ CO_2\ emitted$$

Using a 4.57% by volume of methane slip;

$$1\ Tonne\ of\ CH_4\ gas\ fuel = 2.624tCO_2 + 0.0457tCH_4$$

Based on the 100 year life cycle of methane, the GWP is 21 times that of CO_2, then;

$$Total\ CO_{2equiv} = 2.624 + (0.0457 \times 21) = 3.5837tCO_{2equiv}$$

Based on the 20 year life cycle of methane, the GWP is 72 times that of CO_2, then;

$$Total\ CO_{2equiv} = 2.624 + (0.0457 \times 72) = 5.9144tCO_{2equiv}$$

Therefore, accounting for CO_2 and Methane Slip; one tonne of NG is equivalent to 3.5837t CO_2 using the 100 year NG life cycle and 5.9144t CO_2 using the 20 year life cycle. Using these figures then it is possible to recalculate the EEOI values for the DFDE vessels in Table 2 to include the impact of methane slip as summarised in Table 6.

Table 6: Recalculated EEOI for case DFDE Vessel taking into account methane slip

Voyage	Distance (nm)	LNG Consumed(t)	HFO Consumed(t)	EEOI (CO_2/t.nm)	EEOI-100Yr (CO_{2eq}/t.nm)	EEOI- 25Yr (CO_{2eq}/t.nm)
1- NG-FRA	7,960	2,666	44	29.7	38.5	63.0
2- NG-SKR	19,050	5314	103.3	23.9	31.0	50.7
3- NG-SKR	19,050	5100	61.2	23.0	29.8	48.9
4- NG-PGL	7,306	1635	21.1	17.0	22.1	36.1
5- NG-FRA	7,960	2173	30.7	21.2	27.4	44.7
6- NG-FRA	7,960	2233	22.7	21.6	28.0	45.9
7- NG-JPN	25,260	6425	50.8	20.5	26.6	43.6
8- NG-PGL	7,306	1833	20.8	19.3	24.9	40.9
9- NG-BRA	6,784	2992	16.6	34.0	44.1	72.4
10- NG-BRA	6,784	3408	40.7	39.3	50.9	83.4

When methane slip is taken into account, it is seen that the DFDE vessel is not so attractive because:

- When considering the voyage to Japan, the EEOI is 38.5 gCO_2/ton.NM when considering a 100 year life cycle of methane. This value is 9.2% higher than the EEOI value of the steam vessel on a similar voyage. If the 25 year lifecycle of methane considered then the EEOI for the DFDE LNG carrier is doubled over that of the steam LNG carrier.
- For the voyages to Korea, when the 100 year methane cycle is considered the index values for both the DFDE and steam LNG carriers are similar but when the 25 year life cycle is considered then the EEOI value for the DFDE is 58% greater. A similar result is seen with the

voyages to Europe however when the 25 year life cycle is considered, then the EEOI value is 27% more.

Therefore, when methane slip is considered as part of the EEOI calculations which are designed to aid reductions in atmospheric gasses that contribute to global warming then the performance of the DFDE is generally worse than the steam counterpart, regardless of the voyage being analysed. However general opinion is otherwise since methane slip is not accounted for. This clearly highlights the need for methane slip to be regulated if the overall goal of IMO is to reduce the impact of anthropogenic shipping emissions on global warming.

5.2 CASE STUDY B

The key points from the trials are summarized in the table below:

Table 7: Case study B results summary

Engine Load	Speed (knots)	Shaft Power (kW)	SFC (g/kWh)
30%	11.75	7660	204
50%	15.05	12466	197
75%	17.79	15589	189
90%	19.56	22010	189
100%	20.69	24605	189

It is important to note that the correlation between the figures obtained from the sea trials and the actual operating conditions obtained from case study vessel described in Table 5. From the figures it is also seen that the vessels in service only spend less than 5% of using HFO. In fact the only times the vessel used HFO were periods when the vessel was in port or undergoing maintenance. The normal operating condition of the vessel is primarily utilising the BOG as the main fuel with the HFO or MGO as back up. Bearing in mind that the sea trial results become a benchmark from which the performance of the vessel would be evaluated during her lifetime and data from the case study vessel and other DFDE vessels have shown that over 90% of the time the vessels are continually utilising NG as fuel, it therefore follows that the results from sea trials when the fuel being used is HFO is not sufficient in providing an accurate benchmark needed for evaluating future vessel performance.

As a further point then when calculating the Energy Efficiency Design Index (EEDI), which is now mandatory for LNGCs as of September 2015, should be calculated from the sea trials using figures obtained while using BOG as fuel as opposed to the current practice of using HFO as fuel. Research has shown that it usual practice to use HFO during sea trials where the operating parameters are evaluated and gas burning is not used.

It is also worthy of note that since load conditions are not steady over the given period of sea trials, the measurements can be inaccurate when considering other sea conditions. Shipbuilders therefore guarantee fuel consumption for the engines on the basis of the measurement taken at shop trials only with the data obtained from sea trials used for verification of the shop trials results. The focus of shop trials like sea trails is also based on the use of HFO/MGO and again is not representative to current industry operational practice.

6. CONCLUSIONS AND RECOMMENDATIONS

A case vessel was analysed over a 12 month period including voyages from Africa to Europe, Asia and South America. The results were then compared to a similar steam vessel which was analysed within a similar period. The results indicated that in terms of EEOI, the case DFDE vessel performed an average of 45% better than the steam vessel over the periods and voyages analysed. However, when methane slip was analysed because of its detrimental impact as an exhaust gas, the results were significantly different. Based the 100Yr life cycle of methane, the DFDE vessel performed an average of 9% worse than the case steam vessel, while based on the 25Yr life cycle of methane; the DFDE vessel performed 40% worse than the steam vessel. The results show the impact of methane emissions on the performance in terms of CO_2 equivalents and the significant impact this can have on the emissions performance of the vessel. Also seen during this analysis was the effect of not loading to full capacity as it was seen that one voyage where the vessel loaded to 88% capacity had a 43% higher index figure when compared to a similar voyage where the vessel loaded to full capacity. Reduced transport efficiency when discharging to FSRUs as opposed to terminals was also recorded.

The second case study involved the analysis of a newly constructed DFDE vessel during design sea trials stage from whence results would become the standard/benchmark within which the performance of the ship is evaluated during her lifetime, and this is a good guidance in planning the future voyage requirement. However it was seen that the sea trials were dissimilar and unrelated to the actual operating conditions of the DFDEs as the sea trials were conducted with HFO as fuel and the initial values and conditions were based on this fuel, while in actual operating conditions, the fuel used is Natural Gas and the properties and performance based on this fuel is different from that based on HFO. Also, the EEDI for LNG carriers which has been introduced by the IMO as at September 2015 is based on BOG as fuel, and this is the standard used by the IMO from which new vessels being delivered are evaluated. However, new vessels being built are having their EEDI being evaluated based on using HFO as fuel, and from the case study analysed as well as well as further industry research as shown that the vessel is rarely on HFO thus a benchmark based on HFO is inadequate.

From the above studies there are two key important items to note. First, is the relevance of methane slip in estimating indexes related to emissions, as quite easily the DFDE vessel went from being less polluting to being as much as 40% worse. It is therefore proposed that methane slip be included in the EEDI/EEOI calculation procedures in order to capture the reality in accurate detail. Secondly, the scheme of sea trials for new DFDE vessels would need to be updated to capture the operating profile of DFDE vessels as well as the current EEDI requirements of new vessels. The proposal would be that the sea trials be conducted using natural gas as fuel, so that the results obtained would be a more effective and realistic benchmark for evaluating performance during vessel lifetime.

For further study, the compiled dataset can actually be used to determine the actual differences between sea trial and actual operating conditions in terms of energy usage. A similar study was carried out on steam LNG vessels and it was seen that in actual operating conditions the vessel consumed between 22% and 29% extra fuel than sea trial conditions. It would be insightful if a similar study could be carried out on the DFDE vessels as this will highlight the extra energy usage, identify the sources of this extra usage and offer opportunities for reduction of energy use and consequently reduce emissions.

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