Delft University of Technology

FUNDAMENTALS OF MARINE ENGINEERING

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Assignment:
Retrofit of a shipboard power plant

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1 Vessel choice

In 2003 the United States Navy started the Littoral Combat Ship (LCS) program. The LCS program consists of two ship classes, the Freedom Class and the Independence Class, the latter is the object of this document. It is a particular ship, build completely in aluminium and was developed by the Australian shipyard Austal. The first ship was delivered to the US Navy in 2009, since then a total of 19 ships of this class have been ordered. The Independence class can be reconfigured for a number of different missions such as anti-submarine warfare, mine countermeasures and surface warfare. It can complete these missions by itself or work together with other ships, for example in a carrier strike group. The requirements from the US Navy to Austal where a ship capable of reaching really high speed, sufficient range to cross the Atlantic Ocean and a low draft to be able to complete missions close to shore in shallow waters.

Figure 1: Picture of the LCS-2 in port (TorinoGT, 2002)

The trimaran design presents numerous advantages such as a low draft and a good resistance especially at higher speeds such as the ones required by the Navy. The one ship that this paper focuses on is the USS Independence, also called LCS-2, which is the first ship of it's class (LCS-1 being the first ship of the Freedom class).

USS Independence (LCS-2)	
Length [m]	128,4
Beam [m]	31,6
Draft [m]	4,27
Displacement [t]	3200
Speed [kn]	44
Range at 18kn [nm]	4300
Complement	up to 78 crew

Figure 2:
General data of the USS Independence

Onboard of the USS Independence we find a highly interesting power plant which will be analysed and exchanged with a power plant which will be running with liquefied natural gas (LNG). The goal of this paper is to present an alternative and more environmental friendly design while maintaining the main purpose of the ship.

2 Propulsion power

Before starting to make any changes to the power plant it is crucial to have enough information about the current power in order to take educated decisions. To gain further knowledge about the installed power the non-dimensional delivered power coefficient needs to be calculated. In order to do this it is needed to know or estimate the installed engines. From (*USS Independence (LCS-2)*, 2022) it is acquired that the installed engines are two GE2500+ gas turbines and two MTU 20V 8000 M91 diesel engines able to deliver 30200 kW and 9100 kW per engine respectively. The diesel generators on board are four MTU 8V 396 TE74L with a break power of 1 MW per generator. The generators are a vital part of the power plant and must supply sufficient energy to the various auxiliary systems, hotel systems, the bow thruster but also the armament and surveillance systems.

The engines onboard a ship are only rarely used at their maximum power capacity to increase their longevity and reduce maintenance. Because of the fact that the vessel is a naval vessel reliability is very important and therefore an engine margin of 15% is estimated.

Knowing the break power it is now needed to get the transmission efficiency (η_{TRM}).
The ship has a CODOG drive and uses a gearbox in order to reduce the turning speeds of the propellers inside the waterjets.

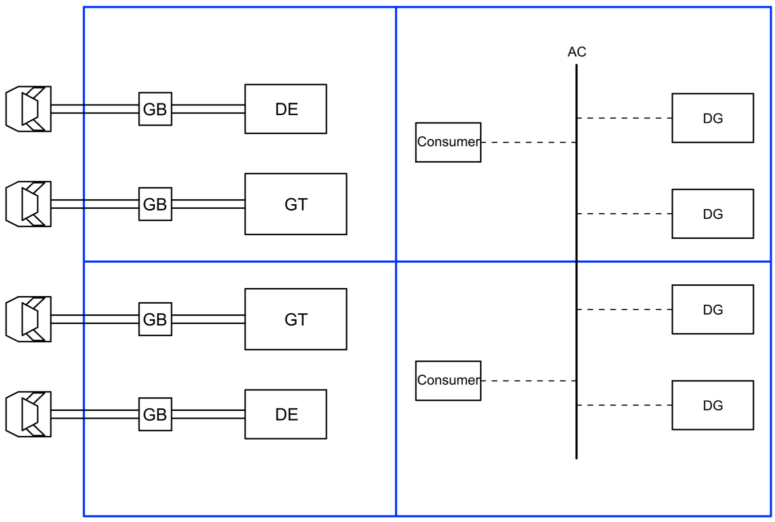

Figure 3:
CODAG power plant of the LCS-2

The blue lines in Figure 3 represent the assumed position of the bulkheads which are fundamental to the redundancy of the power plant.

Having this layout of the power plant the η_{TRM} consists of a gearbox efficiency η_{GB} and a shaft efficiency η_S. For the gearbox efficiency an estimated value of 0.98 has been chosen for all the gearboxes as there is only one engine per shaft line (be it a diesel engine or a gas turbine) and this is at the lower end of these kind of gearboxes.(Klein Woud & Stapersma, 2002) Furthermore the shaft efficiency has been taken to be 0.99 as there are very limited losses in a straight shaft.(Klein Woud & Stapersma, 2002) Because of this the overall transmission efficiency becomes 0,9702.

The propulsion power will be the installed power multiplied with the transmission efficiency. This will give a total propulsion power of 7504,5 kW per diesel engine and 24905,034 kW per gas turbine.

The delivered power of the vessel will be the propulsion power times the amount of propulsors. The two inner ones are connected to the two gas turbines whereas the external waterjets are powered by the diesel engines. This means that the delivered power will be 15009 kW for the external waterjets and 49810 kW for the two internal waterjets.

Finally, the non-dimensional delivered power coefficient can be calculated as:

$$C_D = \frac{P_D}{\rho^{1/3}\Delta^{2/3}v_s^3} \tag{1}$$

With the density ρ of seawater being 1.025 kg/m^3 and the displacement of the vessel being 3200 metric tonnes. This gives a C_D at 18 kn of 0,0432 [-] and 1000· C_D of 43,2 [-], and for 44 kn it C_D becomes 0,0098 [-] and 1000· C_D 9,8 [-].

The result of the coefficient at 18 knots is a normal value when compared to similar vessels. The value of C_D in the condition of 44 knots seams to be really low but can be explained by the extraordinary high velocity of the ship.

To better visualize the propulsive layout an Energy flow diagram is created. Figure 4 shows the various energy transformations and their flows starting from chemical energy.

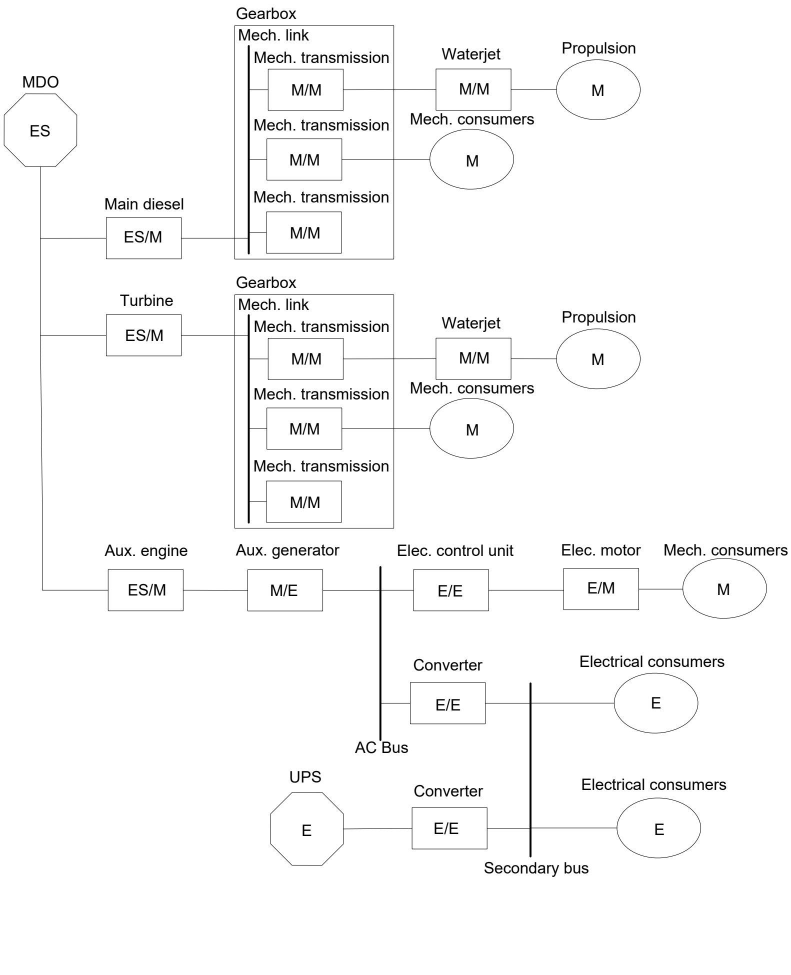

Figure 4:
Energy Flow Diagram of the original Layout

2.1 Operational Profile

Within the operational profile there are various modes in which the LCS-2 can operate. The main modes that can be defined are patrolling, intercepting, manoeuvring and while docked in the harbour. We can observe that the ship sails at 18 knots when it is patrolling and accelerates to 44 knots when it has to intercept another ship. It is important to note that these modes are based purely on statistical analysis. The vessel can also operate in a different way although we can categorize most operations as part of one of these four operational profiles with the exception for the time in which the ship is out of the water and undergoing maintenance.

A Frigate spends an average of 2500 hours at sea of which 95% are spend patrolling and only 5% are spend at high speeds. Considering one month in which the ship undergoes maintenance it becomes clear that the LCS-2 spends most of the time in the harbour preparing for the next operation.

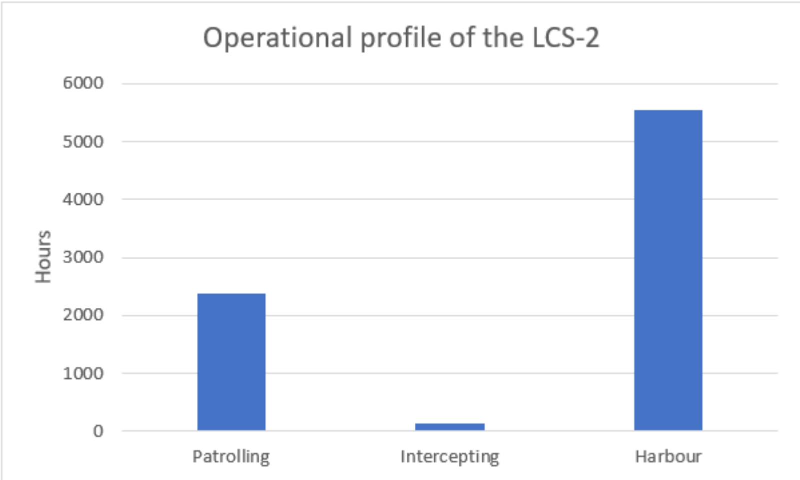

Figure 5:
Energy Flow Diagram of the original Layout

During patrolling and manoeuvring the ship operates on the two main diesel engines and sails at a speed of 18 knots. When the USS Independence has to sail at high speeds it relays on the power of both the diesel engines and the two gas turbines with which it manages to reach speeds of 44 knots.

An electrical load balance indicates the power demand in the different modes which becomes crucial for the design and choice of the power plant. The electrical load balance consists of a list of all main electrical consumers and their maximum power demand to the generators. In each condition a contemporaneity factor is assumed which indicates the percentage of the maximum power demand that is requested in each mode. Consumers can be classified into three different priority classes denominated by the letters A, B and C. A indicates that the consumer is vital to the operation of the ship can not be shut off. A consumer with priority B can be shut off in certain conditions but require permission to do so. Finally, consumers with priority C can be taken off the grid without the need of any permission.

The diesel generators are completely independent from the main engines and the gas turbines and are solely responsible for the electrical power supply. As a consequent of this they can be operated in a number of different combinations and load factors. From the electrical load balance (Figure 6) we can see that the maximum power demand to the generators will be around 2,1MW. As a result of the electrical load balance we can assume that three/four generators will be in operation at any time while at sea to have a certain redundancy and make them run not as heavy and therefore increase their efficiency and to rapidly respond to a change in the power demand.

Systems	Power at full load	Priority	Amount	Patrolling		Intercepting		Manoeuvring		Harbour	
				Contemp. Factor	Used Power	Contemp. Factor	Used Power	Contemp. Factor	Used Power	Contemp. Factor	Used Power
	[Watt]			[%]	[watt]	[%]	[watt]	[%]	[watt]	[%]	[watt]
Propulsion											
Cooling water pumps	6,3	A	8	0,5	25,2	0,7	35,28	0,2	10,08	0,1	5,04
Fuel oil service pumps	2,1	A	8	0,5	8,4	0,7	11,76	0,2	3,36	0,1	1,68
Lube oil pumps	20,8	A	8	0,5	83,2	0,7	116,48	0,2	33,28	0,1	16,64
Auxiliary systems											
Fuel oil separators	2,52	A	8	0,5	10,08	0,5	10,08	0,1	2,016	0,1	2,016
fuel oil transfer pumps	7,4	A	8	0,5	29,6	0,5	29,6	0,1	5,92	0,1	5,92
Machinery											
Steering gear pumps	20,16	B	4	1	80,64	1	80,64	1	80,64	0	0
Winches	32	B	6	0,2	38,4	0,1	19,2	1	192	0,8	153,6
Bow thruster	300	B	1	0	0	0	0	1	300	0,05	15
Bilge pumps	20	A	4	0,3	24	0,3	24	0,5	40	0,5	40
Hotel systems											
Hot water heater	13,5	B	2	1	27	0,7	18,9	0,3	8,1	0,8	21,6
Hot water circulation pump	8,5	B	2	1	17	0,7	11,9	0,2	3,4	0,7	11,9
HVAC	700	B	1	0,7	490	0,6	420	0,6	420	0,6	420
Fire fighting systems	100	A	1	1	100	1	100	1	100	1	100
Gray water sytsems	21	B	1	0,8	16,8	0,8	16,8	0,6	12,6	0,7	14,7
Black water systems	13	B	1	0,8	10,4	0,8	10,4	0,6	7,8	0,7	9,1
Fresh water systems	34	B	1	0,8	27,2	0,8	27,2	0,6	20,4	0,7	23,8
Ballast Systems											
Ballast pumps	22	A	6	0,2	26,4	0,05	6,6	0,1	13,2	0,8	105,6
Combat systems											
Armament	150	A	1	0,7	105	1	150	0,05	7,5	0,05	7,5
Command & surveillance	1050	A	1	1	1050	1	1050	0,2	210	0,1	105
		Total [kW]			**2169**		**2139**		**1470**		**1059**

Figure 6:
Energy Flow Diagram of the original Layout

3 LNG retrofit

To be able to make the change to LNG suitable engines need to be found that work on LNG. This is easily done for the gas turbine as it is already able to function on LNG, so the engine can be kept during the retrofit. The power plant layout remains the same with two gas turbines, two main engines and generators running on LNG connected to the same waterjets, see Figure 7.

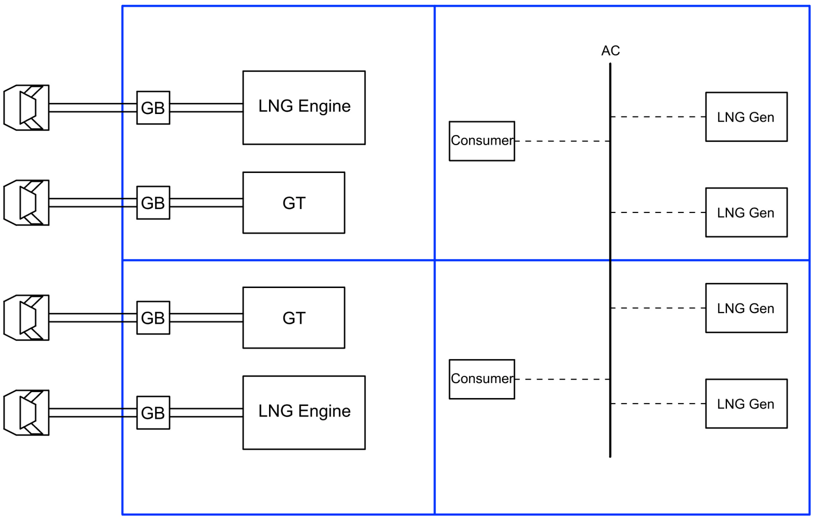

Figure 7:
New power plant of the LCS-2

The diesel engines have been replaced with the Wärtsilä 16V31SG since they output a similar power as the previously installed diesel engines. Since the new engines have slightly less break power (P_B) and generate this power at lower RPM the gearbox may have to be changed in order to maintain a similar performance. The engine will most likely run with a slightly lower engine margin than the one adapted to the old engines. This is not completely sure though, since the matching between the waterjet and the engine will change. The diesel engines and generators are being changed with an equal amount of LNG engines and generators since the redundancy needs to be kept the same and therefore the correct functioning of the ship has to be given at any moment.

	MTU 20V 800 M91	Wärtsilä 16V31SG	new/old comparison
Weigth [t]	47,67	93,2	195,51%
Dimensions [mm]	6645x2040x3375	9113x3144x4700	294,34%
PB [kW]	9100	8800	96,70%
Engine speed [RPM]	1150	750	65,22%
specific fuel consumption [g/kWh]	189	170	89,95%
specific fuel consumption [kJ/kWh]	8316	7154	86,03%

Figure 8:
Comparison between old and new engines

As can be seen from Figure 8, the Wärtsilä engines are almost twice as heavy as the previously installed MTU engines and need also considerably more space. The change in weight will result in a change of the structural parts on which the engine weight gets distributed whereas the need for more space means that the layout of the engine room will need to be changed. It can also be noted that the new engine runs at a higher efficiency which helps with fuel consumption.

The four diesel generators are being replaced with four LNG generators with the same power output to deliver enough power for the electrical loads. The substitution of the diesel LNG generator is the CAT CG132B V16, delivering 1 MW of break power at a maximum engine speed of 750 RPM.

	MTU 8V 396 TE74L	CAT CG132B V16	new/old comparison
Weigth [t]	3,8	8,56	225,26%
Dimensions [mm]	2005x1525x1540	4200x1780x2150	341,35%
PB [kW]	1000	1000	100,00%
Engine speed [RPM]	1900	1500	78,95%
specific fuel consumption [g/kWh]	206	185	89,81%

Figure 9:
Comparison between old and new generators

For the generator similar conclusions as for the main engines apply. The weight increase is not as dramatic as it is in the case of the main engines. The increase in occupied volume remains high and presents a challenge. The specific fuel consumption for smaller engines is lower than the one of the bigger main engines. Not possessing enough information about the fuel consumption of the CAT CG132B V16 the same decrease in fuel efficiency for LNG engines as for the diesel engines was taken into account.

Changing the fuel from diesel to LNG the tanks and their arrangement inside the ship will need to be adapted consequently. LNG is stored at -162°C in order to reduce its volume and as a consequence maximise the vessels range. The LNG is going to be stored in type C tanks which have a cylindrical shape which takes up more space onboard compared to typical fuel tanks. With time a small amount of LNG will evaporate and cool the tank, this makes sure that the tank stays at around -162°C. During this process the pressure in the tank will build up if the evaporated gas is not being used by the engines or generators. Normally the tanks are designed to withstand a pressure build up over the time of two weeks before having to open valve to release some of the Gas and lower the pressure inside the tank.

Considering the operational profile of this naval vessel this will not often be the case since the ship will constantly have to move for it's missions when not in port. Even if the ship remains stationary while out of harbour it will have to run a generator to supply electricity which will consume some LNG. When the ship is docked in a naval base for a longer period it will not have any problems with the pressure build up in the tanks onboard since it can be attached to shore power and the remaining (evaporated) fuel can easily be removed from the vessel.

LNG has a lower specific energy which by itself is a disadvantage if compared to the high energy density of MDO. The low density of LNG can be seen as an advantage since it results in less weight onboard and also in a lower variation of the overall displacement.

Two situations with respectively two different solutions will be analyzed. In the first one the autonomy of 4300 nautical miles at 18 knots was maintained and the additionally needed volume was evaluated. The lower density and lower specific energy of LNG compared to MDO results into a significant increase of additionally needed volume. Not having this much free volume onboard a second solution was developed in which the volume of the tanks was kept the same. This led to a notable loss in autonomy and therefore in a greatly reduced range.

	MDO	LNG Option 1	LNG Option 2
Weight of engines [t]	110,54	220,64	220,64
Fuel weight [t]	874,722	686,499	398,325
Total weight [t]	985,262	907,139	618,965
Safed weight [t]	0	78,123	366,297
weight [%]	100,00%	92,07%	62,82%
Range at 18kn [nm]	4300	4300	2400
Tank volume [m^3]	972	1373	972

Figure 10:
Weight calculations for different solutions

It is interesting to note that the weight of the liquid inside the tanks in solution 1 is 8% less. In the more realistic solution 2 the weight of the fuel was reduced by 37% resulting into a range of 2400 nautical miles. The

average Atlantic crossing is 2880 nautical miles long which leads to solution 2 not being capable of satisfying the US Navy's original requirements when the ship was ordered. Another disadvantage of storing LNG is that the type C tanks have a cylindrical shape and therefore only make use of roughly 78% of the volume when compared to traditional fuel tanks.
In order to satisfy the contractual requirement 200 cubic meters of LNG need to be added to the tanks for a total range of 3000 nautical miles. This could be achieved in different ways, for example with the help of external tanks on the aft deck. In the case the LCS-2 is sent on a mission across the Atlantic ocean it will most likely be part of a carrier strike group. In this case refueling will not be a problem since there is at least one tanker in the strike group that can refuel the ship while sailing. This tanker ship will however have to carry LNG.

These changes will only slightly effect the Energy Flow Diagram (figure 11) since only a few components have been changed, and stayed as the same energy conversions.

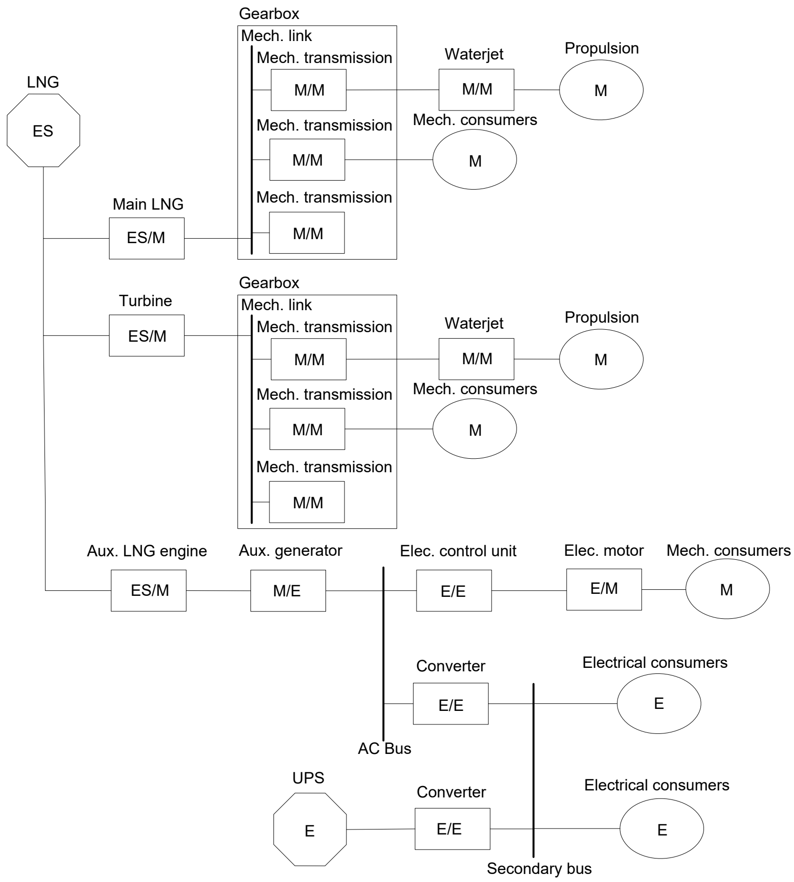

Figure 11:
Energy Flow Diagram of the new Layout

4 Emissions

The main reason for the change from Diesel oil to LNG is the reduced impact on the environment. This happens on one hand due to the reduced impact from LNG in comparison to traditional MDO and on the other hand due to the possibility of implementing emission reducing systems like carbon capture.
Before fully analysing the emissions concerning the operability of the LCS-2 and the consequent reflections concerning the criticality of the system it is first needed to contextualise on a scientific, experimental and faithful vision of the real world of sustainability.
After considering all the main regulations for analysing the situation of pollutants from a real-life point of view and the reason why emissions are a sensitive issue, the procedure can now be describe and verified. Contextualising and motivating the emission calculation for this specific ship.
Starting by calculating the initial emissions of the originally installed power plant and then, adopting the LNG zero project strategy, we will compare and justify the main explanations for the emission differences.

In accordance with the known main characteristics of the power plant we will calculate the emissions for each individual engine. This is done firstly because of the different nature of prime mover installed on the LCS-2, and secondly because of the operational profile of the ship. The two characterising speeds, the service speed and maximum speed, do not affect a change in the percentage value of the MCR power for each individual component. The characteristic speeds must be contextualised according to the potential required. Therefore the 85% load will remain constant, but the coupling of the use of the engines will change. More specifically, the service speed of 18 knots will take into account only the use of the diesel engines coupled to the waterjets and the diesel generators, while the maximum speed of 44 knots will imply a maximum use of the propulsion systems CODAG. The single-engine analysis allows us to more accurately understand the amount of emissions created in reference to the different operating speeds and thus obtain a more realistic final result.

Having established this, the calculation of initial emissions will be based on the definition of certain fundamental values in order to understand the topic. Assuming that the LCS before the retrofit operates with MDO with a density of $0.9g/cm^3$ and that its chemical composition is known (85% C, 13% H, 1% S and 1% other components)(Klein Woud & Stapersma, 2002).

Knowing the chemical balance of the reactants and products, it is possible to deduce that the quantities of CO_2 and SO_x are derived solely from the chemical composition of the fuel taken into account, the relationship of these two components within the MDO is taken into account to be constant and can be summarised in a table. This will consequently also be used to calculate the other pollutants. Bearing in mind that this is only valid for engines operating with this fuel and having a specific fuel consumption sfc between 160-220 g/kWh. In our case all installed engines are eligible for this calculation.

	pollutant emission ratio (per) in g/kg	*specific pollutant emission (spe) in g/kWh*
CO_2 (86% C in fuel)	3200	500–700
SO_x per % S in fuel	20	3.2–4.4
NO_x	40–100	6–22
HC (gaseous)	0.5– 4	0.1–0.9
CO	2–20	0.3–4.4
Particulates (depending on fuel)	0.5–2	0.1–0.4

Figure 12:
MDO emission components for a range of specific fuel consumption

As we can see from figure 12, the other components are still dependent on the chemical composition of the fuel, but much more related to the specific fuel consumption parameters per engine. The elements that are most affected by this factor are nitrogen oxides NO_x. In order to obtain a more precise estimation and representation according to the technical characteristics of the engine in relation to its power load and specific consumption.

Than only the calculation according to the specific pollutant emission (spe) measured in g/kWh will need to be considered.

$$spe = \frac{m_{pe}}{P_B} \tag{2}$$

Where the numerator is the mass flow of pollutant emissions, which considers any existing type of emission, and the denominator is the engine's brake power.
Once all assumptions have been clarified and the various choices in the different parameters have been explained, the calculation begins by separating the different pollutants and evaluating them engine by engine.

Knowing that the LCS-2 is powered by two main engines, which are gas turbines fully powered by MDO. Combined with the assumption from the verification and the comparison of the trend graph of the average diesel engine and single-cycle gas turbine with reference to NO_X emission ration production from (Klein Woud & Stapersma, 2002). It turns out to be identical to the same percentage of the MCR, for the production of pollutants dependent on specific consumption (the gas turbines were considered purely as diesel engines).

Noting this, the current situation results in 2 diesel engines, 2 gas turbines and 4 diesel-generators all having different specific fuel consumption values within the range required by the table from (Klein Woud & Stapersma, 2002). Knowing that the range of fuel consumption binds exactly to the range of specific pollutant emission (spe) (relative to each pollutant CO_2, SO_x, NO_x, etc.), by means of a linear regression. It was possible to obtain the precise value of *spe* matched to that specific engine by inputting the precise fuel consumption. So having two ranges of values, one known for sfc and with engine sfc included, and one known for *spe* values but with specific *spe* for the engine unknown, through linear interpolation it was possible to know the precise *spe* for each engine with known sfc present in the powerplant. Subsequently, as explained above, all our engines working at a powerplant P_B underestimated by 85% with respect to maximum power, made it possible to calculate, by multiplication of the exact spe by the P_B, the correct mass quantity per hour of the pollutant for each individual engine.

Once the mass per hour of the pollutant has been calculated for a specific engine, it is multiplied by the number of engines of the same type. Finally, a total consumption in tonnes per hour for that engine block is obtained. In the following tables we present the data and values calculated according to previously discussed procedure.

%MCR	sfc diesel engine [g/kWh]	sfc gas turbine [g/kWh]	sfc diesel-generator [g/kWh]
85	189	215	206
	x2	x2	x4

Figure 13:
Specific fuel consumption for each type of engine.

The emissions are based on the fixed load of the MCR 85% engines, but expressed as a function of the selected operational profiles. Given the low induced consumption and related pollutant emissions, the annual emission calculation will be based on the weighted average of the two fundamental navigation modes for the study and only possible to be contextualised on the basis of the following project LNG zero, patrolling and intercepting considering 2500 hours in a year.
In the harbour mode, emissions are less relevant to the question of pollutant abatement, as the generators are more involved in assisting the main engines at sea. The harbour mode also includes the hours related to on-shore/offshore maintenance, as well as the very stay in ports for the purpose of the respective navigation mission, in which there is always an external aid in maintaining the ship's internal electrical load, via shore connection or auxiliary vessels, making the emission considerations for this operational profile misleading.(Carrasco et al., 2020)

CO2	spe value	Pb 85%MCR	mCO2 [g/h]	mCO2 total engines [g/h]	t/h	t/OPY(patroling-intercepting/year)
spe diesel engine [g/kWh]	597	7735	4615216,7	9230433,3	9,2	23076,1
spe gas turbine [g/kWh]	683	25670	17541166,7	35082333,3	35,1	87705,8
spe diesel-generator [g/kWh]	653	850	555333,3	2221333,3	2,2	5553,3

Figure 14:
Emission of CO_2 per engine type.

SOx	spe value	Pb 85%MCR	mSOx [g/h]	mSOx total engines [g/h]	t/h	t/OPY(patroling-intercepting/year)
spe diesel engine [g/kWh]	3,8	7735	29238,3	58476,6	0,058	146,19
spe gas turbine [g/kWh]	4,3	25670	110381	220762	0,221	551,91
spe diesel-generator [g/kWh]	4,1	850	3502	14008	0,014	35,02

Figure 15:
Emission of SO_x per engine type.

NOx	spe value	Pb 85%MCR	mNOx [g/h]	mNOx total engines [g/h]	t/h	t/OPY(patroling-intercepting/year)
spe diesel engine [g/kWh]	14	7735	106227,3	212454,7	0,212	531,14
spe gas turbine [g/kWh]	21	25670	530513,3	1061026,7	1,061	2652,57
spe diesel-generator [g/kWh]	18	850	15526,7	62106,7	0,062	155,27

Figure 16:
Emission of NO_x per engine type.

HC	spe value	Pb 85%MCR	mHC [g/h]	mHC total engines [g/h]	t/h	t/OPY(patroling-intercepting/year)
spe diesel engine [g/kWh]	0,5	7735	3764,4	7528,7	0,0075	18,8
spe gas turbine [g/kWh]	0,8	25670	21391,7	42783,3	0,0428	107,0
spe diesel-generator [g/kWh]	0,7	850	606,3	2425,3	0,0024	6,1

Figure 17:
Emission of HC per engine type.

CO	spe value	Pb 85%MCR	mCO [g/h]	mCO total engines [g/h]	t/h	t/OPY(patroling-intercepting/year)
spe diesel engine [g/kWh]	2,3	7735	17648,7	35297,4	0,035	88,2
spe gas turbine [g/kWh]	4,1	25670	104177,4	208354,8	0,208	520,9
spe diesel-generator [g/kWh]	3,4	850	2926,8	11707,3	0,012	29,3

Figure 18:
Emission of CO per engine type.

PM	spe value	Pb 85%MCR	mPM [g/h]	mPM total engines [g/h]	t/h	t/OPY(patroling-intercepting/year)
spe diesel engine [g/kWh]	0,2	7735	1895,1	3790,15	0,0038	9,475
spe gas turbine [g/kWh]	0,4	25670	9626,3	19252,5	0,0193	48,131
spe diesel-generator [g/kWh]	0,3	850	280,5	1122	0,0011	2,805

Figure 19:
Emission of PM10 per engine type.

Having obtained these values, our operational profile dictates the total amount of emissions produced over 2500 operating hours in one year in the respective patrolling (95%) and interception (5%) modes. The total and absolute consumption will therefore be calculated with reference to the weighted average of the two operating modes, bearing in mind however that the total actual sailing takes place in the mode in which maximum power and the use of all engines, does not occur, but at the same time it is crucial to consider the inherent effect on emissions when maximum speed is reached.

As adequately explained in the chapter on operational profiles, the only engines that are constantly operational and relevant to the calculation of pollutants are the main diesels and diesel generators, as the speed of 18 knots is maintained for almost the entire time spent at sea, denoting how the highest consumption on the scale of one year of operation occurs in the patrolling mode. In the remaining time phase, the gas turbines are also called into participation, denoting a greater specific consumption and consequently a greater production of emissions, which classify the intercepting phase, which at the basis of our study is crucial for the correct weighting according to the time taken by the ship's operational profile.
The international regulations are used as a reference that quantify our accessibility, at the same time it is important to remember that the USS Independence was designed to sail at very high speeds and therefore not to modulate the required emissions through specific consumption.(Delft, 2021)

4.1 LNG post-retrofit emissions

The next step will allow us to observe with a different criticism, the reliability of emissions for this type of ship, which is obliged to maintain certain performances. The aim of this study is to quantify total methane and CO_2 emissions associated with an LNG power plant using direct measurement to identify the key contributors to total emissions.

Minimizing methane emissions is critical for attaining global climate objectives, but there is a lack of understanding of emissions and reduction options. The natural gas supply chain is a major source of pollutants, with methane emissions from LNG shipments previously unmeasured. From scientific literature (Advisory, 2019)(Boretti, 2014)(Harrison, Heggo, & Balcombe, 2022), we observe that the choice of LNG is decisive for the reduction of pollutants, since the chemical composition and specific calorific power do not allow the same formation of pollutants as in MDO.

There is a drastic cut in the components formed by the high temperatures of the combustion chamber and those that are part of the chemical nature of oil derivatives. Consequently, it is necessary to analyse the substantial difference between the two emissions and assess the environmental impact inherent in our type of ship and its fundamental prerequisites. Unlike the procedure carried out specifically for MDO, the calculation of pollutant emissions from LNG is difficult for two macroscopic reasons. It is not possible to know with certainty what the type of LNG used is and match it to the actual operation of the selected engines. In fact, the objective was to initially calculate the new specific fuel consumption's (sfc) for engines operating at different power levels and with different fluid properties. Having done this, the real complication was; given the same technical data of the engine and type of LNG selected, to properly link a range of specific fuel consumption with a range of *spe*. This would allow for the exact amount of pollutants produced by combustion to be found, with the power of the various engines known (Boretti, 2014).

At this point, two solutions are made to try and obtain values that could faithfully represent the real values. The first solution was to analyse the chemical formula of LNG and understand the various equations in order to focus more on the products that would give useful information on pollutants (Verbeek & Verbeek, 2015). In our case, a rich LNG with a density of $0.465 kg/mm^3$ was chosen, which is the most suitable due to its high calorific value during combustion and consequently the possibility of releasing more power to the ship. Having said this, the chemical composition of this LNG sees a percentage of methane (CH4) in it of about 98%. By means of this definition, the breakdown of the fuel during the various chemical processes is analysed, considering it as a fuel consisting almost 100% of a known molecule in its products (Harrison et al., 2022).

$$C_m H_n + (m + \frac{n}{4}) O_2 \Rightarrow mCO_2 + \frac{n}{2} H_2O \tag{3}$$

Using this reasoning, it is possible to calculate the mass amount of CO_2. Unfortunately this estimate is unstable due to the fact that it is not possible to apply these concepts to the specific fuel consumption of each engine. Which is why the final determination will be made on the basis of this and with references taken from the scientific literature(Advisory, 2019)(Boretti, 2014)(Harrison et al., 2022)(Pavlenko, Comer, Zhou, Clark, & Rutherford, 2020). Through the experimental research studies analysed in the context of the environmental impact inherent in the difference in emissions between MDO and LNG for existing ships. It was possible to rely on the estimates and percentages calculated for different engines and ships, in order to identify the different percentages of reduction or growth of the amount of pollutants. Therefore, by optimising the process through the calculation of the mass of carbon dioxide as a product of methane combustion and consequently analysing the experimental evidence on pollutant abatement available in the scientific literature, it was possible to estimate the emission quantities inherent to LNG combustion.

	Emissions (tons/year)			
	Conventional Fuels (MDO)	Alternative Fuels (LNG)	Difference (tons/year)	Percentage of Change
CO_2	35,564.2	28,202.53	7361.67	20.70%
NO_x	893.13	145.94	747.19	83.66%
CO	31.97	87.12	−55.15	Increase in emissions
HC	0.69	9.56	−8.87	Increase in emissions
PM	10.24	0.19	10.05	98.14%
SO_2	36.28	0.19	36.09	99.48%
CH_4	0.69	332.71	−332.02	Increase in emissions
Total	36,537.2	28,778.24	7758.96	21.24%

Figure 20:
The estimated amounts of emissions (tons/year) by pollutant category and fuel type (Boretti, 2014).

Figure 20 shows the results from a study based on the different emission profiles of similar ships with different propulsion systems. The percentage values are calibrated for all diversities and will be used as a reference of reduction against MDO emissions.

	Emissions MDO [t/OPY(patroling-intercepting/year)]	Percentage of change	Emissions LNG [t/OPY(patroling-intercepting/year]	Emission LNG modes [tons/h]
CO2	116335,25	-21%	91904,8475	36,76
SOx	733,1165	-99%	7,331165	0,003
NOx	3338,97	-84%	534,2352	0,21
CO	638,398875	270%	2362,075838	0,94
HC	131,8435	1400%	1977,6525	0,79
PM	60,411625	-98%	1,2082325	0,0005
CH4	\	\	98% of the starage fuel	98% of the starage fuel

Figure 21:
Emission comparison of MDO and LNG.

As we can therefore denote, the calculation of LNG emissions sees that carbon dioxide, sulphur oxide, nitrogen oxide and particulate matter are the pollutants with the greatest reduction.

5 Carbon capture

In order to reach the goal of reducing the CO_2 emissions by 50% by 2050 ships that are already existing will need to reduce there emissions. For this it is either needed to change their fuel with a fuel type that does not produce CO_2 or to implement carbon capture. As CO_2 neutral fuel's are not yet fully mature at the moment due to multiple difficulties the implementation of carbon capture is a valid solution to sail carbon neutral.

There are multiple methods of CO_2 capture currently available like Chemical absorption, Cryogenic separation, Membrane separation and Adsorption.

Adsorption is a recent technology that uses porous materials to capture CO_2 by adherence to the surface. At the moment this method requires the exhaust gasses to be at a high pressure, expensive materials and does not have a great CO_2 capture rate.(Sai Bhargava Reddy, Ponnamma, Kumar Sadasivuni, Kumar, & Abdullah, 2021) Because of these properties adsorption is not a suitable solution for use in the vessel of this paper.

Membrane separation is the least mature technology from all the carbon capture techniques. With the currently used membrane materials only a small amount of CO_2 gets captured from the air, even with a second stage the maximum purity that can be achieved is 50%.(Castel, Bounaceur, & Favre, 2021)(OIL & INITIATIVE, 2021) This also has the added problem of having to store other substances in the carbon capture tanks and having a less pure form of captured CO_2. Further more a large vacuum pumping installation is required to suck the air through the membranes costing a lot of energy. With future improvements of membrane materials it could become a suitable solution, but this method is currently not feasible yet.

Cryogenic separation works by cooling the air and separating the CO_2 from the rest of the components by the difference in their boiling point.(Font-Palma, Cann, & Udemu, 2021) This means that all of the exhausts needs to be cooled, which costs a lot of energy. Further more the exhaust should first be cleaned of water(vapor) to prevent ice plugging of the separation system. Cryogenic separation gives close to 100% CO_2 purity and can be stored in liquid state, making the storage of captured carbon space efficient. Cryogenic separation is therefore a possible solution to reduce the carbon emission especially if a 'cold source' is part of the redesigned ship.

Chemical absorption is the most mature technology from these capture methods and works by spraying a liquid thru the exhaust that absorbs the CO_2 and can than be reheated to release the CO_2 into a storage tank. This process is able to capture around 90 to 99% of the emitted carbon. (Font-Palma et al., 2021) (OIL & INITIATIVE, 2021) The heating of the absorption liquid can take so much energy that fuel consumption needs to be increased by as much as 20%.(Lou & Wang, 2017)

Hence the industry uses waste heat recovery from the exhaust gasses to reheat the absorbent and not have to use as much fuel. The waste heat recovery can reduce the fuel consumption for an LNG vessel by 20%. (Kalinowski, Hwang, Radermacher, Al Hashimi, & Rodgers, 2009) With the use of a waste heat recovery system the chemical absorption system can be used without further need of additional fuel consumption, except for the when the engine just started up and the scrubbing chemical is not warmed up enough by just the exhaust.

For this reason it is decided to install a chemical absorption carbon capture system with waste heat recovery over a cryogenic separation carbon capture system.
This system takes up space both in the exhaust pipe and with tanks for the chemicals (amine) used. The scrubbers can be placed in the exhaust pipe but need significant height to be able to work. The LCS-2 already has a radar system that needs no obstructions, so the scrubbing installation will need to be cut into two halves and than be integrated with the existing exhaust treatment plant. This should make it so that the exhaust pipe dos not get significantly taller but will take up some more space within the structure. (van den Akker, 2022)

Furthermore it will be required to store amine for the process. There are different amine's available on the market, one often used in carbon capture is MEA. MEA has an capture absorption efficiency of (0.72kg CO_2/kg MEA).(Huertas, Gomez, Giraldo, & Garzón, 2015) This means the mass flow through the scrubber of amine has to be 1.4 times bigger than that of CO_2 to be able to capture the maximum amount. Before the retrofit The maximum amount of CO_2 flow is 46,5 ton/h (from figure 14) this is a mass flow of 12.97 kg/s. This means that the mass flow of amine needs to be 18,10 kg/s. After The LNG retrofit the maximum amount of CO_2 flow is 36,76 ton/h (from figure 20) this is a mass flow of 10.21 kg/s. This means that the mass flow of amine needs to be 14.30 kg/s for the LNG system.

Amine not only reacts with CO_2 but also with other particles as for instance O_2 and NO_x, this can lead to amine that no longer gets 'cleaned' by the reheating process or other ways of degradation. Because of this and the fact that amine can evaporate in the exhaust pipe it is important to have additional storage of amine on board so that degradation does not impact the CO_2 capture.

5.1 Storage of carbon

If the carbon dioxide can be captured it also needs to be stored on the ship to be offloaded later onto land to be used elsewhere. This space is needed on board to store and cool the liquid carbon dioxide (LCO_2). The amount of volume needed for the LCO_2 storage is about the same as that for LNG as 1 m^3 of LNG produces about 1 m^3 of LCO_2.(van den Akker, 2022) The empty LNG-tanks can possibly be used for the storage of the LCO_2 as the LNG is kept under similar conditions but lower temperature.(van den Akker, 2022) This would of course require adjustments to a normal LNG tank as to make it able to hold LCO_2 as well. But since this is a military vessel the cost to do this will not be a mayor problem as the ship does not have to make money.
This would save a lot of space and weight by not needing an additional 1370 m^3 of LCO_2 specific storage tanks, but instead only a small intermediate tank is required to fill up until a LNG-tank is completely empty and can be filled up with LCO_2. When the LNG-tanks are a series of small TEU sized tanks the intermediate tank can be taken as 2 TEU sized tanks which can easily be added to the structure of the vessel, for instance near the helicopter deck.

The storage of LCO_2 does bring an additional problem with it as it is also a hazardous gas. If it would escape it would evaporate and could suffocate the crew in connected compartment's. This means that the tanks and piping should have safety measures installed to prevent and detect leaks. This also means some of the tanks or piping have to be moved so they are not connected to crew quarters without a ventilated space in between.

When LCO_2 is captured and LNG is burned the ship becomes heavier because burning 1 kg of LNG produces 2.7 kg of LCO_2. (van den Akker, 2022) This becomes an increase of 1167 ton if all the fuel is used to get the same maximum range (option 1). When the same amount of fuel space is used (option 2) the weight increases by 677 ton. Both options are a mayor increase in weight as the original displacement of the ship was 3200 ton. Such a great amount of added weight can not feasibly be added to a high speed craft without mayor changes to the vessel. To be able to carry this additional weight the ship would have to be redesigned with a greater displacement which will add a lot of extra resistance which in turn will require more powerful engines and more fuel to be able to keep sailing the same range and speeds. Such a mayor change can not be done as part of a retrofit.

6 Reflection

There are multiple ways to retrofit the LCS into an LNG powered ship and lower it's emissions, only non are without drawbacks.

Option 1 of the LNG retrofit is not feasible to do due to the fact that adding such a great amount of tank volume to a war ship would severely reduce the speed of the ship and increase the change of mayor damage if the vessel got hit. Therefore the vessel would not keep its operability and this is not a suitable solution.

The second option for the LNG retrofit keeps the same amount of tank space and therefore does not have the same problems as stated above and even has the added benefit of lighter total fuel bunkers. The reduced range that we obtain from the LNG retrofit is a weak point of this design but it does not necessarily have to result in a mayor problem. Whether this is a problem or not depends on the missions on which the ship will be send. As the name Littoral Combat Ship and it's design give away it was designed to mainly operate close to shore where it is much easier to refuel and overcome the challenges that come with a reduced range.

If the LCS-2 is sent on further mission's it is send as part of a carrier strike group, refueling will not be a problem in this case since there is at least one tanker in the strike group that can refuel the ship while sailing. This tanker ship will however have to carry LNG, otherwise this concept will not work. The change to LNG will also have an impact on the hydrodynamics of the ship since we are moving and changing some significant weights. We will not investigate this change in detail since it is not part of this paper although it is not a point that can be neglected when retrofitting a warship to LNG.

The retrofit to LNG on its own does not really decrease the emissions of the ship. For this Carbon capture is required. Unfortunately carbon capture is not feasible on this ship without mayor changes that can not be done in a simple retrofit. Because even with the assumption that LCO_2 can be stored in the LNG tanks, the space and weight this saves does not overcome the problem of the amount of weight that needs to be carried. This would mean a far greater displacement and thus far more resistance. This would cause the ship to either sail slower or larger engines need to be installed which will take up more space and consume more fuel, thus shortening the range even further.

For the ship to maintain its original requirements of 44 knots and ability to cross the Atlantic ocean Carbon capture simple can not be realised. This might also not be as mayor a problem as navies usually do not have emissions as there highest priority. But instead the operatability and survivability are extremely important.

7 Conclusion

After having studied the various advantages and challenges that come with a switch from MDO to LNG the conclusion is that this ship may not benefit as much from this retrofit as the environment does. The reason for this lays in the vast changes that need to be done to the ship while only having a limited amount of space at our disposal. The increase in needed volume for the engines, LNG and carbon storage and carbon capture system results being the biggest disadvantage of this technology. Further does the carbon storage also become to heavy to be added to the ship and maintain the same speeds. Compromises need to be accepted for this retrofit to happen. However, the change from MDO to LNG is a step in the right direction towards a more sustainable way to sail. By using LNG instead of MDO and adding a carbon capture system it is possible to drastically lower the emissions compared to the original design. In fact, it would reduce the emissions by 90 to 99%.

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