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Rejard Villegas Marfe

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WORLD MARITIME UNIVERSITY
Malmö, Sweden

A Study on the Environmental Impact of a Fully Battery-Powered Electric Waterborne Transport Along Davao City to IGACOS Route: A Life Cycle Assessment

By

Rejard Villegas Marfe
Philippines

A dissertation submitted to the World Maritime University in partial fulfillment of the requirements for the reward of the degree of

MASTER OF SCIENCE
in
MARITIME AFFAIRS
(MARITIME ENERGY MANAGEMENT)

2020

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Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

(Signature): ....................................................
(Date): ............................................................

Supervised by: ...............................................
Supervisor's affiliation: ........................................}{World Maritime University}
Acknowledgment

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Abstract

Title of Dissertation: A Study on the Environmental Impact of a Fully Electric Waterborne Transport Along Davao City to IGACOS Route: A Life Cycle Assessment

Degree: Masters of Science

This dissertation was conducted to determine the potential environmental impact of fully battery-powered ferries if to replace the existing conventional diesel engine ferries plying the Davao City to IGACOS route in the Philippines.

Aside from the focus on comparing the environmental impact between the two systems using a life cycle assessment (LCA) methodology, the viability of a fully battery-powered ferry to replace the existing ferry operating in the area in terms of volumetric power density and gravimetric energy density was also slightly covered.

The LCA results showed that fully electric ferries powered by lithium-ion batteries (LIB) unexpectedly tend to increase more the Global Warming Potential (GWP) if compared to the conventional diesel engine ferries. This unfavorable result in fully battery-powered electric ferries is attributed to the existing electric power production in the area, which is generated in majority by burning coal.

This study thereby resolves that fully battery-powered electric ferries can only significantly reduce the GWP and other air-related emissions if compared to conventional diesel engine ferries if the electric energy generation is produced through processes that emitted lower or zero GHG emissions such as through renewable energies.

KEY CHARACTERISTICS: Life Cycle Assessment, GHG, Emission Reduction.

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x
<table>
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<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ADO</td>
<td>Automotive Diesel Oil</td>
</tr>
<tr>
<td>AE</td>
<td>Auxiliary Engine</td>
</tr>
<tr>
<td>Ah</td>
<td>Ampere-hour</td>
</tr>
<tr>
<td>BEV</td>
<td>Battery Electric Vehicle</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
</tr>
<tr>
<td>CO₂-eq</td>
<td>Carbon Dioxide Equivalent</td>
</tr>
<tr>
<td>CH₄</td>
<td>Methane</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DENR</td>
<td>Department of Environment and Natural Resources</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>EoL</td>
<td>End of Life</td>
</tr>
<tr>
<td>EV</td>
<td>Electric Vehicle</td>
</tr>
<tr>
<td>GHG</td>
<td>Green House Gas</td>
</tr>
<tr>
<td>GWP</td>
<td>Global Warming Potential</td>
</tr>
<tr>
<td>GloMEEP</td>
<td>Global Maritime Energy Efficiency Partnerships</td>
</tr>
<tr>
<td>ICEV</td>
<td>Internal Combustion Engine Vehicle</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IGACOS</td>
<td>Island Garden City of Samal</td>
</tr>
<tr>
<td>IMO</td>
<td>International Maritime Organization</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>kW</td>
<td>Kilowatts</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt-Hour</td>
</tr>
<tr>
<td>KVA</td>
<td>Kilo Volt-Ampere</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Assessment</td>
</tr>
<tr>
<td>LCE</td>
<td>Levelised Cost of Energy</td>
</tr>
<tr>
<td>LCIA</td>
<td>Life Cycle Impact Assessment</td>
</tr>
<tr>
<td>LIB</td>
<td>Lithium-ion Battery</td>
</tr>
<tr>
<td>MARPOL</td>
<td>Maritime Pollution</td>
</tr>
<tr>
<td>MCR</td>
<td>Maximum Continuous Rating</td>
</tr>
</tbody>
</table>
MEPC - Marine Environment Protection Committee
MDO - Marine Diesel Oil
MGO - Marine Gas Oil
Mtoe - Million Tons of Oil Equivalent
N₂O - Nitrous Oxide
nm - Nautical Miles
NMP - N-methyl pyrrolidone
NOₓ - Nitrogen Oxides
PHEV - Plug-in Hybrid Electric Vehicle
PSV - Platform Supply Vessel
PKT - Person Kilometre Travelled
SOC - State of Charge
SOₓ - Sulphur Dioxide
TFEC - Total Final Energy Consumption
RORO - Roll-on/Roll-off
UNFCCC - United Nations Framework Convention on Climate Change
US EPA - United States Environmental Protection Agency (USEPA)
UWS - Urban Water Shuttle
VKT - Vehicle Kilometre Travelled
Wh - Watt-hour
WTP - Well-to-Pump
WTW - Well-to-Wheel
CHAPTER 1: INTRODUCTION

1.1 Background information

There is 2748 million tons of oil equivalent (Mtoe) energy that the global transportation sector used and consumed in 2016, accounting for about 29% of the world's total consumption (IEA, 2018). In the coming years, the world may face enormous challenges that may be brought about by the continuous increase of transportation, resulting in a massive growth of climate change, which would eventually increase global temperature, a substantial rise in sea level, and more extreme weather phenomena.

In December 2015, due to apparent and noticeable effects of climate change, during the 21st United Nations Climate Change Conference in Paris, the Paris Agreement was characterized and signed by 195 countries, making this the most challenging global climate agreement in an ambition to reduce global greenhouse gas (GHG) emissions and other air-related emissions by setting a target of future global surface temperature increases to remain within 2°C (Lee, 2016). If this agreement is to be met, the Intergovernmental Panel on Climate Change (IPCC) states that 40 to 70 percent of global air emissions should be reduced by 2050 compared to 2010. If not reached, the IPCC then suggests a more complicated and challenging target of implementing negative emissions at the end of this century (Petersen et al., 2016).

Roughly 90 percent of the world's commodities are transported by ships. Accordingly, water transportation will continue to rise to as much as 3.8 percent annually by 2022 (UNCTAD, 2014). Though shipping is generally considered a highly fuel-efficient mode of transportation in terms of cargo per ton-nautical mile, its rapid growth and sheer volume make it a significant user of energy and source of air-polluting emissions. Arguably, global maritime shipping is the next biggest energy consumer and carbon emitter after commercial vehicles and road passengers considering that it
uses about 11% of the worldwide transportation sector's petroleum, which is equivalent to about 5 million barrels per day. This emission equates to 1 Gt CO2 emissions annually (EC, SEC, 2005).

Recently, the International Maritime Organization (IMO) has agreed on the "IMO Strategy on Reduction of GHG Emission from Ships" with the aim of reducing GHG emissions from international shipping as environmental pollution has become a primary global concern (IMO MEPC 72nd session, 2018). These regulations are in response to the rapid development of the worldwide economy that prompted the sober crisis of fast depletion of fossil fuels and increased environmental pollution (Xie et al., 2018). As an added response, different research efforts on alternative energy sources are carried out to cope with environmental regulations that are strengthening internationally in the shipbuilding and shipping industries (ABB Group, 2011). As such, the possibility of using ship electrification is one of the emerging countermeasures being highly considered for short-distance shipping (McCoy, 2002). The 2017 World Fleet Register by Clarkson's Research says that environmentally-friendly electric propulsion ship is dramatically increased (Vasquez, 2017).

Strengthening and implementing electric transportation on short-distance routes in the maritime sector is no longer impossible with the now presence of low specific energy and state of the art batteries like lithium-ion batteries (Postilione et al., 2012). Mobility electrification is becoming a reality, and batteries can be a sustainable solution not only in the household and commercial sectors but also in transportation. The implementation of electric boat usage was already materialized in some islands in Europe and isolated communities in response to the challenges in the price of energy and the demand for efficient renewable energy sources. The first-ever fully electric ferry powered by lithium-ion batteries named "Ampere" can be found in Europe and even became the "ship of the year" in 2014. Similar type ferry, named "Movitz Ferry" and uses Nickel-Metal-Hydride (Ni-MH) batteries, was built and operated in Sweden. Its operation is anticipated to cut down 130 tons of CO₂ emissions per year when it uses electricity produced from renewable energy resources rather than fossil diesel fuel (Gagatsi et al., 2016). The boat is powered and operated by lithium-ion batteries, which can then be charged at any ports with prepared and installed power charging stations.
after a short voyage. The development aims to have zero emissions (Spagnolo et al., 2012).

With battery propulsion technologies potentially providing zero-emission when they employ electricity produced from renewable resources, GHG emissions could only potentially come from battery manufacturing or the electricity mix. Battery technology is now considered viable for having all the potential to mitigate GHG emissions (Zackrisson et al., 2010). And with battery technology improving in recent years, the batteries' price has also reduced, making it a more economically viable option (Borah et al., 2020). Combining having a potentially zero-emission technology and product affordability makes batteries more attractive in most transportation systems. It is now similarly introduced and presented to both road vehicles and ships (Kullmann, 2016).

In a developing country like the Philippines, going to greener maritime transportation could answer the high price of fossil fuels and higher GHG emissions happening in the country. The Philippines is composed of a water area of 2.2 million km² wherein 88% (1.934 million km²) are oceanic water while the remaining 12% (267,000 km²) are coastal waters. The country has a total coastline estimated of about 32,400 km, with 65% of municipalities and cities and 80% of provinces sharing the coast (DENR, 1999). With the Philippines' archipelagic setting, shipping provides the primary means of inter-island transportation, and the shipping transport industry plays a vital role in the country's aim of lowering GHG emissions. And aside from the possibility of utilizing the usage of alternative fuels, moving towards electric propulsion on ships as powered by batteries could also be an effective and efficient solution to ease the air pollution in the country (Makhsoos et al., 2018).

In recent years, the country has continuously grown to become a newly industrialized country and one among Southeast Asia's growth leaders. The Philippines' economy was even the fastest growing economy in Asia and even overtook China for a few months at the beginning of the year 2016. The Philippines, a country that is very rich in natural resources, is entirely dependent on the shipping sector in goods and people's movement. Without shipping, goods, and passengers from one part of the island will
not reach the other. Therefore, shipping is considered vital to the Philippine economy (Richter, 2016).

The Department of Energy (DOE) in the Philippines states that the Total Final Energy Consumption (TFEC) of the country is anticipated to increase at an annual average rate of 4.3%, from 33.1 Mtoe in 2016 to 91.0 Mtoe in 2040 with the transportation sector to continue as the largest energy-consuming sector with an average share of 38.2% across the entire planning range (DOE, 2017). Figure 1.0 shows the Total Final Energy Consumption in the Philippines by Sectoral Share.

![Figure 1.0 Total Final Energy Consumption in the Philippines by Sectoral Share (Actual 2000–2016, Clean Energy Scenario 2017–2040) (Source: Philippine Energy Plan 2017-2040)](image)

With a 50.5% average share in the demand mix, petroleum products will continue to comprise most TFEC. From 2016 to 2040, irrespective of the volatility of its price in the international market, it is anticipated that the demand for petroleum products will increase by an average of 4.5% per year. Diesel fuel and gasoline will continue to be the most widely-used petroleum products, with average shares of 44.0% and 34.8% in
the total oil demand. Transportation will remain the significant petroleum-consuming sector with an average percentage of 71.9% in the whole oil demand for the entire planning period (DOE, 2017). Figure 2.0 shows the Final Energy Consumption in the Philippines by Fuel, 2000-2040.

![Figure 2.0 Final Energy Consumption in the Philippines by Fuel, 2000–2040 (Source: Philippine Energy Plan 2017-2040)](image)

### 1.2 Problem statement/motivation

Climate change is a very emotional issue for the Philippines. It is viewed not only as creating extra economic burdens but as a critical component that would influence the country's survival as a nation. Many Filipinos live in the coastal areas, making them at risk and at the forefront of the threats of full climatic effects, sea-level rise, and marine ecosystems degradation (DENR, 1999). The Philippines have been known as one of the most vulnerable countries to the impact of climate change, as regularly visited by an average of 22 typhoons annually. The country was even rated as the third most vulnerable country to natural disasters in the world according to the World Risk Report.
2016 and ranks fifth in the Germanwatch Global Climate Risk Index 2017. Notably, in 2013, a first of a kind super typhoon with an international name "Haiyan" has severely hit the country and left more than 7000 people perished and devastated billions of dollars in the amount of infrastructures and agricultural products. Thus, as one of the mitigation responses, in the 2015 Paris Climate Conference, the Philippine government committed of reducing carbon emissions from waste, energy, forestry, industry, and transport sectors by 70% by 2030 to help curb climate change (World Bank, 2015). With that envision, the Philippine government commit to implement policies and look for mitigation measures to ensure the provision of the ecosystem and green services to address the GHG emission and environmental degradation happening in the country (Mogato, 2015).

The Philippine government's strong commitment to do its share in the reduction of carbon emissions and lessen environmental degradation motivates this study, hoping to help pave the way of moving towards green maritime transportation in the Philippines and provide a feasible and effective solution to mitigate climate change.

1.3 Aims and objectives

This study aims to explore the potential of a fully electric ferry powered by a lithium-ion battery by comparing the system to an existing conventional diesel engine ferry plying the Davao City to IGACOS route in the Philippines as the modeled ferry through a comparative LCA method. This study wants to analyse and provide a bigger picture in terms of the environmental impact if ever fully electric ferry powered by lithium-ion battery can significantly reduce the GHG emissions and degradation of the marine environment caused by the shipping industry if 'well-to-wake' (WTW) emissions are considered. The objectives of this paper include the following:

- To determine the feasibility and viability of lithium-ion batteries to fully propel and power ferries typically used in the Philippines and that are involved in short-distance voyages; and
- To performed a life cycle assessment (LCA) between a Fully Electric RORO Ferry powered by Lithium-ion Batteries and the Conventional Diesel Engine RORO Ferry to compare and analyze the environmental impact of these two systems and determine if fully electric ferries could significantly reduce GHG emissions created by the shipping industry.

1.4 Research questions or hypothesis

To achieve the objectives of this study, the following questions have been asked to direct the research:

- How much battery-electric propulsive power and energy storage capacity are needed to propel the modeled ship to achieve its needs in terms of usual operations and without compromising safety?

- Which among the Fully Electric RORO Ferry powered by Lithium-ion Batteries and the Conventional Diesel Engine RORO Ferry in the Philippine setting is more environmentally friendly if GHG emissions were considered from well-to-wake?

1.5 Research scope

This study focused on having a comparative analysis on the GHG impact of a Conventional Diesel Engine RORO Ferry plying the Davao City - IGACOS route in the Philippines and a Fully Electric RORO Ferry powered by a Lithium-ion Battery to determine whether a fully battery-operated ferry would reduce or not the GHG emission emitted from shipping, and if so, by how much.

1.6 Research outline
This dissertation comprises five chapters as organized as follows: Chapter one (1) introduces and gives the background information of the topic, stipulated the problem statement, provides an outline of both the primary and specific objectives, and the scope of the study. Chapter two (2) discusses the technical aspects of the study, such as the components of an electric ferry and LIB’s theoretical background. Chapter three (3) outlines the potential of the electric ferry and the current situation of maritime transportation in the Philippines. This chapter also reviews existing literature on battery storage system applications onboard vessels and life cycle assessments (LCA) conducted on lithium-ion batteries used on different types of vehicles and ships, on fully electric ferry powered by batteries, and on conventional diesel engine ferries. Chapter four (4) outlines the methodologies that have been used in this study, which includes all the calculations of data of the modeled ferry, a comparative LCA between Fully Electric RORO Ferry Powered by Lithium-ion Batteries and Conventional Diesel Engine RORO ferry, presents the results, and discusses them. Lastly, Chapter five (5) gives the conclusion and recommendations of the study.

CHAPTER 2: TECHNOLOGICAL ASPECTS
2.1 Chapter overview

This chapter discusses the technical aspects of the study. This includes the components of an electric ferry and the theoretical background of the lithium-ion battery and its application onboard ships.

2.2 Electric propulsion components

A long way of research and development has been achieved by the shipping industry to strive for low-cost and less-polluting ships. Among all the potential alternative power sources studied, presently, the electrical propulsion system has been considered as one of the best options for short-distance shipping (AbdelGawad et al., 2018). There are different levels of electrification solutions for a ship; diesel-electric, hybrid ferries, and fully electric (Santen, 2018).

The diesel-electric system consists of a propeller connected to an electric motor through a shaft. A diesel engine connected to an electric generator through another shaft. The motor is connected to the generator through suitable electrical wires and drive. Figure 3.0 shows the simple diagram of a diesel-electric system.
A hybrid ferry is a combination of multiple sources of power. An example of this system is a combination of the traditional diesel with electric battery power, which may result in lesser fossil fuel consumption and reduction of carbon emissions and other pollutants.

In hybrid propulsion, the direct mechanical drive provided the thrust for high speeds with high efficiency. Also, to avoid the main engine of running inefficiently when in part load, an electric motor connected to the same shaft through a gearbox or directly to the shaft driving the propeller provides propulsion for low speeds. This motor could also be utilized as a generator and provide electricity on the ship's electrical network (Geertsma et al., 2017). Presented in Figure 4.0 is a typical layout for such a hybrid propulsion system.
While on the other hand, the fully electric ferry only has entirely batteries that provide full propulsion and ship’s power. In terms of the operational profile for electrical operation, this system is suitable for shorter ferry distance routes. While the passengers and rolling cargoes embark and disembark from the ferry, the batteries can be quickly charged from an onshore charging station (SPBES, 2017). Figure 5.0 illustrated the Single-line diagram of a typical, fully electric ferry.
2.3 Battery Technology

A battery is a device that stores chemical energy and, upon demand, converts it into electrical energy that can power numerous types of applications. This is known as electrochemistry, and the system that underpins a battery is known as an electrochemical cell. The electron flow from the electrode to another material, through an external circuit, involves the chemical reactions in a battery wherein this electron flows then provides an electric current that can be used to do work (Bhatt et al., 2016). Recently, battery applications have gained interest, given some promising marine applications. These large-scale applications are due to a collection of factors such as improvement within the area of lithium-ion batteries with more developed capacity, reliability, and lower battery prices (Electronicnotes, n.d).

2.3.1 Battery operations

Electrical energy is stored as chemical energy in batteries and can be released in the form of electrical energy again through redox reactions. Redox reactions are a type of chemical reaction in which simultaneous reduction and oxidation of two types of chemical substances are taking place, usually increasing the oxidation state of one type of atoms and reducing the oxidation state of another. The batteries comprise one or more electrochemical cells wherein each cell is built-up of two electrodes, the anode, and the cathode. These electrodes are immersed in at least one electrolyte solution as separated by a separator (Electronicnotes, n.d.).
Figure 6.0 illustrates the block diagram of a cell or battery powering a device that depicts its essential elements. During charging of the battery, the load is changed with an energy source that applies a reverse voltage that is bigger than the battery voltage, and subsequently reversed the flow of electrons (Winter et al., 2004).

![Figure 6.0 Block diagram of a cell or battery powering a device (Winter et al. 2004)](image)

Figure 7.0, on the other hand, illustrates the operation of a battery, displaying the electrolyte in electronvolts and the energy levels at the anode (negative) and cathode (positive) poles. The negative electrode is an excellent reducing agent or electron donors such as lithium, lead, or zinc. The positive electrode is an electron acceptor like manganese dioxide, lithium cobalt oxide, or lead oxide. While, the electrolyte is purely an ionic conductor and physically set-apart the anode from the cathode (Winter et al., 2004).
2.3.2 Chemical reactions and conversion of energy

To enable the electron flow, you need to have something for the electrons to flow from, and something for the electrons to flow to. These are the cell’s electrodes. The electrodes are made up of active material and a binder material, which keeps the structure of the active material together—during battery discharging, the electrons flow from one electrode, from the negative electrode called the anode, to a positive electrode called the cathode (Goodenough et al., 2007). What defines the characteristic terminal voltage of a cell is the potential difference between the two electrodes. The negative is the anode reduction potential or voltage, while the positive is the cathode reduction potential. In calculating the standard cell potential in a battery, the reduction potential can be used, as shown in equation 1.0 (Linden, 1995).

\[
\text{Standard cell potential} = \text{Oxidation potential} + \text{Reduction potential} \quad \ldots \quad (Equation \ 1.0)
\]
During a redox reaction, which is the transfer of the emitted electrons of the oxidation partner to the reduction partner, the change in Gibbs free energy can be used to calculate the maximum theoretical energy released in a battery, as described in Equation 2.0.

\[ \Delta G^\circ = -nFE^\circ \]  \hspace{1cm} (Equation 2.0)

Where;

- \( \Delta G^\circ \) - Gibbs free energy in Joules
- \( n \) - Amount of electrons in the reaction in mol
- \( F \) - Faraday constant in C/mol
- \( E^\circ \) - Standard potential in Volt

There are three different polarizations in the battery: activation polarization, concentration polarization, and ohmic polarization. The energy released as heat losses during the chemical redox reaction is due to these different polarization (Winter et al., 2004). The energy needed to move the electrons from the electrodes through the external circuit is the activation polarization. While, the energy drop from the impedance in the cell's components is the Ohmic polarization. The ohmic polarization provided by ohm’s law and is proportional to the circuit current, as represented in Equation 3.0 (Linden, 1995).

\[ U = RI \]  \hspace{1cm} (Equation 3.0)

Where;

- \( U \) - Ohmic polarization in Volts
- \( R \) - Resistance in Ohms
- \( I \) - Current flow in the circuit in Amperes
Concentration polarization on the other hand is the change in electrolytic concentration between the electrodes and electrolytes (Linden, 1995). Shown in Figure 8.0 is an example of a polarization processes during one discharge cycle.

![Polarization curve](image)

**Figure 8.0 Polarization curve (FuelCellStore, n.d.)**

### 2.3.3 Capacity and Discharge

The capacity of the battery specifies the measure of available electric energy in the battery. In other words, battery capacity is the battery’s power as a function of time to describe the time duration a battery will be able to power a device. It is quantified within the cell the amount of charge in ampere-hours (Ah). By multiplying the cell potential and Ampere-hours, as shown in Equation 4.0, you can convert Ampere-hours into Watt-hours (Linden, 1995) (Winter et al., 2004). While specific power is the measurement of the power available in a battery to charge or discharge and measured as power per weight of the active material W/kg.
Capacity (Wh) = Ampere-hours (Ah) x Cell potential (V)… (Equation 4.0)

2.3.4 Lithium-ion batteries

Lithium-ion batteries can utilize several materials as electrodes. The usual combination nowadays is lithium cobalt oxide as the cathode and graphite as the anode. Lithium-ion batteries are commonly used in portable electronic devices such as laptop computers and cellphones. Lithium manganese oxide that is used in hybrid electric and electric automobiles and lithium iron phosphate are the other materials used in the cathode. As an electrolyte, lithium-ion batteries typically use ether (Clean Energy Institute, 2020).

After developing the nickel-cadmium battery, a new battery, which is the lithium-ion secondary battery, was then created, which becomes a very significant development to mitigate the crisis of energy and resources and solve environmental pollution problems. Today, lithium-ion batteries have been widely used in laptop computers, cell phones, digital cameras, and many other products (Battery Industry Association, 2011).

2.3.4.1 Basic Operating Principles

A schematic diagram of the basic operation of a lithium-ion cell is illustrated in Figure 9.0. The separator isolates the positive and negative electrodes. Simultaneously, during charging, the lithium ions are separated from the positive electrode material. They proceed within the membrane to cut-in into the bedded structure of the negative electrode material. During discharge, the lithium ions are removed from the negative electrode material and re-migrated through the diaphragm (Flurin, 2019). The minerals in the positive electrode are transition metals. A lithium metal oxide (LiMOₓ) and
lithiated carbon are the positive and negative electrodes' active materials (Rahn et al., 2013).

![Diagram of LIB](image)

**Figure 9.0 Basic operation of an LIB (Battery University, n.d.)**

In Equation 5.0, the positive electrode, the active material is oxidized during charge (Rahn et al., 2013):

\[
\text{Li}_{1-x} \text{FePO}_4 + x\text{Li}^+ + xe^- \overset{\text{discharge}}{\underset{\text{charge}}{\leftrightarrow}} \text{LiFePO}_4 \quad \text{......... (Equation 5.0)}
\]

During charging, the active material is reduced in the negative electrode. Lithium ions then moved from the positive electrode and passing the separator with the aid of electrolyte to the negative electrode (Rahn et al., 2013):

\[
\text{Li} \overset{\text{discharge}}{\underset{\text{charge}}{\leftrightarrow}} \text{Li}^+ + e^- \quad \text{......... (Equation 6.0)}
\]
Nonetheless, because of the chemical and physical degradation of the positive and negative electrodes and the electrolyte over time, lithium-ion batteries can lose capacity as they are subject to numerous cycles. Late studies have shown that the rise in impedance and fading of capacity during cycling are primarily due to the positive electrode (Zhang, Y. et al., 2009).

### 2.3.5 Application on board ship

Fully electric ships may no longer need fuel tanks, fuel processing, exhaust, and air trunking. In the part of generator requirements, it would likely be modified to some extent since the higher efficiency decreases the cooling load requirement. Nonetheless, it stays that the relatively poor volumetric density and mass density of the batteries raise the biggest challenges for the naval architects; thus, performance will need to consist of lower design speed and reduced range. Current batteries are limited in the life cycle (current maximum lifetime is ten years but typically five years), which means that several battery replacements through the ship's life shall be made. The cost of the battery replacement and the cost of electricity consumption from the local grid is the leading operational cost of the propulsion plant. However, this is assumed to be offset by the fact that diesel fuel bunkering and regular maintenance of diesel engines are no longer needed. Electric systems tend to be reliable and easily re-configurable; thus, a reduction in the number of ship's engineering crew may be possible (Wu et al., 2016).

**CHAPTER 3: LITERATURE REVIEW**
3.1 Chapter overview

As a highly dependent country on maritime shipping for its economic growth, this chapter presents the potential of utilizing electric ferry in the Philippines in terms of the number of domestic ships registered and the number of ports capable of providing these ships' facilities. This chapter also reviews and summarizes the results of previous LCA studies on lithium-ion batteries used on different types of vehicles and LCA on ship's electric propulsion concerning more on ships using battery technologies, being the focus of this study.

3.2 Potential of electric ferry in the Philippines

There are 33,670 ships that are registered in the Philippines as of December 2017 (MARINA, 2017). These ships are vital aspects of the continuous improvement of the country's economy and the quality of life of the people; however, they also largely contribute to the increase in GHG emissions.

In terms of seaports, there are 83 ports and 110 ferry terminals in the country as of 2016 (PPA, 2016). Having the majority of these ports located in big cities and municipalities where commercial electric power is readily available makes it a viable potential for the idea of electrifying the RORO fleet in the Philippines (Mogato, 2015).

As shown in Figure 10.0 are the different service types of these registered ships. Figure 11.0, on the other hand, shows the categorization of different service types of ships in the primary islands of Luzon, Visayas, and Mindanao (MARINA, 2017).
3.3 Life-cycle Assessment (LCA) on fully electric ferry and lithium-ion battery

In recent years, numerous research papers on the environmental impact of electric transportation and lithium-ion batteries (LIB) were published. An LCA applicable to automotive applications entitled "Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles - critical issues" was published in 2017, which focused
on the batteries' production and operation phases. In this paper, it was concluded that battery production had a larger GHG impact than the operation of the batteries when modeling the life-cycle of the battery using both European and Scandinavian electricity mixtures. The study confirmed that it is environmentally preferable to use water as a solvent instead of N-Methyl pyrrolidone (NMP) in the slurry for casting cathodes and anodes of lithium-ion batteries. Nevertheless, in commercial applications, it was not yet established that LiFePO₄ electrodes made by utilizing water as a solvent are the same as those made by using NMP in terms of characteristics. Accordingly, during the production phase, global warming impacts are dominated by energy use in manufacturing, while the transportation of raw materials and components has minimal impact. Past years, improvements were seen in battery technology, particularly on its cycle life. These improvements have decreased the effects on the production phase to almost the same with the use phase impacts, but, still, the sensitivity calculations attested that the impact for the production phase is mostly higher than the environmental effects in the use phase. Only when the Plug-in Hybrid Electric Vehicle (PHEV) is driven in very coal-dependent countries in its electricity generation the impacts are the same with all the five impact categories. Pertaining with the relative significance of battery weight and internal battery efficiency, due to battery weight in PHEVs, the sensitivity analysis demonstrates that the environmental impact from internal battery efficiency losses is two to six times bigger than the effect from losses. For ships, which have a lower CO₂ emission per tonne-km of transport work, the battery's weight would be expected to have an even lower impact than for automotive road vehicles, for which this study was conducted. Thus, internal battery efficiency is a critical parameter, at least as necessary as the battery weight. However, the same study had different results when modeling with the Chinese energy mix as the operation phase showed more emissions than the production phase of the battery. This study's mentioned results are substantially visible in Figure 12.0, Figure 13.0, and Figure 14.0. These figures well describe the environmental influence on five impact categories emissions on global warming potential (CO₂). These impacts wherein battery operation, battery production, and transport to recycling with three energy mixes (Scandinavian, Chinese, and European) are presented include; photochemical smog (ethane); eutrophication (PO₄); acidification (SO₂); and ozone depletion (CFC11) (Zackrisson et al., 2017).
In Figure 12.0, the batteries’ environmental impact when operating in Scandinavia is described. This study was conducted in the context of automotive batteries for road vehicles. As shown, the battery production had the biggest impact on all categories, followed by battery use. What is illustrated is that, when the car is using the Scandinavian electricity mix, the production phase dominated in all environmental impact categories because the use phase emissions will decrease a lot.

![Graph](image)

Figure 12.0 Environmental impact from a battery life operating in Scandinavia (Zackrisson et al., 2017)

When operating in China, as illustrated in Figure 13.0, the highest impact arises from batteries' users. Battery production has the biggest impact on Eutrophication and Ozone depletion. It can also be observed that when the vehicle is used in China, the production and use phases are a bit similar.
Figure 14.0 illustrates the environmental potential when operating in Europe. It demonstrates that battery manufacturing has more emissions on all categories, except in global warming, where the battery operation shows to have the most significant impact. It can be visualized; if compared to the use phase and the production phase, the transport to recycling is negligible and the other environmental impact categories. On the other hand, much more the same is the production phase and the operation phase, with four out of five environmental impact categories dominated by the production phase with the global warming impact slightly dominated by the operation phase.
Nonetheless, Zackrisson et al.’s study coincides with the results on the studies of Taglaferri et al. entitled "Life cycle assessment of future electric and hybrid vehicles: a cradle-to-grave systems engineering approach." This paper made a life cycle assessment between an electric passenger vehicle using a lithium-ion battery and an internal combustion engine and a hybrid vehicle. For the future EU energy mix, the LCA methodology was used to anticipate the environmental impacts of the Internal Combustion Engine Vehicle (ICEV) and Battery Electric Vehicle (BEV). Overall, this study has confirmed that vehicles' electrification is a promising technology that can contribute and help decrease GHG emissions compared with vehicles using conventional fuels. The direction of the results has shown that the GWP is anticipated to decrease for both technologies. Still, there is a need to develop further advanced processes for biodiesel manufacturing for ICEV and battery for BEV for the significant reduction of toxicity impacts of both systems. However, the manufacturing phase still represents the leading impediment to the technology’s total performance (Tagliaferri et al., 2016).

These studies coincide as well as on the studies of Ma et al. entitled "A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal combustion vehicles". Same also on the studies of Noshadravan et al. entitled "Stochastic comparative assessment of life-cycle greenhouse gas emissions from conventional and electric vehicles" wherein, it can be said that the results of these
studies entirely depends on where the electricity generation originated (Ma et al., 2012) (Noshadravan et al., 2015).

Another author, named Espen Nordtveit, also performed a study entitled "Life Cycle Assessment of a Battery Passenger Ferry". Future fully-electric passenger ferry, which will operate in three locations in the "Indre Oslo-fjord" was studied on this paper in an aim to determine its environmental potential. Four scenario cases were conducted in this study with the life cycle assessment (LCA) methodology: Scenario 1, as the reference scenario compared with the other scenarios, is the one using a conventional diesel combustion propulsion system. Scenario 2 uses the batteries to power its propulsion system wherein these batteries are charged from the commercial grid. Scenario 3, on the other hand, uses batteries which are charged both by solar modules and by the grid. While Scenario 4 also uses batteries that are charged from the grid but are implemented with additional support batteries that are stationed within the charging stations and help the grid in charging (Nordveit, 2017).

The outcome of this study demonstrated that electric propulsion powered by batteries is very much promising to reduce the global warming potential (GWP) when compared to the reference scenario. Based on this study's results, the GWP payback time for the scenarios with electric propulsion powered by batteries was estimated to be five months, six months, and six and a half months for Scenario 2, Scenario 3, and Scenario 4, respectively. Thereby, it was concluded that electric propulsion powered by batteries could significantly reduce the GWP and other air-related emissions. Compared to the reference scenario, the scenarios with the electric propulsion system powered by batteries substantially impacted various depletion and toxicity categories. The following are the life cycle analyses of the four scenarios, as mentioned above (Nordtveit, 2017):

For Scenario 1, the environmental impact is expressed in Figure 15.0. It shows that the Urban Water Shuttle (UWS) operation phase is the largest among all categories. It can also be observed that the other groups' effect is meaningless in most of the categories. Simultaneously, some contributory from the boat production includes human toxicity, emissions to freshwater eutrophication, and terrestrial ecotoxicity. On the other hand,
the high emissions from the refining and combustion of diesel justified the high participation from the operation phase (Nordtveit, 2017).

For Scenario 2, as illustrated in Figure 16.0, it shows that the boat production, battery production, and operation phase had an enormous impact on all categories. In contrast, battery operation, as well as its production, had an equal effect on climate change.
Scenario 2 is considered as the most crucial scene in this study because most of the inventory is suited for this case. As part of Scenario 2, Figure 17.0 shows the GWP analysis on the battery, where it can be seen that battery manufacturing had the largest impact on GWP. Figure 18.0, on the other hand, shows that also the battery cell had a significant effect on the GWP. In the illustration, the cells' parameters show that the lithium for the cathode and lithium hexafluorophosphate in the electrolyte had the largest emissions to the GWP.
In Figure 19.0, it was shown that the drivetrain stands for the biggest impact based on the analysis of the boat production. Within the drivetrain, it shows in the illustration that the transformers represented the most significant impact for the drivetrain, followed by the converters and cables. Figure 20.0, on the other hand, shows the analysis of one transformer with copper as being an important contributor with more than 50% of the emissions to GWP (Nordtveit 2017).
For Scenario 3, Figure 21.0 shows the impact results. This scenario includes the PV modules and energy production from the modules. Based on the illustration, it can be said that battery manufacturing has the biggest impact on climate change, terrestrial acidification, photochemical oxidant formation, urban land occupation, particulate matter formation, and fossil depletion.
For Scenario 4, Figure 22.0 shows the result of the midpoint categories. It can be noted that Scenario 4 has a battery capacity with the additional batteries stationed at each port to assist in the charging, and this can be seen in the results wherein the battery manufacturing stands for a vital share to all the impact categories.
Another study conducted by Maritime Battery Forum in cooperation with Greenland Energy, ABB, and DNV GL for the Norwegian NOₓ-fund was issued in 2016. This study was basically made to perform a life cycle assessment (LCA) of batteries used in a maritime setting. Two different cases have been studied in this report. The first case is the hybrid platform supply vessel (PSV), while the second case is that of a fully electric ferry, which was structured with a comparative cost-benefit analysis. What was compared in the study before the environmental payback time was computed, is the additional costs of manufacturing the battery to the emission savings of utilizing the battery. Greenhouse gases contributing to Global Warming Potential (GWP) and NOₓ are the emissions considered in this study. Eventually, the results showed that the environmental CAPEX of manufacturing batteries for a PSV and ferry was minimal if compared to the fuel that will be saved from using batteries. This LCA showed that electric propulsion achieved emissions savings larger than the GHG associated with battery production. Though there are uncertainties in some aspects of the environmental CAPEX of the battery systems, nevertheless, these uncertainties were not big enough to change the conclusion of the study. Notably, in a maritime setting, the battery systems represent significant emissions savings with the potential for an even shorter environmental payback time. Such savings cannot be achieved with continued use of Marine Gas Oil (MGO). This study showed that the environmental
impact of making the battery system was less significant when compared to the emissions savings. These likely emission reductions brought by batteries used in a maritime setting are vital in reducing the emissions from domestic and international shipping (ABB, 2016).

Figure 23.0 illustrates the life-cycle GWP while Figure 24.0 illustrates the life-cycle NOₓ emissions of the hybrid PSV. Shown for 10 years is the life-cycle emissions as it is the assumed life of the battery. The emissions in year 0 represent the extra environmental cost due to the production of the battery system or simply the environmental CAPEX. On the other hand, the emissions savings as compared to using a diesel PSV are the negative emissions in years 1-10. The results shown on these illustrations are generated using the Norwegian electricity mix, which is 99% produced from a 31 GW hydropower plants (Wikipedia.org, 2020).
Figure 25.0 illustrates the life-cycle GWP, while Figure 26.0 illustrates the life-cycle NOₓ emissions of the fully electric ferry. For ten years, shown is the life-cycle emission as it was assumed in the study as the battery's life. The emissions in year zero represent the added environmental costs because of the battery system's production or the environmental CAPEX in comparison to the diesel ferry. On the other hand, the emission savings compared to using diesel ferry are the negative emissions in years 1-10. The emission savings of utilizing a battery system over the diesel system and the emissions of manufacturing electricity to charge the battery composed the total emission savings, assuming that the electricity emissions are associated with the Norwegian electricity mix.
Another study entitled “Comparative life cycle impact assessment of a battery-electric and a conventional powertrains for a passenger transport ferryboat. A case study of the entire integrated system for the vessel propulsion,” as conducted by Mihaylov et al., carried out a comparative LCA on battery-driven and diesel driven ferry. The study corresponds to a life cycle impact assessment of a state-of-the-art electrically driven power train anticipated to be installed in a diesel-engine passenger ferry boat operating in the Stockholm archipelago. The assessment made is comparative comparing the now operating and the new power train to distinguish

![Figure 26.0 Life cycle NOx emissions of electric ferry (ABB, 2016)]
which of these two propulsion options would be preferable as far as environmental protection is concerned.

The representation of the final results shows that the processing phases represent almost no impact on overall environmental performance from both life cycles. Additionally, within the framework of the study, it can be said that the life span considered is too big, and if in a shorter life span state, most likely that the manufacturing and End-of-Life (EoL) stages can alter their marginal now character to a more critical variable in the impact’s sensitivity equation. Accordingly, the present direction shows that immense attention is sensitive in the environmental performance improvement of electricity mixes in Sweden, which says that instead of keeping the same environmental score, the electricity mix profile will lower in impact and slowly mimic the profile of the hydropower mix (Mihaylov et al., 2014).

3.4 Summary of Literature Review

The literature review in this study is based on similar existing technologies. Most of the studies on battery propulsion in road vehicles and ships are almost identical in numerous cases. For example, in the extraction and manufacturing of the materials, batteries' production had more significant emissions than the vehicle or ship operation. This resulted in a higher contribution to environmental degradation from the production of electric propulsion technology powered by a battery than conventional combustion engine technologies. The operation phase shows that the grid-mix had the biggest impact on the ship's overall environmental impact, especially for countries using fossil fuels in producing electricity. The high load on the electricity grid is also essential when planning high energy demand technologies such as those systems of high-speed, zero-emissions ships running on battery power like Urban Water Shuttle (UWS) (The Explorer, n.d). Considering the efficient means of charging and conversion of power is essential to save on energy consumption and costs. Reducing a significant share of energy consumption could also reduce the grid-load and be a significant factor from an environmental perspective.
CHAPTER 4: RESEARCH METHODOLOGY

4.1 Chapter overview

In this chapter, two different powered designs of the ferry were being investigated and analyzed using life cycle assessments (LCA) from well-to-wheel. Additionally, a
hypothetical scenario analysis is also conducted assuming that the area of operation is 100% produced by electricity generated from renewable sources. The specific LCA assessment tool chosen was the GREET 2019 LCA software, which is specialized on transportation studies.

Such an evaluation is to determine which among these two systems has a lesser environmental impact in terms of GHG emissions if the entire life cycle of the propulsion system is considered. The modeled ferry was an existing ferry named LCT MAE WESS-4 operating in the southern part of the Philippines, the Davao City - IGACOS route. The first assessment was made to a Conventional Diesel Engine RORO Ferry. While the second assessment was done to a simulated Fully Electric RORO Ferry powered by a Lithium-ion Battery, assuming that the same power capacity, energy requirements, and routes are applied. In the assessments, the life cycle for both the power designs mentioned above is divided into two stages. The first stage is composed of the essential parts of processes from the life cycle of fuel without its use in the ferry, and the second stage constitutes the ferry operation.

4.2 Life Cycle Assessment (LCA) Methodology

For the purpose of intensifying the awareness on the importance of environmental protection corresponding to the possible impacts of products, one method was being developed called the Life Cycle Assessment (LCA) (ISO 14044). The LCA is a cradle-to-grave or cradle-to-cradle analysis technique to assess environmental impacts related to all the phases of a product’s life. This product life is composed of raw material extraction through materials processing, manufacture, distribution, and use. This analysis can be done through compiling a list of applicable inputs and outputs of a product system such as evaluating the possible impacts on the environment as associated with those inputs and outputs and then by interpreting the results of the inventory analysis and impact assessment phases concerning the objectives of the study (Muralikrishna et al., 2017).
LCA is considered an iterative process for determining a product or service's environmental impact with the so-called “functional unit” as the basis for computation. This functional unit may be a unit of material, a unit of energy, or a unit of service. The underlying thought of LCA is that the analysis is made over the entire ‘life cycle’ of the product or service not only during the production phase, but also includes all stages from pre-manufacture, manufacture, use, and disposal of the product plus all relevant infrastructures (Jonker et al., 2012). LCA can be illustrated in 4 steps, as shown in Figure 27.0 below.

![Figure 27.0 Steps of LCA, as per ISO 14040](image)

4.2.1 Goal, scope and functional unit

As mentioned, this study will investigate two different powered designs systems of a ferry, the conventional diesel engine ferry and a fully battery-powered electric ferry. This is to determine which among the two has a lower GHG impact if cradle-to-grave emissions are considered.
For the Conventional Diesel Engine RORO Ferry, the analysis begins from the extraction of crude oil. Upon extraction of crude oil, it is then shipped to the refinery in Bataan, the Philippines through an ocean tanker vessel to be processed into diesel fuel which then again transported by another oil tanker to Davao City Bulk Plant later to pumps and eventually ends up in the diesel engine of the RORO ferry. While, for the Fully Electric RORO Ferry Powered by Lithium-ion Battery, the analysis began with the manufacturing of lithium-ion batteries, the bill of materials of a lithium-ion battery, then electricity generation, electricity transmission, distribution, battery charging, and electric ferry operation.

In cradle-to-gate, the studies acquired here used the functional unit per MJ. This is a useful functional unit from the perspective of cradle-to-gate, considering that both petrol and diesel are used as fuel and quantified for the energy content. In the gate-to-propeller aspect, what is used is a more usual functional unit of per distance. This gives more focus on the ships and engines' efficiency, considering that the actual distance that something can be transported is highly regarded when using the fuels.

4.2.2 Life cycle inventory analysis

To perform the stages of life cycle inventory analysis and the impact assessment of LCA of the two technological systems investigated in this study, an environmental life cycle was employed using the GREET 2019 software. In the GREET 2019 software, the raw material processes such as extraction/recovery, production of fuel, and provision of fuel to the ferry are called as “Well to Pump” (WTP), while WTP processes plus the use of fuel in ferry operations referred as “Well to Wheel” (WTW), or “Well to Wake” in the maritime context.

Within the processes that are referred and as illustrated in Figure 28.0, GHG emissions are emitted. The comparison of these two different design ship powered systems is based and focuses on the results that are describing the total emitted GHG emissions throughout the entire fuel life cycles.
4.2.3 Impact assessment

This comparative study between Conventional Diesel Engine RORO Ferry and Fully Electric RORO Ferry powered by LIB only focused on one impact category, the Global Warming Potential (GWP). It only considered greenhouse gases (GHGs) that contribute to global warming. Given in Table 1.0 is the emission factor of GHG emission from Automotive Diesel Oil (ADO) (distillate fuel number 2) combustion in a marine engine acquired from Emission Factors for Greenhouse Gas Inventories of United States Environmental Protection Agency (USEPA). The acquired values are in g/mmbtu diesel, which are then converted to g/kg diesel for uniformity (EPA, 2019).

GHG emissions are in units of CO₂ equivalent (CO₂ -eq), and gases can be converted to CO₂ -eq by multiplying their emission factors to global warming potential (GWP) over 100 years. The GWP was developed for comparing global warming impacts of different gases. GWP measures how much energy the emissions of 1 ton of a gas will
absorb over a given period, relative to the emission of 1 ton of CO₂. The time horizon usually used is 100 years (EPA, 2018).

<table>
<thead>
<tr>
<th>Emission</th>
<th>Emission factor</th>
<th>Emission factor</th>
<th>GWP 100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g emission/mmbtu diesel</td>
<td>g emission/kg diesel</td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>73,960</td>
<td>3156</td>
<td>1</td>
</tr>
<tr>
<td>CH₄</td>
<td>3.0</td>
<td>0.128</td>
<td>25</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.60</td>
<td>0.026</td>
<td>298</td>
</tr>
</tbody>
</table>

Table 1.0 Emission factors of GHG emitted from combustion of marine diesel engine (EPA, 2018)

The total amount of GHG emissions emitted from conventional diesel engine RORO ferry and fully electric ferry powered by lithium-ion batteries were calculated by using the default data from GREET 2019 and also adapting the software with the data acquired from some processes in the Philippines.

4.3 Case Study number 1: Conventional diesel engine RORO ferry
The first case study covered a conventional diesel engine RORO ferry. This case is based on the existing conventional diesel ferry as the modeled ferry named LCT MAE WESS-4. LCT MAE WESS-4 has the following ship main particulars:

<table>
<thead>
<tr>
<th>Name</th>
<th>LCT MAE WESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>RORO Passenger</td>
</tr>
<tr>
<td>LOA</td>
<td>42.72 m</td>
</tr>
<tr>
<td>Breadth</td>
<td>11.2 m</td>
</tr>
<tr>
<td>Draught</td>
<td>2.0 m</td>
</tr>
<tr>
<td>Depth</td>
<td>3.0 m</td>
</tr>
<tr>
<td>GT</td>
<td>291.02 t</td>
</tr>
<tr>
<td>NRT</td>
<td>87.3 t</td>
</tr>
<tr>
<td>Design speed</td>
<td>8 knots</td>
</tr>
</tbody>
</table>

Table 2.0 Ship’s main particulars (Source: MAE WESS operation office)

Since the Displacement of LCT MAE WESS-4 is not available, it is assumed that the "block coefficient" or "coefficient of fineness" of the modeled ferry is 0.65. Displacement in tonnage can be calculated by the product of its three dimensions in feet, its length, breadth, and its depth below the water line, divided by 35 (GG Archives, n.d.). Therefore the ship displacement is equal to 843 tons as per Equation 7.0.

\[ D = \frac{(\text{LOA} \times \text{Breadth} \times \text{Depth}) \times (\text{cf})}{35} \quad (\text{Equation 7.0}) \]
Where:

D - Displacement of ferry in tons
LOA - Length overall in Feet
Breadth - Breadth in Feet
Depth - Depth in Feet
cf - coefficient of fineness

The displacement of 843 tons can also be converted and is equal to 835m³ as per Equation 8.0 (conversion.org,n.d.).

\[
D \text{ in } \text{m}^3 = D \text{ in tons } \times 0.99108963072 \quad \text{(Equation 8.0)}
\]

4.3.1 Ferry technical specifications and operational profile
LCT MAE WESS-4 is the biggest ferry in the combined Mae Wess and CW Cole fleet, a passenger shipping company based in Davao City, Philippines. The ferry’s capacity is 200 passengers and 30 standard cars. This ferry has two Weichai marine engines, each with Maximum Continuous Rating (MCR) of 335 kW. Its design speed is at 8 knots at 80% MCR (536 kW) of main engines. Her trips run from early morning up to evening almost without pause as she averages about 15 round-trips per day. If she has any weakness that could be considered, it could emanate from her design where the deck is much wider than the hull wherein on heeling; it may seem she takes longer than usual to regain balance. Nevertheless, LCT MAE WESS-4 has no recorded incident so far, even though the cross-current within her area of operation is considerably strong anytime (PSSS, 2015).

LCT MAE WESS-4 is operating in Pakiputan Strait in Davao Gulf and connects Island Garden City of Samal (IGACOS) to the mainland of Davao City through the private Caliclic port in IGACOS and the private Mae Wess port in Sasa, Davao City. The distance between these ports is 1.6 nautical miles (nm), and as per with the operations office of MAE WESS, the average duration of one round trip, if time, is more or less 50 minutes. If not to include the maneuvering while leaving and entering ports and the embarkation and disembarkation of cars and passengers, the ship is assumed to sail only about 30 minutes in one round-trip. With this assumption, the average speed of LCT MAE WESS-4 can be calculated as 6.4 knots as per Equation 9.0.
\[ V_a = \frac{d}{t} \] ………………………………………… \( (Equation\ 9.0) \)

Where:

\( V_a \) - Average Speed in Knots
\( d \) - Distance travelled in Nautical Miles
\( t \) - time in Hours

Knowing that the ship power is relative to the cube of speed, therefore, the Power Average of the ferry on that route is then computed equal to 275kW as per Equation 10.0.

\[ P_a = P_{@80\%MCR}(V_a/V_{@80\%MCR})^3 \] ………………… (Equation 10.0)

Where:

\( P \) - Power
\( P_a \) - Average Power
\( V \) - Speed
\( V_a \) - Average Speed

On the other hand, to obtain the total power consumption on board, the power of the auxiliary engines (AE) needs to be added. On the part of LCT MAE WESS-4, the ferry is equipped on board with two (2) Denyo brand diesel generators with a rating of 60 kVA each, which is used alternately. If the power factor is assumed to be 0.85, the electric power is then computed as per Equation 11.0 at 51 kW as the ship auxiliary system.

\[ P_{aux} = \text{KVA} \times \text{pf} \] ……………………………….. \( (Equation\ 11.0) \)

Where:

\( P_{aux} \) - Auxiliary Power
\( \text{KVA} \) - Voltage Rating of AE
\( \text{pf} \) - Power Factor
Assuming a 95% efficiency of auxiliary engines, these auxiliary engines’ total power output was computed at 49 kW as per Equation 12.0.

\[ PT_{aux} = P_{aux} \times \text{Eff} \]  \hspace{1cm} (Equation 12.0)

Where:
- \( PT_{aux} \) - Total Power of each AE
- \( P_{aux} \) - Auxiliary Power
- \( \text{Eff} \) - AE efficiency

Adding the powers of main engines and auxiliary engines, the Total Power of the ferry was calculated at 324 kW as per Equation 13.0.

\[ P_{total} = PT_{aux} + P_{ave} \]  \hspace{1cm} (Equation 13.0)

The ship's energy consumption was calculated at 51 kWh/nm as per Equation 14.0, upon consideration of the average sailing speed of 6.4 knots.

\[ E_c = P_{total} \times V_{average} \]  \hspace{1cm} (Equation 14.0)

Where:
- \( E_c \) - Energy Consumption in kWh/nm

On the other hand, the ship's fuel consumption can be computed if the energy consumption is multiplied with specific fuel oil consumption (SFOC). \( SFOC \) is ascertained based on the engine’s speed of the ship. For high-speed diesel engines, it is assumed that the \( SFOC \) is 215 g/kWh. On the other hand, for medium-speed diesel
engines, the \( SFOC \) is 180 g/kWh, which is used in this assessment (Ancic et al., 2018). This ship’s fuel consumption on the one round trip route Davao City to IGACOS and back is then calculated and equal to 9.18 kg/nm as per Equation 15.0.

\[
F_c = SFOC \times (E_c) \quad \text{(Equation 15.0)}
\]

Where;
- \( F_c \) - Fuel consumption in kg/nm
- \( SFOC \) - Specific Fuel Oil Consumption in g/kWh
- \( E_c \) - Energy Consumption in kWh/nm

### 4.3.2 Phases of LCA of conventional diesel engine RORO ferry

Processes from raw material (crude oil) extraction, transport to the refinery, production of diesel, to its combustion in the marine engine are the phases of the LCA of a conventional diesel engine RORO ferry wherein all these phases of the life cycle of diesel oil, GHG emissions are released in the atmosphere.

#### 4.3.2.1 Extraction of crude oil

A naturally appearing flammable liquid, crude oil can be found in geological formations beneath the Earth's surface. In finding crude oil, prospective areas undergo careful analysis that even includes sedimentary basin analysis and reservoir characterization in terms of porosity and porous structures. The crude oil found is then extracted mostly through oil drilling. Presently, the largest producers of crude oil are Russia, Saudi Arabia, and the USA. The mixture of the oil is decisive for its quality and price; thus, various reference blends are utilized to set the oil price on the world
market (Eriksson et.al., 2013). The location of some of these reference blends is illustrated in Figure 29.0, which shows the region of production instead of the wells’ exact location.

![Figure 31.0 World map indicating the regions from which different reference crude oil blends originate (EIA, 2013).](image)

The Philippines, which is the second-most populous country of Southeast Asia next to Indonesia, is entirely dependent on Middle Eastern for its crude supply. In 2017, the Philippines saw its total crude imports to 73.94 million barrels, with 90% of it is supplied from the Middle East. Saudi Arabia was its largest supplier, which accounts for 36.6% of the total crude imported in 2017. Kuwait was the second-largest supplier at 30.2%. Crude imports from the UAE, the third-largest supplier to the Philippines, accounted for 17.6% of the total. Other small imports of crude come from Russia and other neighboring countries in Southeast Asia like Indonesia and Malaysia (Yep, 2018).

Due to the unavailability of data specific for Saudi Arabia on the process of crude oil recovery, for this assessment, inputs, outputs, and process parameters have been used from GREET 2019 database (process Conventional Crude Recovery).

4.3.2.2 Transportation of crude oil
For this assessment, considering that majority of crude oil supply in the Philippines comes from Middle East area, it is then assumed that the crude oil has been imported from this area specifically in Saudi Arabia which is then transported via ocean tankers to Bataan refinery in Limay, Bataan, which is the biggest oil refinery in the Philippines with a nautical distance of 6896 nm (Ports.com, n.d.). The length of the pipeline from the offshore terminal to the refinery is also considered and assumed to be 2 km in length (Petron, 2014).

### 4.3.2.3 Processing

In more advanced refineries, distillation is still used as a first step in the production of petrol and diesel though several steps were added to make the process more profitable. Modern refineries are specifically designed to convert certain raw materials to particular end products with detailed quality requirements. Figure 32.0 shows the typical schematic diagram of an oil refinery process.
In the refinery plants, crude oil is then refined in the stationary process in order to produce diesel fuel. Conventional diesel engine RORO ferries in the Philippines use Automotive Diesel Oil (ADO) as a fuel since it is readily available in all areas of the country. According to the viscosity, it corresponds to Conventional Diesel from GREET 2019 database; therefore, process inputs, outputs, and parameters are obtained from GREET 2019 default process of refining conventional diesel (Conventional Diesel Refining-CA Crude oil mixes).

4.3.2.4 Diesel Transportation

Upon production of diesel in the refinery plant in Limay, Bataan, it is distributed to oil depots all over the country either by tank trucks or by domestic oil tankers. In the case of this study, the diesel fuel is distributed to Davao Depot using oil tankers. The supply of diesel fuel for LCT MAE WESS-4, on the other hand, is distributed from the depot to the ferry by a tank truck. The nautical distance from Bataan refinery offshore facilities to Davao depot offshore facilities is 910 nautical miles (Ports.com, n.d.). While the distance from Davao depot to Sasa Port, where LCT MAE WESS-4 is stationed for refueling, is assumed at 3 km. Model parameters are obtained from default GREET 2019 mode for a heavy-duty truck.

4.3.2.5 Ferry operations
As calculated above, 51 kWh/nm is the energy needs of LCT MAE WESS-4. The diesel consumption is 9.18 kg/nm. To calculate the exhaust emissions generated by the combustion of diesel in the marine engine, the emission factors taken in Table 1.0 are multiplied by diesel consumption. The calculated exhaust emissions per Equation 16.0, expressed in mass of gas released per nautical mile, are presented in Table 3.0.

\[
\text{Exhaust Emission} = \text{EF} \times \text{FC} \quad (Equation\ 16)
\]

Where:

EF - Emission factor in g/kg diesel (taken from Table 1.0)
FC - Fuel consumption in kg/nm

<table>
<thead>
<tr>
<th>Exhaust emissions</th>
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<tr>
<td>CO₂</td>
<td>28.972 kg CO₂/nm</td>
</tr>
<tr>
<td>CH₄</td>
<td>1.175 g CH₄/nm</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.238 g N₂O/nm</td>
</tr>
</tbody>
</table>

Table 3.0 Exhaust emission of the conventional DE ferry

### 4.4 Case Study number 2: Fully electric RORO ferry powered by Lithium-ion battery

The second case analyzed in this study is that of a Fully Electric Ferry powered by Lithium-ion Battery with data based on the modeled RORO ferry, the conventional diesel engine RORO ferry LCT MAE WESS-4. The electrification of ferries, especially in archipelagic countries like the Philippines, would be a great significance in an aim to comply with the stringent regulations set by IMO on releasing emissions of pollutant gases in the atmosphere from ships. This is taking into consideration that electric ships emitted zero emissions during operations. However, to quantify all
emissions emitted and prove that electric ferries are a more environmentally-friendly system, all emissions emitted throughout the whole life cycle of fuel used should be quantified.

For electric propulsion, ferries like LCT MAE WESS-4 are an interesting study because they operate in relatively short voyages or fixed routes, which allows for manageable battery sizes and frequent charging, thus made it easy to optimize from a safety and financial perspective.

### 4.4.1 Ferry technical specifications and operational profile

For this case study, a lithium-ion battery is used onboard and assumed to power LCT MAE WESS-4 in one round-trip from Sasa, Davao City to Babak, IGACOS, and back, assuming that the charging station will be just set-up in Davao City port where land-based higher commercial electric grid power capacity is available. From this land-based net, a transformer takes down the voltage; then, a converter converts AC from the net to DC. On the other hand, the battery system is connected to a DC grid with converters and rectifiers. The Single-line diagram for the fully electric ferry powered by a battery is illustrated in Figure 34.0.
In this case analysis, it is assumed that the modeled ferry is a fully electric ferry powered by a lithium-ion battery with the same power capacity and energy requirements of conventional diesel engine ferry LCT MAE WESS-4. The electric ferry is also assumed to run 15 round-trips per day from Davao City to IGACOS and back with the same average speed. In every round-trip, she is assumed to have her battery charging at Sasa port to maintain a minimum of 50% state of charge (SOC) at all times.

The battery for the electric ferry has higher power consumption than the modeled ferry because of losses during the charging and discharging of the battery. Therefore, a 10% total loss per round-trip is assumed, which composed a 5% loss for charging and another 5% loss for discharging. Thus, assuming the required power should correspond to 80% MCR, the power requirements for a fully electric ferry powered by a lithium-ion battery to handle the maximum propulsion power for one round-trip of 3.2 nm distance, including the losses during charging is computed equals to 595 kW as per Equation 17.0.

\[ P = \frac{P_{@80\%MCR}}{0.90} \]  \hspace{1cm} \text{(Equation 17.0)}

Where;

\( P = \) Propulsive Power requirements of fully electric ferry in kw
Lithium-ion batteries have an approximate energy density per volume of 200 kWh/m³, and an approximate volumetric power density of 1500 kw/m³, and gravimetric energy density of 200 kWh/ton (Schönborn, 2020).

4.4.2 Phases of LCA of fully electric ferry powered by LIB

To determine the environmental impact of the life cycle of fully electric ferry powered by lithium-ion batteries, all emissions associated throughout the whole life cycle should also be quantified through an LCA process. The emissions from the process of Li-ion battery manufacturing are obtained from GREET 2019.

4.4.2.1 Battery manufacturing

The volatility of fuel prices and environmental regulations that needs to be complied with, as well as with the recent innovations on battery technologies has open the way to the electrification of RORO ferries in some parts of the world mostly in Europe with Norway leading on this aspect with their introduction in 2014 of the first fully electric ferry powered by Lithium-ion (Li-ion) batteries (Gagatsi et al., 2016).

Li-ion batteries are quite expensive as compared with other types of batteries but, by far, it has the highest energy density. Though lead-acid batteries look more economical solution, however, the low material resistance in the marine environment and the short life period makes them more expensive in the life cycle of a ship (Dedes et al. 2012).

In this study, it is assumed that the lithium-ion batteries used are locally made in the Philippines. Due to the unavailability of data, it is hereby assumed that no significant transportation emissions are emitted during the delivery of batteries from manufacturing until it reaches to the ferry.

4.4.2.2 Electricity generation, transmission, and distribution

55
The availability of electric energy should be considered as it charges the batteries and drives the electric ferry. Electricity generation is the process of generating electric power from sources of primary energy. As per Mindanao Development Authority (MinDA), hydropower courtesy of the Agus-Pulangi hydropower plant remains the biggest and cheapest single source in terms of electricity generation in Mindanao. However, several coal power plants have come online in the last two years and now account for more than half of the whole city (MinDA 2020). For the main entire City of Davao, which is located in the main Island of Mindanao and where the charging of the electric ferry shall be installed, the electric power generation in 2019 from coal power plants is composed 60.45%. Other electrical energy are generated by hydro power plants, which composed 36.92%, oil power plant (diesel), which generate 2.62%, and renewable source (solar), which composed of a mere 0.01% of the total generation (DLPC, 2019). The electric power generation in Davao City is presented in Figure 34.0.

![Shares of energy sources in Davao City](image)
The electricity generation data are obtained from the GREET 2019 database, where shares of total electricity production were adapted to this case study as described above. After its generation, electric energy was assumed to be transmitted and distributed to consumers.

4.4.2.3. Ferry operations

A fully electric ferry in this study is assumed to be only powered by Lithium-ion batteries onboard. At an average speed of 6.4 knots, using the cubic law as presented in Equation 2.0, the Power Average is calculated to equal to 305 kW. Summing up with the auxiliary engine power based on Equation 5.0, the Power Total can be calculated and equal to 354 kW. With the average sailing speed of 6.4 knots, the energy consumption of a fully electric ferry powered by a lithium-ion battery is calculated at 55 kWh/nm as per Equation 6.0.

In a 3.2 nm one round-trip journey, the required energy for the fully electric ferry powered by a lithium-ion battery is estimated at 176 kWh as per Equation 18.0.

\[
E_{\text{required}} = \frac{d}{E_c} \quad \text{................................................. (Equation 18.0)}
\]

Where;

- \(E_{\text{required}}\) - Energy requirements per one round-trip in kWh
- \(d\) - Distance in nm
- \(E_c\) - Energy consumption in kWh/nm
Considering the required 50% minimum State of Charge (SOC), the capacity of the battery is assumed at 400 kWh of energy, which is good enough for the ferry to sail and return while maintaining the required SOC.

The total volume necessary to store lithium-ion batteries capable of supplying energy for the one round-trip can be calculated by energy capacity divided by energy density per volume, equal to 2 m³ as per Equation 19.0. This is 0.239% of the displacement volume of the ferry.

\[
V = \frac{B_{\text{capacity}}}{\text{LIB energy density per vol}} \quad \text{(Equation 19.0)}
\]

Where;

- \( V \) - Total volume to store LIB in m³
- \( B_{\text{capacity}} \) - Battery energy capacity in kWh
- \( \text{LIB energy density per vol} \) - LIB energy density per volume in kWh/m³

On the other hand, the total volume necessary to store lithium-ion batteries capable of supplying the required power of 354 kW can be calculated by dividing the power total by the volumetric power density, which is equal to 0.236 m³ as per Equation 20.0. This is 0.028% of the displacement volume of the ferry.

\[
V = \frac{P_{\text{total}}}{\text{LIB power density per vol}} \quad \text{(Equation 20.0)}
\]

Where;

- \( V \) - Total volume to store LIB in kw
- \( P_{\text{total}} \) - Power total in kw
- \( \text{LIB power density per vol} \) - LIB power density per volume in kw/m³

While the mass of the lithium-ion battery can be calculated by dividing the energy capacity by gravimetric energy density equal to 2 tons as per Equation 21.0. This is 0.237% of the entire displacement of 843 tons of the ferry.
\[
M_{\text{battery}} = \frac{B_{\text{capacity}}}{E_{\text{gravimetric density}}} \quad (\text{Equation 21.0})
\]

Where:

- \( M_{\text{battery}} \) - Mass of the lithium-ion battery in tons
- \( B_{\text{capacity}} \) - Battery energy capacity in kWh
- \( E_{\text{gravimetric density}} \) - LIB gravimetric energy density

### 4.5 Results and Discussion

LCAs are performed using the GREET 2019 software to thoroughly evaluate the environmental impact of two different systems, first with a Conventional Diesel Engine RORO Ferry; and secondly with a Fully Electric Ferry powered by a Lithium-ion Battery. The analysis results are presented through WTP, and WTW assessments wherein GHG emissions are expressed in CO\(_2\) equivalent.

The well-to-pump (WTP) designed pathway of the LCA conducted on diesel is composed of the following different processes: (1) crude oil extraction in the Middle East; (2) Transportation to refinery plant to the Philippines; (3) Refinery process; (4) Transportation of diesel oil to Davao City; and (5) Storage of diesel at the oil depot.

On the other hand, the WTP designed pathway of the LCA conducted on a Fully Electric Ferry powered by a Lithium-ion Battery includes the following processes: (1) Lithium-ion battery manufacturing; (2) Electricity generation; (3) Electricity transmission; and (4) Electricity distribution.

With the assessments of the two systems using the GREET software, the existing conventional diesel engine-driven ferry through its life cycle emits at total GHG emissions of 34.032 kg CO\(_2\)-eq/nm. Ferry operations have the biggest share in these total emissions of GHG computed at 29.072 kg CO\(_2\)-eq/nm as per Equation 22.0.
TTP = (C02 x GWP 100)+(CH4 x GWP100)+(N2O x GWP 100)….. (Equation 22.0)

Where;

TTP - Tank-to-propeller GHG emission in kg CO2-eq/nm
CO2 - CO2 exhaust emission in kg CO2/nm
CH4 - CH4 exhaust emission in g CH4/nm
N2O - N2O exhaust emission in g N2O/nm
GWP - Global Warming Potential 100 years

The total amount of WTP GHG emissions for diesel obtained from GREET 2019 software is 21.52 g CO2-eq per MJ of diesel, where the process of diesel refining contributes the most with the release of GHG emissions. Therefore, the total WTP GHG emissions per distance is computed at 4.96 kg CO2-eq/nm per Equation 23.0.

\[ WTP_{distance} = WTP_{energy} \times 3.6 \text{ MJ/kWh} \times EC \] \(\text{……..(Equation 23.0)}\)

Where;

\(WTP_{distance}\) - WTP GHG emission in kg CO2-eq/nm
\(WTP_{energy}\) - WTP GHG emission in kg CO2-eq/MJ
EC - Energy consumption in kWh/nm

The total GHG emissions emitted by a Conventional Diesel Engine RORO ferry are shown in Figure 35.0.
Option for electrifying the existing conventional diesel engine RORO ferry in Davao City has been explored by taking into account results from LCA of the battery-driven ship. During its operation, the electric ship has zero-emission; however, different emissions are released during battery production. The emissions during the generation of electricity used for charging the batteries were also taken into account. The total amount of GHG emissions is 187.347 g CO2-eq/MJ. Results in Figure 36.0 correspond to the WTP GHG emissions from the life cycle of electricity. In the GREET software, the processes of generation of electricity by hydropower are assumed to be emission-free. On the other hand, the electricity generation processes from the burning of coal contribute the most to the GHG emissions, which composed the 60.45% of the total electricity production in Davao City. The results of WTP GHG emission from the generation of electricity is illustrated in Figure 36.0.

![Figure 36.0 WTP GHG emissions during generation of electricity](image)
The amount of WTP GHG emissions obtained from GREET 2019 software is 176.284 g CO2-eq/MJ from electricity generation and 11.064 g CO2-eq/MJ during Li-ion battery manufacturing. WTW GHG emissions from fully electric ferry powered by LIB are presented in Figure 37.0, and they only contain the emissions from the WTP life cycle of electricity and emissions from battery manufacturing as we considered the TTP GHG emissions of fully electric ferry equal to zero.
The emissions of a ship propelled by different power systems during its total life cycle are expressed in kg CO$_2$-eq/nm. Therefore, the WTW emission of Fully Electric Ferry powered by LIB is calculated at 37.095 kg CO$_2$-eq/nm as per Equation 17.0.

As it can be seen from the Figure 38.0, emissions within the life cycle of a conventional diesel-engine driven ferry is even lower with 34.032 kg CO$_2$-eq/nm, versus the fully electric battery-driven ship which emitted a total of 37.095 kg CO$_2$-eq/nm, wherein 34.904 kg CO$_2$-eq/nm of this is released from processes of electricity generation in Davao City, while the rest which is equal to 2.191 kg CO$_2$-eq/nm is emitted during battery manufacturing.
4.6 Hypothetical Scenario Analysis: Fully Electric Ferry powered by LIB operating in an area with 100% electricity generated from renewable sources

Additionally, a hypothetical scenario analysis is performed to analyze and compare the environmental impact of fully electric ferry powered by LIB to a conventional diesel engine ferry if assuming that the area of operation has a 100% electricity generated from renewable sources. For simplicity, it is assumed that the electricity is fully generated only through hydropower. Except on the generation processes of electricity from the commercial grid, all the data and results used on the above study on a fully electric ferry powered by LIB are carried out.

The electricity generation data are also obtained from the GREET 2019 database. After its generation from hydro power plants, electrical energy was assumed to be transmitted and distributed to consumers.

In GREET 2019 LCA software, the process of electricity generation by hydropower is assumed to be emission-free. Thereby, in this scenario, the total amount of GHG emissions during WTW assessment as well as during the generation of electricity used for charging the batteries is computed at 11.064 g CO2-eq/MJ with only the process of battery manufacturing as the lone emission contributor. WTW GHG emissions from fully electric ferry powered by LIB operating in an area with 100% electricity generated from renewable sources are presented in Figure 39.0 which, only contain the emissions from the WTP life cycle from battery manufacturing as the TTP GHG emissions of fully electric ferry powered by LIB is zero.
As emissions of a ship propelled by different power systems in its total life cycle are expressed above in kg CO₂-eq/nm, therefore, the WTW emission of a fully electric ferry powered by LIB operating in an area with 100% electricity generated from renewable sources is calculated only at 2.191 kg CO₂-eq/nm as per Equation 17.0.

If comparing with the emissions within the life cycle of a conventional diesel-engine driven ferry as shown in Figure 40.0, a fully electric ferry powered by LIB operating in an area with 100% electricity generated from renewable sources is significantly much lower with only 2.191 kg CO₂-eq/nm, versus the conventional diesel engine ferry which is emitting 34.032 kg CO₂-eq/nm.

Figure 40.0 WTW GHG emission between fully electric ferry powered by LIB operating in an area with 100% electricity from renewable sources and conventional diesel-engine ferry
CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusions

Moving towards greener energy sources in the Philippines is undoubtedly a great help to mitigate climate change. At first, the idea of thoroughly electrifying ferries engaged in short distance voyages seems a feasible and promising solution on the continuous increase of GHG emissions brought by the shipping sector of the country as well as to comply with the stringent regulations pertaining to the pollution on the marine
environment as mandated by international regulations. Based on the study conducted on a modeled ferry operating in the Davao City area, without a doubt, there are no questions that lithium-ion batteries can fully provide the needs of ferries in terms of supplying enough ship's power and energy to sustain and duplicate the usual operations performed by the existing conventional diesel engine ferry. However, based on the obtained results on the performed LCA, it shows that the conventional diesel engine ferry emits a total WTW emission of 34.032 kg CO₂-eq/nm. In contrast, a Fully Electric Ferry powered by LIB, during its life cycle, emits 37.095 kg CO₂-eq/nm. These results show that the conventional diesel engine driven ferry operating in this area of the Philippines is surprisingly more environmentally friendly over a fully electric ferry powered by batteries if it operates in the same area. During its operation, a conventional diesel engine RORO ferry emits 29.072 kg CO₂-eq/nm. While, emissions from diesel fuel's life cycle, without its use in a ship, amounts to 4.96 kg CO₂-eq/nm. On the part of the fully electric ferry, electric ferries are emission-free during its operation while the LIB manufacturing process emits an emission of 2.191 kg CO₂-eq/nm. Nonetheless, the electricity generation process, specifically through burning coal, which provides 60.45% of the City of Davao's electricity supply, produces a very high GHG emission of 34.904 kg CO₂-eq/nm, and makes the difference in this comparative study of the two systems.

This mentioned significance of the type of electricity processes from the grid is further attested with the conduct of a hypothetical scenario analysis wherein the electricity generation was assumed 100% produced from renewable sources. The WTW result of this scenario analysis shows a huge decrease of about 94% less from the WTW result of the fully electric ferry powered by LIB operating in Davao City. And suppose this result is compared to the WTW result of the conventional diesel engine ferry. In that case, it shows a very big advantage of the fully electric ferry operating in an area with a 100% electricity generated from renewable sources in terms of environmental impact.

By taking these results into account, it can be concluded that utilizing electric ferry in the operational area of Davao City - IGACOS as an alternative type of waterborne transport to ease GHG emission from ships most likely is not a suitable solution to
lessen or mitigate the effect of climate change with the current electricity mix. And it is worthy to note that the electricity generation process provided a very sensitive factor in assessing the electric ferry system's overall environmental impact.

This study's results might not be the same in all areas of the country since some of these areas might be supplied with a lesser amount of electricity produced from power plants using fossil fuels. Nevertheless, it must be put into perspective that unless the Philippines will significantly reduce the number of power plants using fossil fuels to generate electricity and engage more on producing clean electricity, at present, the idea of electrifying the ferries in the country might not be a feasible solution to mitigate the increasing GHG emissions.

5.2 Recommendations

It is worthy of mentioning that the accuracy of the performed comparative assessment between the two systems through an LCA can be further improved by carefully analyzing every step in the pathway. For instance, in the Conventional Diesel Engine RORO Ferry, other sources of crude oil (to include those locally extracted) and other transportation types in crude oil manipulation can be considered. Also, the ship's operational profile can be investigated more thoroughly. In the case of the Fully Electric RORO Ferry Powered by LIB on the other hand, the generation of electricity through hydropower plants and renewable energies may need a deeper analysis as these systems might also produce some emission-to-air pollution somewhere within its processes. Some other areas in the country must also be considered for the same study. These areas may be using the majority of its electricity supply from the grid generated from cleaner sources. Nonetheless, based on this study, it is reasonable to expect that the process of electricity generation is the most significant factor between these two systems and be firstly considered irrespective of the scenario.

On the other hand, it is fair to say that complete insight into the above solutions' feasibility will be achieved and reached by comparing them from the economic viewpoint, subject to further studies.
Suppose this is so, for the meantime, it is recommended that the Philippine government may stick as well with the use of the typical diesel engine-driven system used in most ferries until such time that a more environmentally friendly approach as an alternative solution is available.

REFERENCES


### Davao Light Power Mix for the Year 2019

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<th></th>
<th>Average Volume</th>
<th>Percentage</th>
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<tr>
<td>Coal</td>
<td>141,403,055.54</td>
<td>66.45%</td>
</tr>
<tr>
<td>Hydro</td>
<td>86,395,646.04</td>
<td>36.32%</td>
</tr>
<tr>
<td>Oil</td>
<td>6,243,893.33</td>
<td>2.62%</td>
</tr>
<tr>
<td>Solar</td>
<td>27,496.25</td>
<td>0.01%</td>
</tr>
</tbody>
</table>

Prepared by:
Sarah Rose Deos-Cruz-Guadalupe
Analyst

Noted and Approved by:
Rodger S. Velasco
President and CEO
<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage of mass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HEV</td>
</tr>
<tr>
<td>Lithium manganese oxide (LiMn2O4)</td>
<td>27</td>
</tr>
<tr>
<td>Graphite/Carbon</td>
<td>12</td>
</tr>
<tr>
<td>Binder</td>
<td>2.1</td>
</tr>
<tr>
<td>Copper</td>
<td>13</td>
</tr>
<tr>
<td>Wrought aluminium</td>
<td>24</td>
</tr>
<tr>
<td>Lithium pentafluorophosphate (LiPF6)</td>
<td>1.5</td>
</tr>
<tr>
<td>Ethylene carbonate (EC)</td>
<td>4.4</td>
</tr>
<tr>
<td>Dimethyl carbonate (DMC)</td>
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</tr>
<tr>
<td>Polypropylene</td>
<td>2.0</td>
</tr>
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<td>Polyethylene</td>
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<tr>
<td>Polyethylene terephthalate</td>
<td>2.2</td>
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<tr>
<td>Steel</td>
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<tr>
<td>Thermal insulation</td>
<td>0.43</td>
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<tr>
<td>Glycol</td>
<td>2.3</td>
</tr>
<tr>
<td>Electronic parts</td>
<td>1.5</td>
</tr>
<tr>
<td>Total battery mass (lb)</td>
<td>41</td>
</tr>
</tbody>
</table>

Appendix 2.0: Materials used in LIB manufacturing (Gaines et al., 2014)
Appendix 3.0: Pathway for conventional diesel (Source: GREET 2019)
Appendix 4.0: Pathway LIB manufacturing (Source: GREET 2019)
Appendix 5.0: Pathway for coal electricity mix (Source: GREET 2019)
Appendix 7.0: Pathway for solar electricity mix (Source: GREET 2019)
Appendix 8.0: Pathway for oil electricity mix (Source: GREET 2019)
Appendix 9.0: Pathway for LIB Bill of Materials (Source: GREET 2019)
Appendix 10.0: Pathway for LIB production (Source: GREET 2019)
Appendix 12.0: Excel calculation of WTW of fully electric ferry powered by LIB