EVALUATING CO_2 EMISSIONS OF KLITSA B.C. FERRY USING DIFFERENT PROPULSION ARCHITECTURES

by

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B.Tech., Punjab Technical University 2012

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ABSTRACT

CO_2 is the main contributor of green house gasses. In recent years emissions from maritime transport has increased rapidly. This trend can also be seen for passenger ferries. It is harmful as ferries operate closer to populated areas. To control this, marine vessels and passenger ferries are switching to alternate fuel types and electrical propulsion. In this project three different propulsion architecture approaches are considered and analyzed. To compute the CO_2 emission results from each architecture, two different methodologies are presented and compared. Suitable methodology is used for computational purpose. Real time load data of Klitsa B.C. ferry is used to compute results as a base for comparison. CO_2 emission results are calculated for the diesel-only, dual-fuel and hybrid (battery) architecture. Results of dual-fuel and hybrid architecture are compared with the diesel-only architecture which is presently being used in Klitsa B.C. ferry. Results are analyzed and reduction in emission are calculated and compared to conclude the project.

Contents

List of Tables

List of Figures

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DEDICATION

To my parents and my sisters, my good friends Babak, Sushil and Jasleen Thandi

Chapter 1

INTRODUCTION

Gasses that trap heat in the atmosphere are called greenhouse gasses (GHG). Canada produced 722 megatonnes (Mt) of GHG in year 2015. Since 1990 there has been 18% increase in GHG gas emission in Canada [9]. This growth is mainly driven by increase emissions from mining, oil and gas production and transportation. Transportation sector in 2015 was the second largest source of GHG emissions. It accounted for 24% of total GHG emission which was 173Mt of CO_2 eq. since 1990, 42% increase has been observed in GHG emission from the transportation sector. On a deeper scale, emissions from freight travel increased by 125% between 1990 and 2015 [9]. Subsection of freight travel is marine travel which has become an important topic in the sustainability debate. The reason behind this is that emissions from marine transport sector contribute a significant amount to world climate change [16]. International shipping contributes approximately 2.4% of global GHG gas emissions as mentioned in [22]. According to international marine organization (IMO) this share is expected to increase drastically. As a result the problem of GHG emissions and climate change has received increased attention. This is justified since shipping is expected to grow significantly [22]. GHG gasses emitted from a marine vessel mainly includes carbon dioxide (CO_2), methane (CH_4) and dinitrogen oxide (N_2O). Out of all these gasses CO_2 dominates the global warming potential. According to [6] maritime transports are responsible for 3.1% of total CO_2 emissions worldwide. Our main goal is study of the amount of CO_2 emissions released into atmosphere from passenger marine vessels that use different propulsion architectures.

1.1 Factors Causing Emissions

The main source of emissions from marine or any other type of transportation vehicle is the exhaust gas. These exhaust gases are released from burning fuel in the combustion engines. The amount of GHG released from the exhaust depends upon various factors such as fuel type, specific fuel consumption and engine loading. How engine load profile and specific fuel consumption contribute to CO_2 emissions are presented in Chapter 2. Fuel type mainly affects amount of emissions. The most commonly used fuel to power marine propulsion system is Heavy Fuel Oil (HFO). This is the least expensive marine fuel oil so it is highly popular in marine industry. Though it is cheap but still some cleaning system are required to remove excess impurities.

1.2 Organizations Responsible for Controlling Emissions

Tightening emission standards for GHG and toxic emissions are making the use of HFO more expensive. These regulation are decided by International Maritime Organization (IMO). These regulation were made by revising various annexes of MARPOL. MARPOL is the International Convention for the Prevention of Pollution from Ships. According to [8] Annex VI (prevention of air pollution from ships) was enforced on

May 19, 2005. This set the base for limits on sulfur oxide (SO_X) and oxides of nitrogen (NO_X) emissions from ship exhausts. As both of these pollutants are highly toxic and can harm the ecosystem closer to ports, so some regulation were put on marine transport to control these pollutants. IMO has designated waters along the United States and Canada as emission control areas (ECA) for the control of these highly toxic pollutants. This tightening of emission limits for sulfur oxide and oxides of nitrogen has resulted in use of HFO with low sulphur content. According to the new data, the sulphur content in HFO will be reduced to 0.5% from 3.5% outside emission control areas. But inside ECAs, IMO restricted the use of 0.1% maximum sulphur content inside emission control areas. This has resulted in three different categories of HFOs. For this project, HFO with sulphur content of 0.5% for outside and inside of ECAs is used [15].

1.3 Regulations on NO_X and SO_X Emissions

This restriction on sulphur content by IMO has resulted in increased cost of marine fuel oil. Historically fuel cost was low as compared to present day fuel cost. Now to compensate that process marine vessels are trying to reduce fuel consumption.

The limitation made by IMO on SO_X and NO_X regulation are non-questionable. Toxic emission should be reduced when marine vessels are close to ecosystem and populate areas. But the data published in [4] stated that CO_2 emission factor per kWh has not decreased with the decrease of sulphur content in HFO fuel. This indicates that decrease of sulphur in HFO in result reduced the toxic emission but did not affect the CO_2 emissions. So the main aim of this project is to study different methodologies that are available to calculate the amount of CO_2 emissions and then choose the most reliable one. That methodology then can be used to compute CO_2

emissions for different fuel types and propulsion architectures.

1.4 Research Question of Project

British Columbia government has made an announcement that amount of taxes on CO_2 emission per ton will be increased from \$30 per ton to \$50 per ton and as the environmental effect of CO_2 emission are already known. So two different questions of research arises here.

- Evaluate different computational techniques for calculating CO_2 emission
- Evaluate different propulsion architectures for a passenger ferry
- Analyzing CO_2 emissions during a typical ferry voyage

First question is evaluation and comparison of different methodologies and second question is to uses one of those methodology to analyze CO_2 emissions for different propulsion architectures and fuel types.

1.5 Organization of Project

First chapter gave a brief background about GHG emissions. What amount of GHGs are being released into atmosphere annually and what factors it depend upon. IMO was also considered into account that lead to NO_X and SO_X regulations. Finally the research questions of the project were listed which explains the need and motivation of this project. Second chapter explains methodologies which can be used to compute these GHG gas emission. A comparison between two different methodologies is also presented. Emission factor and global warming potential are also explained in detail. Third chapter is about different propulsion architectures which are presently being used or can be used in future. Chapter 4 presents results and analysis of CO_2 emissions resulting from different engine architectures. In this chapter we will use one of the suitable methodology and compute CO_2 emission using real time data of B.C. ferries. The results will be then compared with the base model that is being used in B.C. ferries now. Finally the conclusion of the project will be provided at the end of this report.

Chapter 2

COMPUTATIONAL METHODS FOR CALCULATING EMISSIONS IN MARITIME TRANSPORT

This chapter will mainly focus on the computational methodologies that can be used to calculate GHG emissions. Ship emissions has been a highly debated topic from past several years. Many research papers have been published which used same methodologies. Emission results of these papers had the same level of uncertainty as per [16] . All these papers used two different methodologies which in some way are similar but just use different marine vessel specifications for computation.

- First method is specific fuel consumption method which mainly depends upon fuel type, fuel consumption, engine speed and emission factor
- Second method is called engine loading method which directly depends upon maximum rated engine power, fuel type, loading factor and emission factor

Several different type of GHGs are released into the atmosphere but in a different percentage. Out of all these GHGs, CO_2 will be our main aim in this project as it is the main exhaust emission from diesel engines that significantly contributes to the GHG effect. As per the data provided in [17], CO_2 accounted for 81% of total GHGs emission produced by Canada in 2012. Which is relatively very high as compared with other GHGs. In this chapter we will evaluate these two methodologies depending upon the vessel information they need. Then we will use one of these methodology to calculate CO_2 emission of our base and proposed architectures in Chapter 4.

2.1 Emission Factor

Emission factor of GHG is defined as the amount of GHG emitted as a result of a given unit energy consumption in kWh or as a results of fuel consumption in liters. Emission factor can be expressed as grams of GHG emitted into the atmosphere by using one unit of energy. Units of emission factor are usually dependent on fuel consumption or energy. So units are expressed as g/Liter of fuel consumed or g/kwh of energy. These units will be explained in Section 2.4. Emission factor is one of the most important information needed to calculate GHG emissions. This same process can be used to calculate CO_2 emissions. Emission factor has different value for different fuel types, different gasses and also for different operations. For example as specified in [18], there are different values of emission factors depending upon the source of emission. For best results this data should be provided by organizations that best reflects individual circumstances. B.C government is still working on developing B.C. - specific emission factor to improve GHG tracking. Standardized emission factor from national and international data sources were be used in situations where B.C. specific information is not available [18]. Emission factors can be taken from

Canadas National GHG inventory report or any other recognized sources. The first methodology uses emission factor depending upon fuel consumption. This data can be obtained from [18] [17]. Second method uses load factor of engine power to calculate CO_2 emissions. So the emission factor should be used in the unit of grams of CO_2 emitted into atmosphere per kWh of energy (g/kWh). Emission factor used in [15] was used for the second methodology and for computing our dual fuel engine emission also. The detailed emission factors for HFO 0.5%S and Dual-fuel (LNG and HFO 0.5%S) are provided in Table 4.1 and Table 4.2

2.2 Global Warming Potential

GWP is defined as the ability of a GHG gas to trap heat. As different gases have different ability to trap heat so GWP is just the numerical number of that ability. GWP for each GHG gas is expressed as the ratio of its heat trapping ability relative to that of CO_2 [18]. This mean after calculation the grams of specific gas emitted into atmosphere, we have to multiply that number with its GWP to get the equivalent amount to CO_2. This can be expressed as

$$E_T = \sum_{i=1}^{n} E_i \times GWP_i \tag{2.1}$$

where E_T is total emission of all pollutants, index (i) is pollutant type, E_i is emissions of specific pollutant type and GWP_i is global warming potential of specific pollutant. So unit of GHG gases after converting with global warming potential becomes grams of CO_2 equivalent (gCO_2 eq.). But this was not used in this project because GWP of CO_2 is 1 so the amount remains the same. This is because the main research motive is to see the amount of CO_2 being emitted as it is the major contributor into global warming.

2.3 Methodologies

Two methods for estimating CO_2 emissions caused by marine vessels are presented in this section. These methods use ship movement data, technical information and emission factor for computation. Total emission produced by a marine vessel in one voyage is sum of emissions produced because of main engine and generator for hotel load [21]. Main engine load includes cruising and docking processes. These are defined individually as.

- Hoteling - Diesel generator of vessel is operating at a constant power to provide electricity for climate control, communications, entertainment, lighting etc
- Cruising - When vessel is sailing at speed
- Docking - when vessel's main engine is operating at low power for docking and loading processes

Two different procedures to calculate emissions are explained below.

2.3.1 Specific Fuel Consumption Method

When fuel consumption of each phase is known, then the emissions can be computed by

$$E_V = \sum_{i=1}^{n} F_C(i) \times E_F(i) \tag{2.2}$$

where E_V is emissions per voyage (g of CO_2), E_F is Emission factor (g/L), index (i) is interval of voyage and $F_C(i)$ is Specific fuel consumption (L) at a specific interval of voyage.

In this method emission factor and Specific fuel consumption are both phase dependent. According to [15] [1] [21] emission factors increases in docking phase.

This is a because of low efficiency of diesel engines and generators at low power. Although total amount of emission in docking phase are less as compared to the cursing phase as total fuel consumption is less. So Vessel movement affects the fuel consumption and in result affects emission factor of that specific fuel type.

2.3.2 Engine Loading Method

This computational method is used when specific fuel consumption of engine is not available. This method uses engine loading factor and engine nominal power to compute emissions. Similar to the specific fuel consumption method, this method also uses emission factor but this factor is power dependent. The units of emission factor in this method are (g/kWh). The equation of this method is give as following:

$$E_V = \sum_{i=1}^{n} \frac{D_i \times P_i \times E_F(i)}{V_i} \tag{2.3}$$

where E_V is emissions per voyage (g of CO_2), index (i) is interval of voyage, E_F is Emission factor (g/kWh), P is engine power and D and V are distance and velocity of vessel respectively. This equation can be further expressed in function of time spent in each phase of the voyage.

$$T = \frac{D}{V} \tag{2.4}$$

Substituting (2.4) in (2.3) will result in the final equation as

$$E_V = \sum_{i=1}^{n} T_i \times P_i \times E_F(i) \tag{2.5}$$

Here P_i can be calculated using engine's nominal power(P_N) and loading factor(L_f). Nominal power is the Engine's maximum rated power in kWh and loading factor is the loading percentage of maximum rated power. This is expressed by

$$P = P_N \times L_f \tag{2.6}$$

Emission factor in this methodology is a function of engine load. These values are provided in Chapter 4. Those values will be used to complete the CO_2 emission computation. Similar to the fuel consumption, emission factor as a function of engine load increases with decrease in engine load [15].

In this methodology emissions are directly dependent on engine loading and engine loading is a factor of maximum rated engine power. Emission factor changes with change in engine loading.

So this chapter of report answers one of the research question of this project, which was to evaluate different type of methodologies to calculate emissions. The Methodologies and their equation presented above have different factors that they depend upon and uses different constant factors accordingly. An overview of two methodologies is given in Table 2.1.

Table 2.1: Summary of methodologies for computing emissions

Specific fuel consumption method	Engine loading method
1. Depends upon fuel consumption	1. Depends upon engine loading
2. Fuel consumption at specific load is needed	2.Engine loading profile is needed
3. Engine specifications are needed	3.Voyage time or velocity and voyage distance is needed
4. Emission factor units in (g/L)	4. Emission factor units in (g/kWh)

This engine loading methodology will be used to compute CO_2 emissions of a typical B.C. ferry and the results will be compared with the results of other proposed propulsion architectures.

Chapter 3

PROPULSION ARCHITECTURES

This chapter is about understanding different propulsion architectures that are presently being used or can be used in passenger ferries. First and base propulsion architecture for this project is Klitsa B.C. ferry which services between Brentwood Bay and Mill Bay. This architecture is also called diesel-only. This base architecture will then be used in second architecture to run on Liquefied Natural Gas (LNG) as the main fuel type. As specified by B.C. Ferries in [10], LNG will be readily available for use close to ferry ports. Also B.C. ferries has already launched a full LNG propelled ferry so it will be interesting to see the effects on CO_2 emission levels with this fuel type. A third architecture of energy storage system (ESS) to run the hotel load will be used with on-shore power supply from B.C hydro. For this architecture, lithium polymer (Li-NMC) battery storage system will be designed to completely run ships hotel load on ESS. Onshore power supply will change this battery during docking time. These results will then be analyzed with the results from the base techniques in Chapter 4.

3.1 Diesel-only Propulsion Architecture

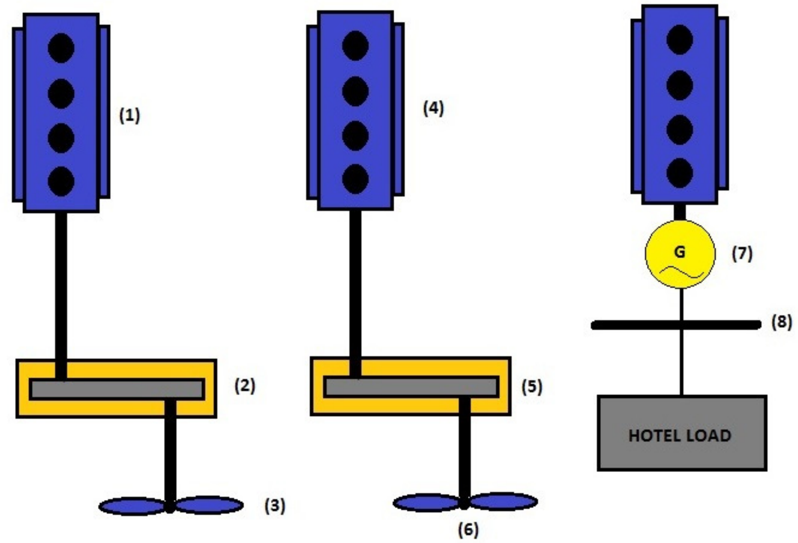

Figure 3.1: Typical diesel-only propulsion architecture

A typical architecture of a modern day ship is a diesel-only architecture. An example of this architecture is shown in Fig. 3.1. This architecture consists of a prime mover (1 and 4), which is typically a diesel engine. This prime mover is responsible for propulsion of the ship. The prime mover is connected to propeller (3 and 6) either directly or through a gearbox (2 and 5). In this architecture another diesel generator (7) is used which is connected to AC network (8). This is responsible to generate power for hotel load which include variable speed drives, heating and ventilation, air conditioning and other electrical loads. Diesel engines are either high speed or low speed. This is determined according to the need of the vessel [12]. This type of Architecture is used in Klitsa B.C. ferry. This architecture will be used as base of the CO_2 emission comparison as it is the most commonly used technology for now. Specific details of the Klitsa's propulsion architecture are given below.

3.1.1 Propulsion Architecture of Klitsa Ferry

Klitsas propulsion architecture consists of two main diesel engines which are used for propulsion. Maximum continues rated power (MCR) of each is 250kW. One is at one end of the vessel and other at the other end. For hotel load there is a 25kW diesel generator. This ferry has maximum output of 700 HP and can load up to 19 cars. This type of ferry uses heavy fuel oil (HFO 0.5% S) which has 0.5% sulphur content in it.

This ferry has a voyage time of 2000 seconds which is approximately 33 minutes. This voyage time can be divided into 10 minutes of docking in which ferry is loaded and unloaded. The remaining 23 minutes of voyage is considered cruising.

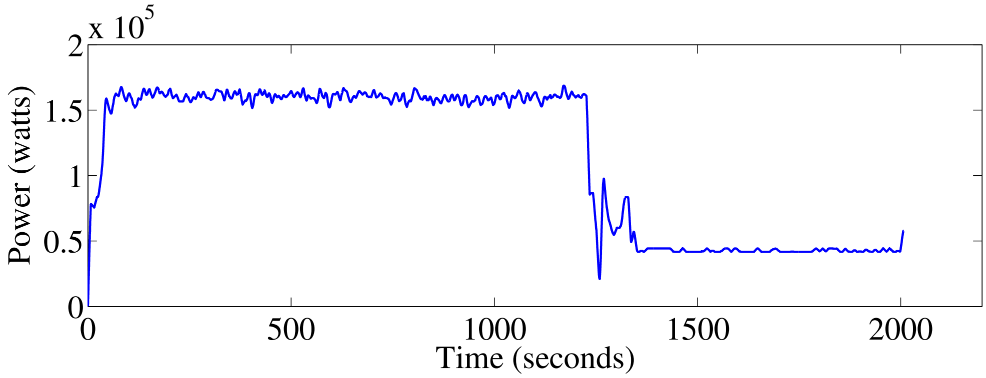

Figure 3.2: Klitsa's main engine loading profile

Fig. 3.2 represents engine loading with respect to voyage time. This is just for 1 of the 250kW main engine. It can be seen in the figure that from (0-1300 seconds) which is cruising time, engine loading factor is 64%. 160 kW of power is consumed during cruising for 1300 seconds. This was calculated using Eq. (2.6). As explained in Chapter 2, that diesel engines using HFO as fuel, produce less emission on higher loads. So this 64% of loading is achieved during the first 50 seconds of operation to run engine in its efficient range to produce less emissions. During the docking period

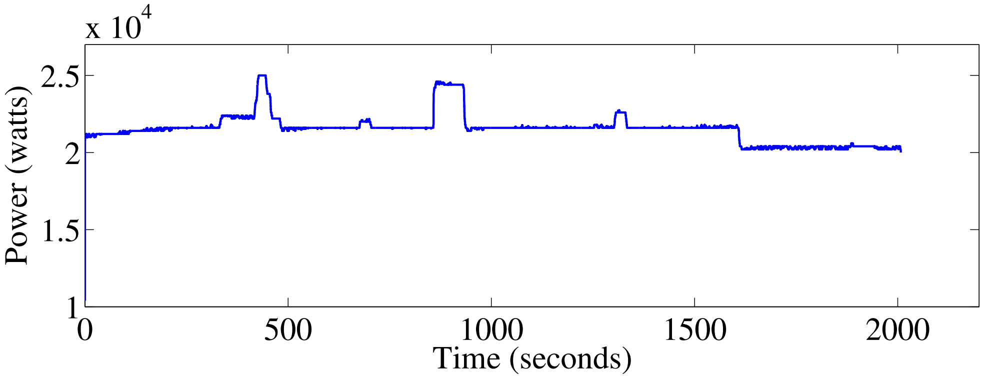

Figure 3.3: Loading profile of Klitsa's generator for hotel loads

engine is running at 16% loading factor and during deceleration period engine loading varies between 40-10% of MCR rating, which is between 100kW and 25kW. Similar to loading of main engine is the loading of diesel generator which is given in Fig. 3.3. Generator loading is almost constant because of the short voyage of this ferry. So the generator runs on a constant load and produces constant power output of 22kW. As this ferry operates for a small voyage so the load of on board heating and air conditioning does not change much which keeps the load profile constant.

3.2 Dual-Fuel Propulsion Architecture

HFO is used in traditional diesel engines, which produces higher emissions. A shift from HFO to LNG is expected to reduce the harmful emission. New proposed techniques presented in [22] [15] [1] [14] uses LNG in the dual-fuel engine architecture. This engine configuration can operate using a mixture of HFO and LNG. All these studies focus their work on either high or low pressure LNG injection system. High pressure injection system was used in this project as it results in complete combustion of methane [15]. This cannot be achieved in low pressure injection methods and methane is emitted into atmosphere.

In this type of architecture the conversion of main engine of the ship to operate on LNG will require some modifications. Some of the modifications presented in [1] includes LNG fuel storage containers and piping and gas safety related changes. The original engine is unchanged but an LNG supply system is added which includes gasholder, gasifier, pressure relief device and two jet valves. An example of this engine conversion is presented in Fig. 3.4 which also includes an electronic control system (ECS) which controls the mixture of LNG and HFO [14]. This Architecture will be used for LNG CO_2 emission computation. It will use HFO at start-up which is diesel mode and will shift to LNG when warmed up. This will be only done once in a day because the ferry does not shut its engines between voyage times as it is really harmful for lifetime of engine. The quantity of natural gas injected is controlled by algorithms which determine the amount of mixture needed. These are optimized to achieve least emission and fuel consumption and best engine performance. To reduce emission it is preferred to reduce HFO oil percent as much as possible. The highest emission reduction of dual-fuel engine can be achieved at 5% HFO and 95% natural

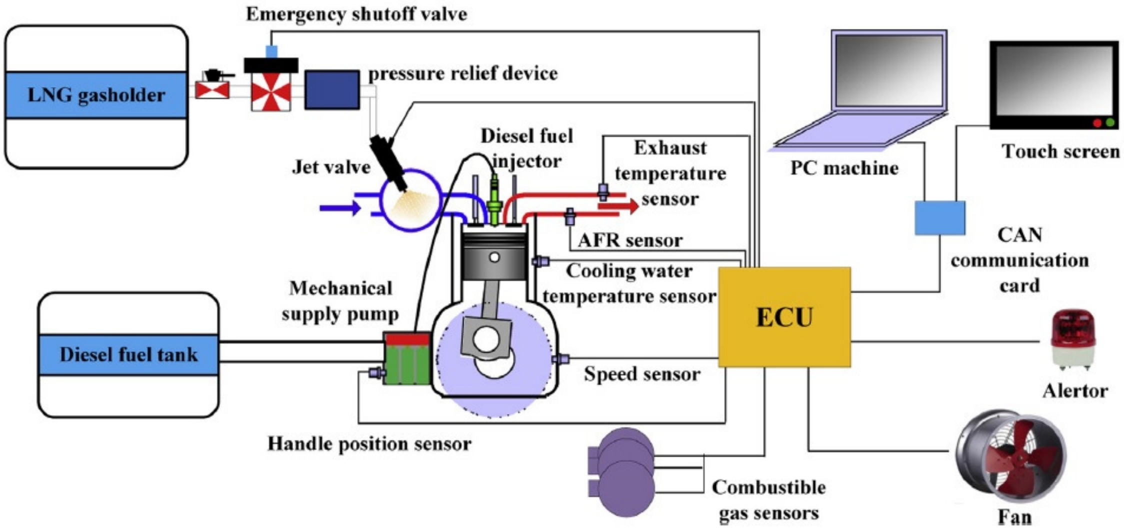

Figure 3.4: Typical dual-fuel propulsion architecture [14], with permission

gas [1].

3.3 Hybrid Propulsion Architecture

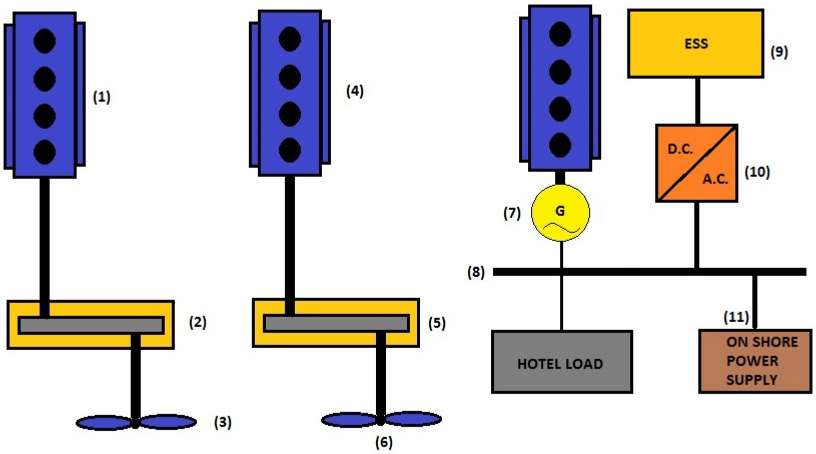

Figure 3.5: Typical hybrid electric propulsion architecture

This Propulsion architecture uses a combination of (ESS), onshore power supply and traditional diesel-only propulsion. This architecture is popular in passenger and ferry class as their voyage time is small and onshore charging is possible. ESS for bigger ships is used to provide power during peak loads. This is called peak shaving. But for ferry class as the load size and voyage time is small so full electrification is possible. Full electrical type of architectures are already in operation. One example of this started its sailing in January 2015. Named as MF Ampere, this ferry can accommodate 120 cars and 360 passengers. Voyage time is 30 minutes. This ferry operates between Oppedal and Lavik in Norway. It operates using 1MW of battery capacity and is charged when it arrives at the dock using shore power supply [19]. The battery system (ESS) was provided by Corvus energy which is a specialized company for ESS and hybridization of ships [4].

3.3.1 Architecture Designed to Calculate CO_2 Emissions

A hybrid electric propulsion architecture that will be used to analyze CO_2 emissions is shown in Fig. 3.5. Similar to the diesel architecture, hubrid architecture includes two individual prime movies (1) and (4) which are connected to individual propellers (3) and (6) through gearbox. Diesel generator (7) is included as a backup power source. On the newer addition side an (ESS) (9) which includes Li-NMC battery racks is included with a DC to AC converter (10). This is connected to the A.C. bus which is also connected to onshore power supply (11). This power supply is at the port which is getting power by utility services (B.C. hydro in our case).

This hybrid electric architecture will uses HFO 0.5% S to fuel for both prime movers. This is kept the same as the one which was used for Klitsa B.C. ferry. On the other hand the electrical generator used for generating power for hotel load will be used only if our ESS fails or loses its charge because of emergency situations. So the main hotel power will be supplied from a battery system which will be sized accordingly and to charge this battery onshore power supply will be used. Onshore power will also be used to power the hotel load during docking times as the battery will be in charging mode. Complete charging of batteries will be done overnight using supply from B.C hydro.

This type of design is selected because of the nature of hotel load. As we know that engine load varies with movement of ship. So basically it depends upon conditions such as wind and tidal effects etc. But on the other had hotel load of Klitsa will remain same during each typical voyage. So it is more feasible to design a battery system for a load that will remain constant during any changing conditions.

3.3.2 Battery Type for Hybrid Electric Architecture

Specifications of the battery that will be used for the hybrid architecture is very important aspects as the ESS systems reliability depends upon that. Battery used in worlds first fully electric-driven ferry (Ampere) could be used as a reference as that ferry is already in operation. The main challenge that is faced in battery selection is weight to power ratio. As we want the weight of the battery to be as minimum as possible. Battery selection for Ampere ferry was also done keeping the same considerations. Ampere [3] contains AT6500 modules which contain 24 Li-NMC cells. This ESS is provided by Corvus Energy Company [3]. According to Corvus lithium polymer cells are selected because of the high power density, which is 951W/kg. This value is really high in comparison with conventional lead-acid battery (41W/kg) and lithium ion (685 W/kg) [3]. So this high power density of lithium polymer keeps the weight of battery low in comparison to it power storage capacity. On addition to that Li-NMC type has a maximum charge/discharge rate which helps to rapidly charge on board batteries during docking time. This can be done by either using a battery bank on the shore or using direct utility power if available close to shore [3].

In the hybrid design architecture presented in this chapter, Li-NMC type battery will be considered and its size will be selected to power the hotel load for whole day without any charging needs. But for reliability onshore power supply will be used to charge the battery during docking time. Onshore power will also be used during docking time to run the hotel needs directly so that battery power is not drained.

3.3.3 Battery Sizing Calculations

For calculating the optimal capacity of battery pack that is needed to operate the hotel load of Klitsa ferry for one whole operational day, first the total energy need should be calculated in kWh. On calculating results concluded that Klitsa requires

22kW of hotel power(P). So to calculate energy consumed per voyage (E_V) Eq. (3.1) is used.

$$E_V = P \times T_C \tag{3.1}$$

According to information provided by B.C. ferries [11]. Total voyage time is about 33 minutes which is about 2000 seconds. So 1600 seconds of cruising(T_C) and 400 seconds of docking if this data is broken into docking and cruising time. So total energy consumed in cruising time(T_C) is 10 kWh.

According to [11], Klitsa ferry has 18 voyages per day. So 180kWh or energy will be consumed by hotel loads of Klitsa ferry in one day. The battery should be able to provide this amount of energy. But battery should not be discharged below 40% of its capacity because this will harm the battery and affect its lifetime. So to consider that, total energy consumption should be increased by 40% so that the battery is sized accordingly. On top of that 20% safety and rounding figure is also added. So the total energy needed for the hotel load becomes 300kWh. So to calculate the capacity of battery for this energy with slow discharge rate, equation provided in [2] is used.

$$DC_{amp} = \frac{KVA \times P_f \times 1000}{E_f \times DCV} \tag{3.2}$$

Where KVA is apparent power, P_f is power factor, E_f is efficiency of battery, DCV is discharge voltage of battery. This efficiency is considered as this battery pack includes D.C. to A.C. converter. To further clarify this formula, true power is equal to

$$P_{true} = KVA \times P_f \tag{3.3}$$

But true power needs to be calculated for this case using 300kWh energy consumed. So calculating the operation time of battery during one day is 8.5 hours as 2 hours is just docking. We get the true power(P_{true}) which is 35kW. As in this case the battery is being used at 100% load so the efficiency of battery(E_f) is considered to be 91% according to battery data-sheet [7]. DCV of the battery is one specific quantity which determines the way battery behaves. Any power (P) can be computed as

$$P = V \times I \tag{3.4}$$

So this explains that power is directly dependent on voltage (V) and current (I). But in this case power is constant (35kW). So if we will increase the DCV, ampere output of the battery will reduce and vice versa. For example for the Ampere ferry the DCV is selected to be between 900V-1100V range [5]. But for this project design 480V was selected from the vendor data-sheet [7].

These specific conditions conclude that, 81 Amp of true continuous current will be needed to power 300kWh of hotel load for Klitsa ferry. This is comparatively lower than Ampere ferry which is reported to be 225 Amp by Corvus in [3]. So to support hotel load for Klitsa ferry, battery similar to the one sized above can be used.

Chapter 4

ANALYSIS OF CO_2 EMISSIONS USING DIFFERENT PROPULSION ARCHITECTURES

In this chapter, results of CO_2 emission of individual architecture are reported. These results are analyzed and then compared using MATLAB. This will help us to examine the potential of reducing CO_2 emissions in dock and coastal areas. For this process engine loading methodology which was explained in Chapter 2 is used. This methodology is selected because the real time loading data was available for the B.C. ferry which is the base architecture to compare the other two proposed propulsion architectures.

4.1 Computation and Results of Diesel-only Propulsion Architecture

As the loading profiles of main propulsion engine and the diesel generator are available and shown in Fig. 3.2 and Fig. 3.3 respectively. So engine loading methodology was used to compute CO_2 emission for this architecture. These loading factor values are used to determine the emission factor in g/kWh. Table 4.1 shows emission factor which is used to calculate CO_2 emission for HFO (0.5% S) operated vessel with high and low loading factor.

Table 4.1: Emission factor of HFO 0.5% sulphur [15]

Loading factor	Emission factor of CO_2
High load (41% - 90% loading)	570 g/kWh
Low load (10% - 40% loading)	630 g/kWh

Eq. (2.5) was used for computation. But there was one problem that occurred as the sampling of the real time data was not uniform. The data was recorded in 60,000 different time intervals which were unequally spaced. So trapezoidal rule methodology was used, which states that total integral can be calculated by integrating each sub-interval and adding them together. A general equation for trapezoidal rule is given as:

$$I = \int_{x_0}^{x_n} f(x)dx = \int_{x_0}^{x_1} f(x)dx + \int_{x_1}^{x_2} f(x)dx + ... + \int_{x_n-1}^{x_n} f(x)dx \qquad (4.1)$$

This can be further derived as:

$$I = (x_1 - x_0)\frac{f(x_0) + f(x_1)}{2} + (x_2 - x_1)\frac{f(x_1) + f(x_2)}{2} + ... + (x_n - x_{n-1})\frac{f(x_{n-1}) + f(x_n)}{2} \qquad (4.2)$$

So for the unequally placed sub-intervals of time in the load data can be sampled using Eq. (4.2) as

$$\Delta T(n) = T_{n+1} - T_n \tag{4.3}$$

Power for the same interval of time can also be sampled using the same equation. This is the specific power for that specific interval of time.

$$P_E(n) = \frac{P_n + P_{n+1}}{2} \tag{4.4}$$

So after this computation Eq. (2.5) can be derived as:

$$E_V = \sum_{n=1}^{n} \Delta T(n) \times P_E(n) \times E_F \tag{4.5}$$

Where E_V is emissions per voyage. This itself is a vector quantity and can be plotted using MATLAB.

4.1.1 CO_2 Emission Results

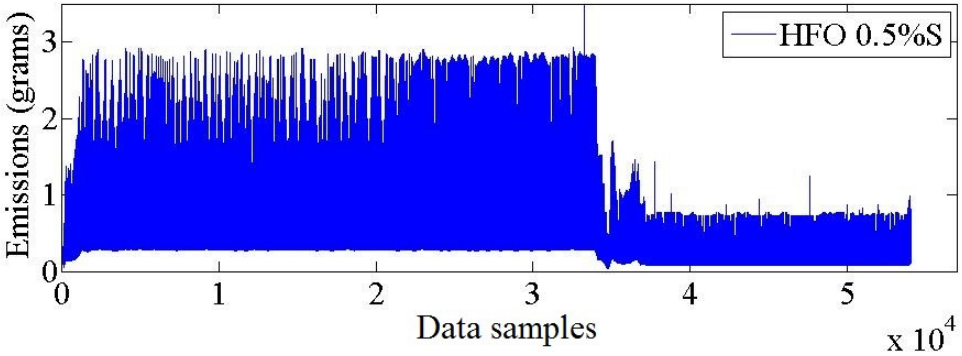

Figure 4.1: CO_2 emissions from Klitsa's main engine

Fig. 4.1 represent emission from one of the main diesel engine per voyage. As calculated in Chapter3, engine runs at 64% loading factor during cruising. Emissions caused because of cruising can seen in Fig. 4.1 from starting till 1300 seconds of voyage. This shows that emission are more during higher engine load and reduces when ship is in the docking phase. Docking phase is between (1301-2000) seconds of voyage. As the loading factor is between 40%-10% in docking so in results emission are also lower. On an average 2.8 gram of CO_2 is released into atmosphere during each time interval in cruising phase and this reduces to 0.8 gram of CO_2 in docking and loading phase. In parallel with this, the diesel generator for hotel load produces a constant of 0.38 gram of CO_2 during each time interval in whole voyage. This result for hotel load emission is shown in Fig. 4.2. Numerical values of total emission per voyage are presented in Table 4.3 for comparison.

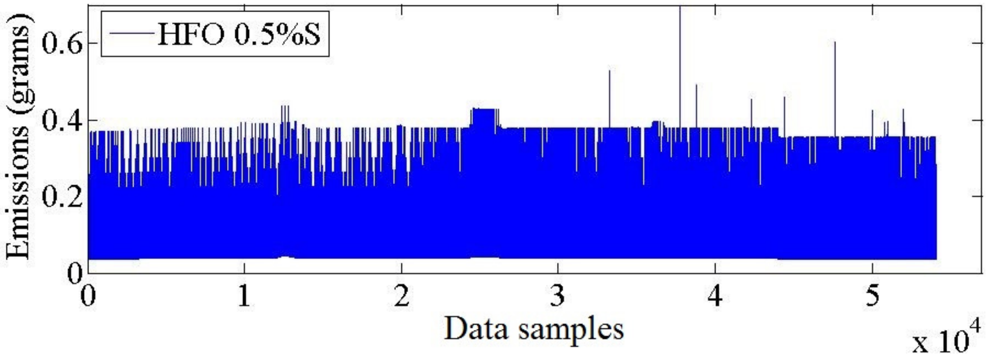

Figure 4.2: CO_2 emissions from Klitsa's generator for hotel loads

4.2 Computation and Results for Dual-Fuel Propulsion Architecture

As per the published data, it is expected that conversion of traditional diesel engine into dual-fuel operated engine should reduce the CO_2 emissions by 15% -25% [1] [20]. So to compare these results we did computation on the same klitsa B.C. ferry. Conditions for this architecture are following:

- Ferry takes the same time per voyage. This mean the velocity of ferry remains the same as it operates in real.
- The real time loading data was considered for the loading of dual-fuel engine as well.
- Emission factor was selected as per mixture of 95% LNG and 5% HFO as it results in least emissions.

Using these conditions the CO_2 emissions were calculated using equation (3.3) and emission factors presented in Table 4.2

Table 4.2: Emission factor of Dual-fuel (LNG and HFO 0.5%S)[15]

Loading factor	Emission factor of CO_2
High load (41% - 90% loading)	450 g/kWh
Low load (10% - 40% loading)	490 g/kWh

4.2.1 CO_2 Emission Results

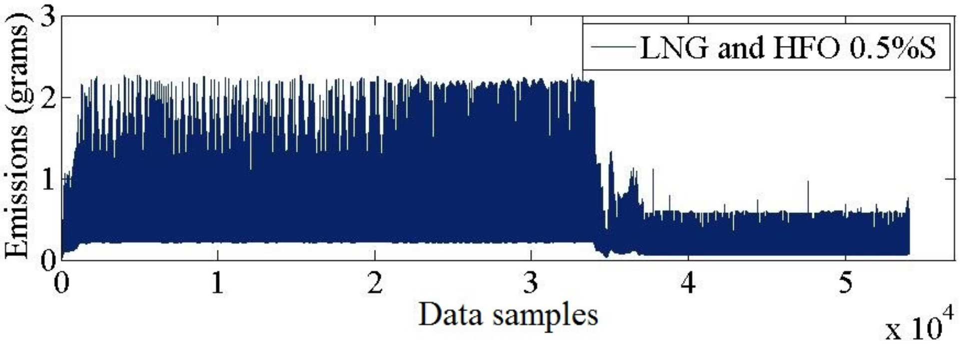

Figure 4.3: CO_2 emissions from dual-fuel operated main engine

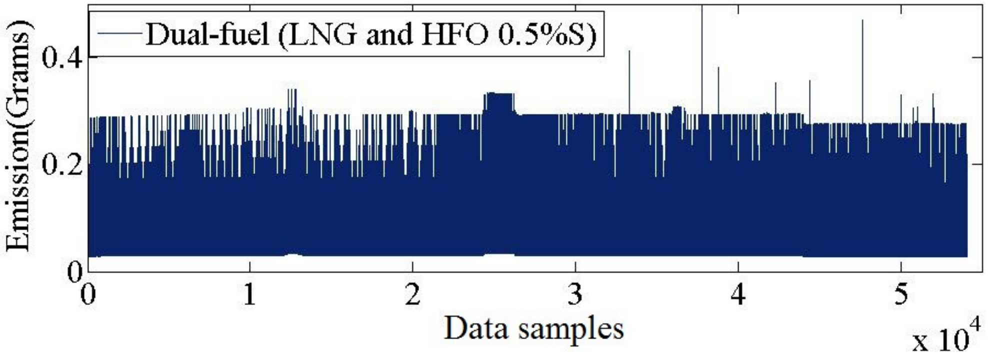

Figure 4.4: CO_2 emissions from dual-fuel operated generator for hotel loads

Fig. 4.3 represent emission per voyage from one of the main engine operating with dual-fuel technology. Similar to diesel-only, engine of dual-fuel also runs at 64% loading factor during cruising. Emissions caused because of cruising can seen in Fig. 4.3 from starting till 1300 seconds of voyage. This shows that emission are more during higher engine load and reduces when ship is in the docking phase. Docking phase is between (1301-2000) seconds of voyage. As the loading factor is between 40%-10% in docking so it results in lower emissions. This shows that emission are more during higher engine load and reduces when ship is in the docking area similar to diesel-only. On an average 2.2 grams of CO_2 is released into atmosphere during each time interval in cruising phase and this reduces to 0.6 grams of CO_2 in docking and loading phase. In parallel with this, the generator for hotel load produces 5884 gram of CO_2 during whole voyage. This result for hotel load emission is shown in Fig. 4.4. Same as above, total emission per voyage are presented in Table 4.3 for comparison.

4.3 Computation and Results for Hybrid Propulsion Architecture

As discussed in Chapter 3, this architecture uses the same engine as diesel-only propulsion architecture for propulsion. So according to that the emission from the prime movers are same as Fig. 4.1. But on the other hand ESS system is used to power hotel load. This energy in ESS will be stored using utility power from B.C hydro in Klitsa's B.C. ferry case. This also counts for the onshore power supply as the utility provider is B.C. hydro itself. So to compute the engine loading methodology emission factor for B.C. hydro was used. According to [13] 10grams of CO_2 is emitted into atmosphere per kWh form B.C. hydro power. As 97% of the power generation is from renewable and hydro generation stations so the emission factor is really low. Lifetime emissions for manufacturing and recycling Li-LNC were not considered for this calculations as that topic is still under research. So no reliable data could be used for the calculations. Total emissions per voyage for hotel load were calculated to be.

4.3.1 CO_2 Emission Results

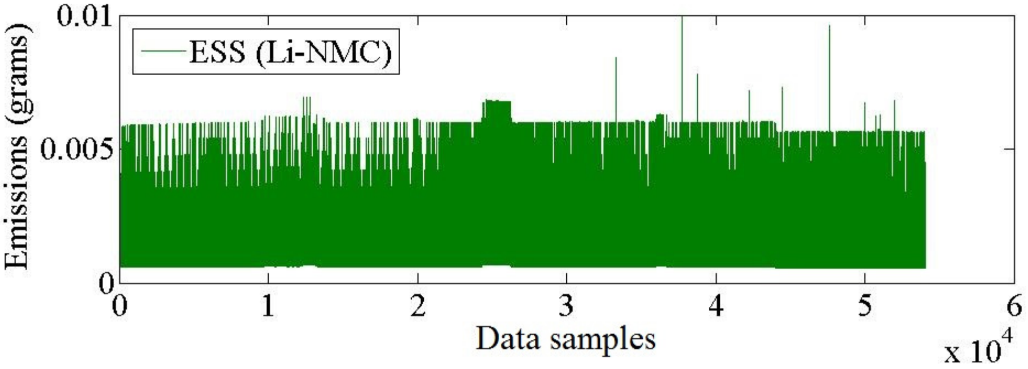

Figure 4.5: CO_2 emissions from using ESS for hotel loads

Main engine emissions of Hybrid architecture are same as Fig. 4.1 as no changes were made. MATLAB results in Fig. 4.5 are emission of hotel load. This figure shows that on average 0.006 gram of CO_2 is released into atmosphere during one voyage. Results of hybrid are really low as compared to the other two architectures. Total emission per voyage are presented in Table 4.3.

4.4 Comparison of CO_2 Emission Results

4.4.1 Comparison of Emissions from Diesel-only and Dual-Fuel Architecture

Fig. 4.6 represents comparison between emissions from prime mover of diesel propulsion architecture using HFO 0.5% S and prime mover of Dual-fuel propulsion architecture. Computation resulted that total 80.448 kg of CO_2 is produced from using two prime movers simultaneously during one voyage. Klitsa B.C. ferry operates for 18 voyages per day. So Total CO_2 emission per day form main engines was calculated as 1.44 ton of CO_2 per day. This results when compared with dual-fuel architecture, indicated about 22.21% reduction in emissions in case of using LNG as primary fuel.

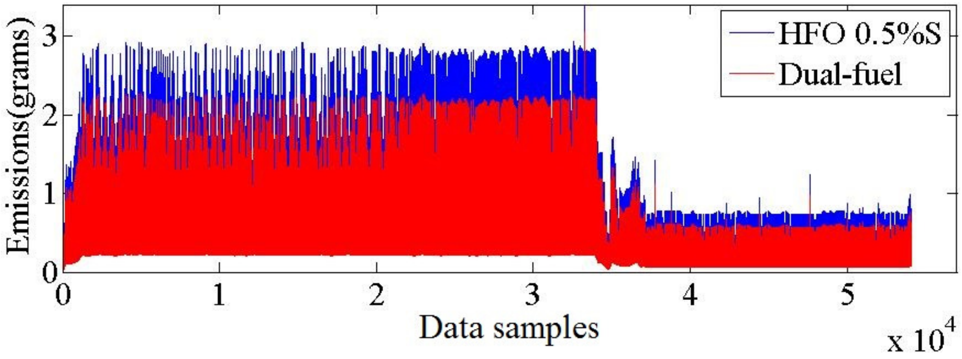

Figure 4.6: Comparison between CO_2 emissions from main engine of diesel-only and Dual-fuel architecture

Results for dual fuel architecture emissions were 62.57 kg of CO_2 in one voyage from 2 main engines and 1.126 ton for whole operational day.

Fig. 4.7 shows comparison between emission form generator using HFO and dual-fuel for hotel power generation. This figure indicates the decrease in the amount of emission by switching to Dual-fuel architecture.

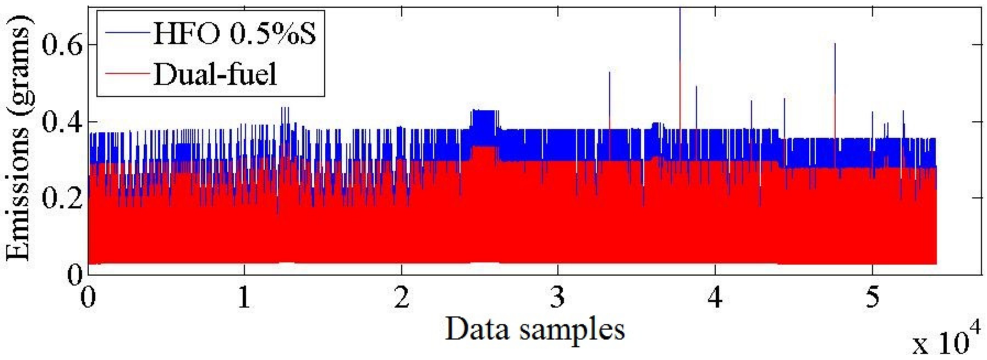

Figure 4.7: Comparison between CO_2 emissions from generator of diesel-only and Dual-fuel architecture

Results show that a total of 7.56 kg of CO_2 is produced from generator of diesel architecture during one voyage. So total CO_2 emissions per day form HFO fueled generator are 136.08 kg. These results when compared with Dual-fuel architecture, indicated about 23% reduction in emissions in case of using LNG as primary fuel. Emission for dual-fuel were, 5.88 kg of CO_2 in one voyage from the generator and 105.84 kg for whole operational day.

4.4.2 Comparison of Emissions from Diesel-only and Hybrid Architecture

Emissions from the main engines in diesel-only and hybrid are same as no changes were made and only hotel load for hybrid architecture was run on ESS and onshore power. Emission reduced by 98% in case of hybrid architecture in comparison to diesel-only architecture. In numerical values only 120 grams of CO_2 was emitted during one voyage which comes out to be 2.16 kg during one whole day of operation.

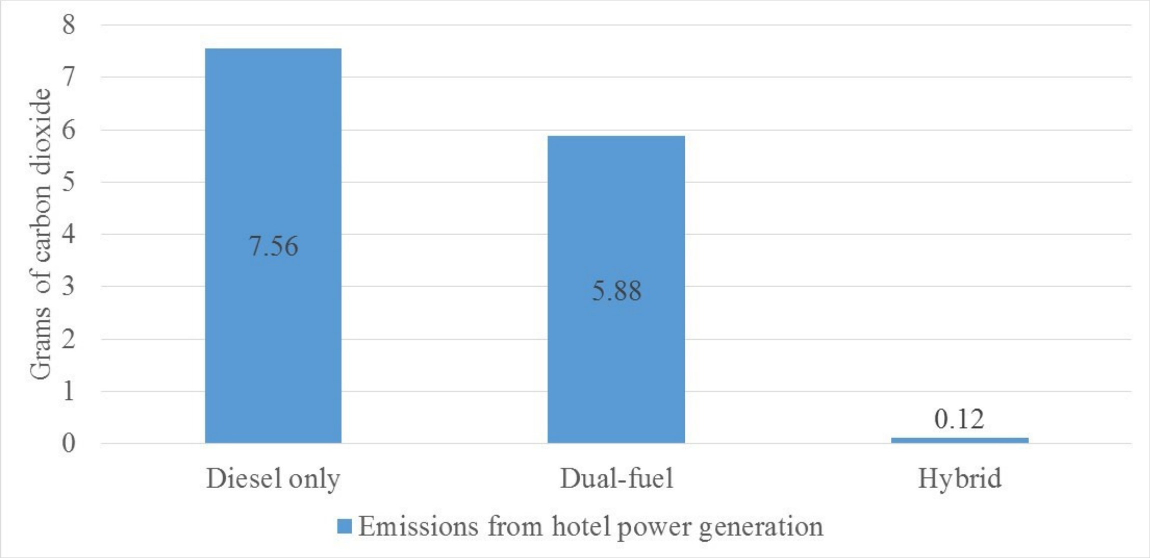

Figure 4.8: CO_2 Emissions from hotel power generation(per voyage)

These emissions in the case of ESS propelled hotel load are really low as compared to HFO fueled generator. So graphical representation method was chosen to show the comparison for whole operational day. Fig. 4.8 shows the total emissions produced related to hotel load per day by diesel, dual-fuel and hybrid architecture.

Fig. 4.9 shows the comparison of total emissions per day for three architectures used in this project.

Table 4.3 shows the detailed numerical results.

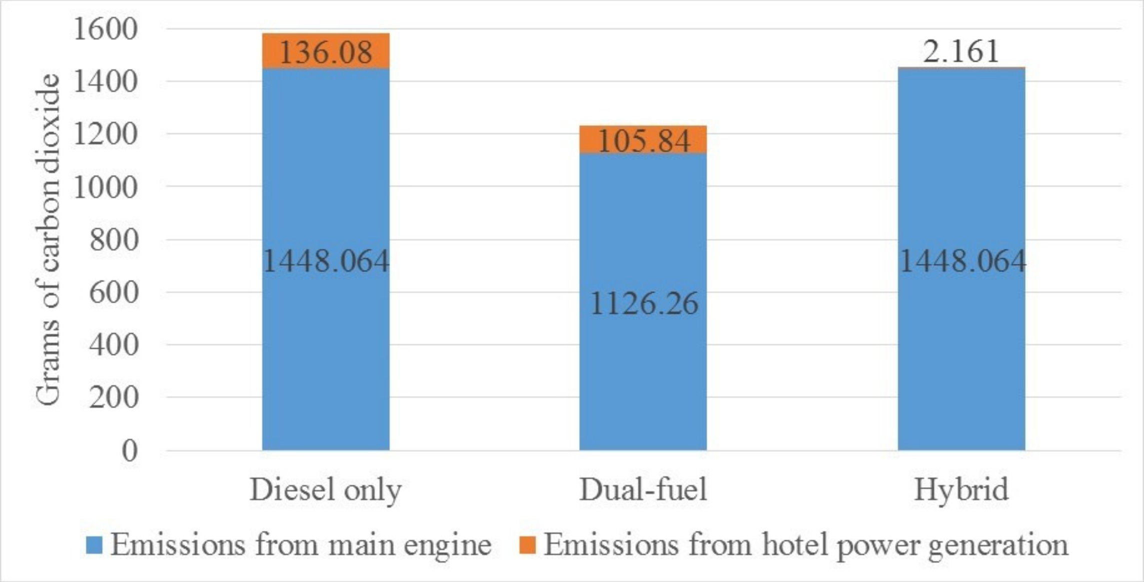

Figure 4.9: Total CO_2 emissions from each architecture (per day)

Table 4.3: Detailed CO_2 emissions per voyage

Propulsion architecture	Fuel type	Emissions (Main engines)	Emissions (Hotel)
Diesel-only	HFO 0.5% Sulphur	80.448 kg	7.56 kg
Dual-fuel	LNG and HFO 0.5% S	62.57 kg	105.84 kg
Hybrid	HFO 0.5% S and Li-NMC battery	80.448 kg	0.120 kg

Chapter 5

Conclusion

Results presented in Chapter 4 indicate that LNG as fuel results in less CO_2 emissions as compared to traditional HFO. As the CO_2 emissions reduced by about 22%. BC Ferries have already moved towards using LNG as a fuel source for its fleet. In addition to the benefits of lower emissions, LNG is also less expensive than the ultra-low sulphur HFO currently used by the B.C. ferries, which translates to lower overall fuel expense, which in turn helps lessen the upward pressure on fares [10].

B.C. ferrie's two largest vessels, the Spirit of Vancouver Island and the Spirit of British Columbia, operating between Swartz Bay and Tsawwassen, are undergoing upgrades, which will include the conversion of their main propulsion systems to dual-fuel capable, such that they will use LNG as their primary fuel [10] which is similar to the Dual-fuel proposed architecture presented in this project. So this architecture can also be used for Klitsa ferry to reduce between 20-25% of CO_2 emissions.

Hybrid Architecture is even cleaner than Dual-fuel only if the power being used to charge the batteries is clean. As B.C. hydro power is 97% clean, So in case of B.C. ferries the ESS system will results in about only 2% emissions as compared to HFO. These values are really low and favorable for the environment. This process can be taken under consideration as there is already a fully electric ferry working in Norway. This ferry uses a ESS system designed by Corvus which is located in Richmond, B.C. So best opportunities are available for B.C. ferries to collaborate with Corvus energy and install either ESS for hotel power or for the whole ship operation. Hybrid Architecture will be better than both diesel-only and dual-fuel because of the clean generated energy available in B.C.

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LIST OF ABBREVIATIONS

AC	Alternating Current
B.C.	British Colombia
CO_2	Carbon Dioxide
CH_4	Carbon monoxide
DC	Direct Current
DCV	Discharge Voltage of Battery
ECA	Emission Control Areas
ESS	Energy Storage System
GHG	Green House Gasses
GWP	Global Wamring Potential
HP	Horse Power
HFO	Heavy Fuel Oil
IMO	International Marine Organization
kWh	Kilo Watt Hour
Li-NMC	Lithium Polymer
LNG	Liquefied Natural Gas
MCR	Maximum Continues Rated Power
Mt	Megatonnes
N_2O	Dinitrogen oxide
NO_X	Nitrogen oxides
RPM	Revolutions Per Minute
SO_X	Sulphur oxides