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NEW LUMMI ISLAND FERRY

Propulsion System Selection Study

Prepared for: Whatcom County Public Works • Bellingham, WA

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LIST OF TERMS

Controllable Pitch Propeller	A propeller with movable blades that can be rotated to vary the angle of attack.
Draft	The distance from the water's surface to the bottom of the boat.
Drydocking	Removing the vessel from the water so that maintenance and repair can be perform on the underwater hull or equipment.
Fixed Pitch Propeller	A propeller with blades which are fixed at an angle of attack.
Hotel Loads	The electrical demands for operating the vessel (excluding propulsion) such as lighting, heating, ventilation, air conditioning, navigation equipment, etc.
IMAC	Integrated Monitoring and Alarm Control System
Knots	A standard measure of speed for marine vessels calculated as the nautical miles traveled per hour.
Reduction Gears	A gear which reduces the rotational speed of the propulsion engine or propulsion motor to an efficient speed for turning the propeller.
Watertight Subdivision	Watertight boundaries within the hull which are spaced in a manner to prevent the vessel from sinking in the event of flooding.

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1 PURPOSE

This report presents a comparison of alternative propulsion system options for the NEW LUMMI ISLAND FERRY (LIF). The LIF is a 34 car, 150 passenger, double-ended ferry approximately 184' long by 54' wide, with a maximum loaded draft of 7'-6". The vessel will be owned and operated by Whatcom County Public Works (WCPW).

This study is intended to refine the analysis of the Alternative Fuels Analysis completed as part of the Level of Service Study [1]. This study includes a defined vessel load profile and the selection of sample equipment to develop a more detailed quantitative study of each propulsion system option. While the general conclusions of this study are consistent with the previous analysis [1], some figures vary due to the defined equipment assumptions and operational loads, as well as the increased size of the vessel[1].

2 PROCEDURE

2.1 Overview

The new ferry is intended to replace Whatcom County's current ferry (M/V WHATCOM CHIEF) on the same route between the ferry terminals on Lummi Island and the mainland at Gooseberry Point. This route requires navigation across a short (0.8 nm) channel with winds to 40 knots and tidal crosscurrents of up to 5-7 knots. During events of extreme inclement weather and/or states of emergency, the new ferry would be called upon to include the Bellingham Ferry Terminal on a revised route, but this condition is rare and does not directly factor into this study.

A broad range of vessel designs, propulsion systems, and fuel alternatives - [2], [3], [1] - have been evaluated by Elliott Bay Design Group (EBDG) and presented to WCPW as possible design options for the new LIF. WCPW, in consultation with EBDG, has reviewed these studies against the long-term Level of Service (LOS) goals and requirements of the Lummi Island Ferry System, and arrived at five (5) possible propulsion system options for the new ferry:

- Diesel Mechanical (DM) – conventional diesel engines with reduction gears and shaft lines
- Diesel Battery Hybrid (DBH) – conventional diesel mechanical with batteries and motor/generators
- Diesel Electric (DE) – diesel generators provide power to electric propulsion motors
- Diesel Electric Hybrid (DEH) – conventional diesel electric with batteries
- All Electric (AE) – No diesel engines or generators, all power is provided by battery with shore charging

Of these five possible propulsion system options, the DE and AE either have fatal flaws or are otherwise not a good match for design of the new ferry or the capabilities of the terminals. The DE option is best suited for and most typically installed in larger vessels with high "hotel" loads (lighting, HVAC, laundry equipment, etc.) or widely fluctuating load profiles, such as cruise ships, oil field and other offshore supply vessels, military craft, etc. Due to the energy losses

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[1] Based on preliminary discussions of the vessel arrangements with WCPW, the vessel is anticipated to be wider and longer than was assumed in the previous study [3].

associated with converting mechanical power to electric power and back to mechanical power, a conventional DE option will consume more fuel and produce more emissions than the other propulsion system options.

The AE option is not feasible for the new ferry until significant battery charging infrastructure can be provided at one or more terminals. This technology exists but is expensive and is still being tested and developed. There is currently no marine application of this technology in North America which operates with the service frequency required of the LIF. Further, if the vessel needs to transit to Bellingham in an emergency situation, an AE propulsion system is not capable of effectively making multiple daily transits to the Bellingham Ferry Terminal.

Based on the above and EBDG's collective engineering and recent real-world experiences with similar ferry designs, constructions, and operations, EBDG recommends that both the DE and AE propulsion system options be eliminated from consideration for the new ferry.

2.2 Candidate Propulsion Systems

For purposes of this study, specific models and manufacturers of diesel engines, reduction gears, generators, batteries, and other propulsion system equipment are identified. These are not the only or exclusive equipment models and manufacturers that are suitable for the LIF design. During the next phase of vessel design, an appropriately wider range of suitable equipment options for all key components will be developed.

2.2.1 Option 1: Diesel Mechanical (DM)

The first configuration, depicted in Figure 1, is a conventional diesel mechanical propulsion system with two independent propulsion drive trains each with a high-speed diesel engine driving a single controllable pitch propeller (CPP) via a conventional reduction gear and shaft line. Electrical ship service power is provided by two diesel generators.

With a DM system, both main engines would operate continuously throughout a service day. The engines would provide thrust for transit, maneuvering, and pushing again the ramp while loading and unloading passengers.

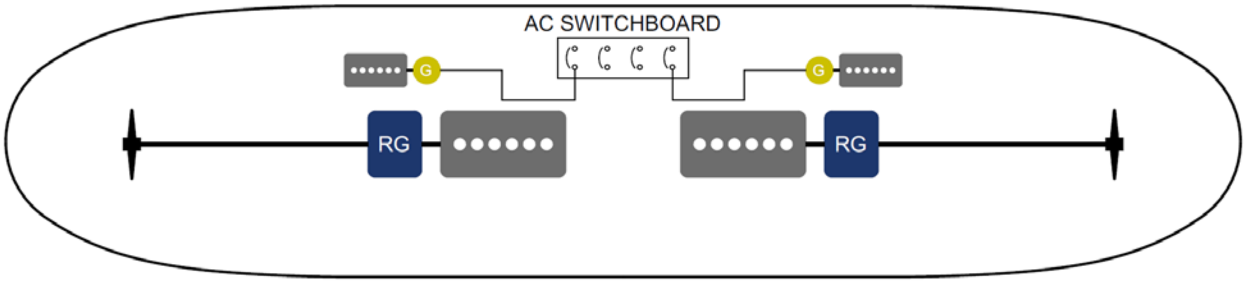

Figure 1:Diesel Mechanical propulsion system diagram

For this option, the following equipment was considered:

- Two Cummins QSK 19-M marine propulsion engines rated 750 BHP at 1800 RPM, Continuous (Caterpillar ACERT C18 or C32 Tier 3 engines could also be used)

- Two Hundested CPG 38 Reduction Gears with MP 500 CPPs
- Two conventional shaft lines
- Ship Service Switchboard
- Two 99 kW Northern Lights generators for ships service electrical loads

2.2.2 Option 2: Diesel Battery Hybrid (DBH)

The diesel battery hybrid system is shown in Figure 2. This system functions similar to a conventional diesel mechanical system, but each reduction gear includes an attached motor/generator which can be used to either provide propulsion power or recharge the battery bank. In this configuration, electrical ship service power is still provided by two diesel generators for redundancy.

This configuration has the unique ability to operate in either a hybrid or a non-hybrid mode. By simply shutting off the battery and electric motor/generator parts of the system, the vessel could continue to operate like a conventional diesel mechanical propulsion system. Therefore, in certain parts of the following analysis, values are provided for the DBH system in both hybrid and non-hybrid mode.

This configuration would reduce the operating hours of the main engines by allowing them to be turned off intermittently throughout the day. While loading and unloading passengers, the thrust for pushing against the dock would be provided by the batteries and motor/generators, thus allowing the main engines to be shut down for a significant portion of each service day. The main engines would be restarted to provide maneuvering and transit loads. During transit, the main engines would also be used to recharge the batteries for the next load/unload cycle.

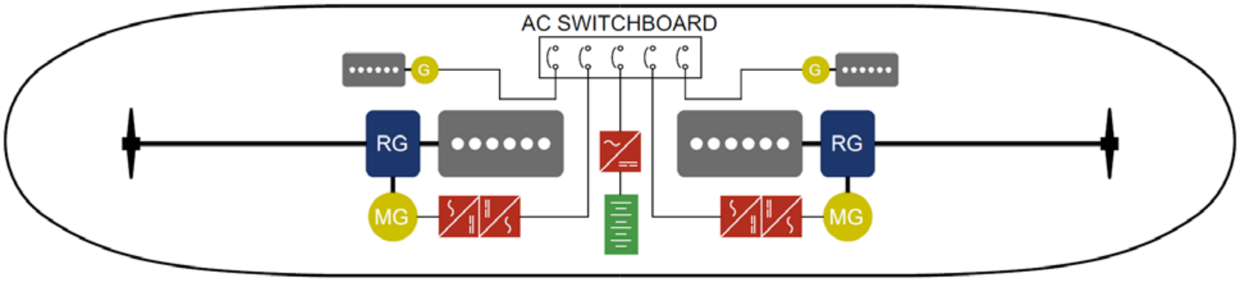

Figure 2: Diesel Battery Hybrid propulsion system diagram

For this option, the following equipment was considered:

- Two Cummins QSK-19 marine propulsion engines rated 750 BHP at 1800 RPM, Continuous (Caterpillar ACERT C18 or C32 Tier 3 engines could also be used)
- Two Hundested CPG 38 Reduction Gears with MP 500 CPPs
- Two conventional shaft lines
- Ship Service Switchboard
- Two 99 kW Northern Lights generators for ships service electrical loads
- 237 kWh battery bank
- Two 560 kWe Motor-Generators
- Two 560 kWe AC Motor Drives

2.2.3 Option 3: Diesel-Electric Hybrid (DEH)

Propulsion Option 3, depicted in Figure 3, is a diesel-electric system supplemented with a large battery bank and electrical power conversion and control equipment. Batteries would supplement the electrical power provided by the diesel engine driven generators, and in turn would also be charged by the generators. This system allows for a single diesel driven generator to be running at any given moment (as opposed to two running diesel engines with the other options, except as noted), thereby increasing the time between overhaul events and reducing long term maintenance costs of the propulsion generator engines.

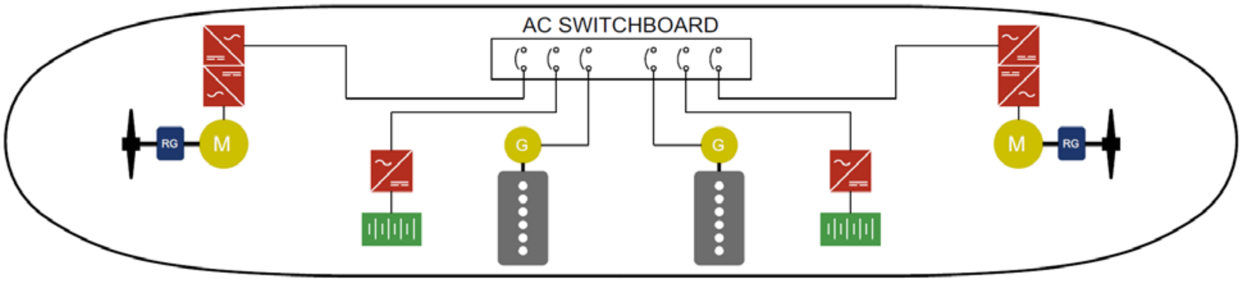

Figure 3: Diesel Electric Hybrid propulsion system diagram

The DEH propulsion configuration is comprised of two high speed diesel generators sized such that any one generator – in simultaneous combination with power stored in the battery banks - can provide power for the ships electrical service and propulsion loads. Two variable speed motors, one at each end of the vessel would then drive the propellers. This propulsion system option would operate in "peak-shaving" mode. See Reference [1] for details of how such a system manages the overall propulsion loads.

Major equipment considered for this option includes:

- Two Cummins QSK 19-DM propulsion generators rated 460 kWe at 1800 RPM (Caterpillar ACERT C18 Tier 3 propulsion generators could also be used)
- A combined ship's propulsion / ship's service switchboard
- A 237-kWh battery bank
- Two 560 kWe propulsion motors
- Two 560 kWe variable speed drives
- Two Twin Disk model MGE5204 SC non-reversing reduction gears
- Two Mathers shaft brakes
- Two fixed pitch propellers

2.3 Evaluation Criteria

In order to compare the propulsion system options, a scoring system consisting of four criteria and weightings was developed by EBDG and WCPW. Each criterion was assigned a weighting factor to define its relative importance in the overall propulsion selection. The criteria and respective weighting factors are presented in the table below:

Table 1: Evaluation Criteria

Criteria	Weighting Factor
Reliability	33%
Maintenance Cost	27%
Capital Cost	22%
Fuel Consumption & Emissions	18%

In the financial analyses, comparisons of capital costs and maintenance costs between the propulsion system options are not all inclusive; meaning, they do not include all costs associated with the propulsion system options. The financial analyses are intended to demonstrate the financial differences between the three propulsion options and are therefore to be used for comparative purposes only. For both the capital and maintenance cost analyses, only the propulsion system design aspects and/or components that are different (to a meaningful degree) between the systems are evaluated.

The DM system is considered the baseline and thus receives an arbitrary score of 1.0 for each criterion. The other propulsion system options are scored relative to the DM system, with lower values representing better performance and higher values representing inferior performance. The scores are then tabulated in a scoring matrix, the weighting factors applied, and the weighted scores summed resulting in a total score for each option. The lowest scoring configuration represents the optimal configuration for the new ferry based on the quantitative analysis of selected scoring criteria. However, additional qualitative consideration should be given to each propulsion system option when evaluating the optimal configuration for the new vessel.

2.3.1 Capital Cost

For purposes of this study, capital costs consist only of the purchase price of major propulsion system components for each propulsion system option. Budgetary estimates from equipment vendors along with cost data from prior studies were used to develop the capital cost estimates, with all costs presented in 2019 dollars. The options with the highest capital costs were scored the highest.

Construction, installation, and outfitting materials and labor costs for the basic construction of the vessel, including items and systems such as structural steel, foundations, system piping, painting, etc., are not included as these costs are expected to be reasonably similar across all three options.

Labor and material costs for engineering and design, shipyard installation, testing, and manufacturer commissioning are also not included. However, a "complexity differential cost" for crew training, system troubleshooting, and extended system testing and commissioning has been added to the capital costs of the DBH and DEH options. This one-time added cost is applicable only to the hybrid options because of the complexity and novelty of their technologies relative to a conventional DM system. This cost is in addition to the typical testing and commissioning costs associated with more conventional propulsion systems.

2.3.2 Maintenance Cost

Maintenance costs for the major propulsion system machinery and equipment for each option are detailed in Appendix B. The maintenance cost includes the parts, consumables, and labor for the recommended maintenance practices provided by the major equipment vendors. Maintenance activities were determined based upon assumed engine and gear operating hours over a 40-year period. For the hybrid options, battery replacement is also considered a maintenance activity and is based upon a 10-year battery life[2].

The option with the highest maintenance cost is scored the highest.

2.3.3 Fuel Consumption & Emissions

Total fuel consumption and emissions are based on the estimated amount of diesel fuel each of the design options would consume on an annual basis. Estimated fuel consumption for each option is calculated based on an analysis of the propulsion power, load factors, route timing during operations, and fuel consumption data provided by the manufacturers for the assumed equipment.

Emissions are divided into two categories: short-term and long-term. Short-term emissions are those currently regulated by the United States Environmental Protection Agency (EPA) and are diesel exhaust emissions that are known to cause health issues locally close to the diesel emission point. Long-term emissions are also referred to as greenhouse gas emissions and are a key component of global climate change.

2.3.4 Reliability

A relative comparison of the reliability of each propulsion configuration was developed to compare the effects of system complexity. For purposes of this study, reliability is intended to represent a relative likelihood the vessel can meet and maintain the published sailing schedule. In order to evaluate and compare the reliability of the three propulsion system options, EBDG developed a scoring matrix and assigned reliability scores to each of the three options' major drive train components that have the potential to affect reliability.

Key terms and guidelines used to define and assign reliability scores for each options' drive train components are as follows:

- **Failure** of a system or component is defined as any system or component malfunction that prevents or delays the vessel from sailing. Failure also refers to the most likely type of failure, as seen and experienced by EBDG's field engineers with similar type propulsion systems, vessels, and vessel operations.
- **Probability of Failure (PoF)** refers to a typical type of failure that might occur on any given system at any given time. The PoF score also considers system or component redundancy and is integrated in this way with the definition of failure above.

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[2] In the previous study [1], a five-year battery replacement schedule was assumed. Based on the more detailed battery sizing calculations completed as part of this analysis, a 10-year battery replacement schedule was found to be feasible.

- **Complexity of Failure** similarly incorporates an anticipated cost of repair and time to repair necessary to return the vessel to service. Time to Repair incorporates likely spare parts availability and the relative availability of support personnel and services to complete the repairs.
- **Failure Scores** for identical components such as engines, generators, and gears were assumed identical between configurations. (Note: There are several drive train components that are similar but not identical to each other. Where this occurs, the differences between the components were considered in the assignment of scores.)
    - Several identical or near identical drive train components were not included in the scoring matrix.

All equipment listed in the reliability scoring matrix is assumed to be required. Note that it is possible to increase the reliability of an option by accounting for additional equipment (that would add or improve redundancy) over and beyond what is required by regulation. For example, adding a third generator to the DEH system would prevent a limited or no-sail scenario in the event of a propulsion generator failure. Another way to affect redundancy and minimize failures would be to maintain an inventory of critical spare parts, and/or an "immediate" on call service agreement with original equipment manufacturers and other marine service professionals. These approaches were not considered in the scoring.

The option with the highest level of reliability was scored the lowest in the scoring matrix, but it must be understood that this is a comparative score – it is not an absolute score and should not be used or viewed this way.

3 GIVEN AND ASSUMED PARAMETERS

3.1 Vessel Route and Power Requirements

The new LIF will operate on the same 0.8 nm route between the ferry terminals on Lummi Island and Gooseberry Point. The vessel must be capable of contending with winds of up to 40 knots and tidal cross currents of up to 5-7 knots. As the new ferry design progresses, EBDG will develop a detailed analysis of the hull's resistance and powering requirements which will be used to select the specific propulsion engines and define the powering needs of the vessel.

For purposes of this report, "power factors" are used to help establish a propulsive load profile for the primary vessel route, and these are listed in Table 2. These trip segments and power factors were developed with input from WCPW and represent the average engine load during each trip segment. For example, during the arrival segment, the forward and aft engine loads may vary between idle and full load while the vessel maneuvers into the terminal, but it is estimated that the average load of each engine would be 50%.

Table 2: Propulsion Loads

Route Segment	Aft Propeller	Forward Propeller	Overall	Time (min)
Loading	20%	0%	10%	4.10
Departure	100%	10%	55%	0.95
Transit	80%	10%	45%	3.30
Arrival	50%	50%	50%	1.25
Unload	20%	0%	10%	4.10
Slack (at dock)	5%	0%	2.5%	1.30
			Total:	**15.00**

A baseline 750 HP engine on each end is assumed for determining the propulsion loads. This represents the highest power engine that would likely be considered for installation on the vessel. Further analysis during later phases of design may indicate that a smaller engine is feasible for safe operation of the ferry.

3.2 Operational Requirements

The analysis assumes the new vessel will operate 350 days per year with 60 one-way trips on weekdays and 30 one-way trips on weekends. This equates to 1,800 one-way trips per year and 4,500 annual operating hours.

3.3 Ships Service Electrical and HVAC Requirements

For the purpose of this study, the assumed ships service electrical load is 50 kW. This accounts for lighting, heating, ventilation, air conditioning, fluid pumping, and other such normal operation loads. The use of electric heat is assumed for this analysis. The ships service fuel consumption is calculated using published fuel consumption data provided by Cummins or by Northern Lights, based upon the arrangement.

3.4 Financial Assumptions

For the capital, maintenance, and life cycle cost estimates, the following assumptions were used:

- All capital equipment costs are based on 2019 pricing.
- In comparing the options, only propulsion system components that are significantly different, have different estimated or quoted costs, or if identical between options but are used in a manner that would drive maintenance events, are incorporated into this analysis. For example, all options utilize the same propellers and there is nothing significantly different in any option that would drive maintenance of the propellers. Therefore, the costs of purchasing and maintaining propellers are not considered in this analysis. The result of this approach is a relative and comparative evaluation of the capital and maintenance costs between the systems. This is purely to be used to evaluate the merits of the systems and is not a true representation of the total capital and maintenance costs for each option.
- The drydocking time is anticipated to be approximately equal between all options considered, so drydocking expenses were not included in the maintenance cost comparison.

- When the vessel is out of service for scheduled maintenance events, no financial consideration has been made or applied to these calculations for leasing a replacement vessel.
- Capital costs for major propulsion system machinery, equipment, and components are based primarily on current and applicable manufacturer and vendor quotations. Where specific quotes could not be obtained, inflation and size adjusted estimates based on previous quotations are used.
- The cost of propulsion system maintenance was estimated using a two-tiered labor rate. First, for all oil changes, inspections, and other minor, routine maintenance activities typically performed by the crew, a fully burdened labor rate of $80/hr was used. Second, a fully burdened labor rate of $160/hr was applied to all scheduled major overhaul or equipment replacement events utilizing manufacturer's technicians.
- No propulsion engine replacements are assumed to occur.
- Batteries are assumed to cost $800/kW-hr. Battery sizing calculations are provided in Appendix F and were confirmed with the manufacturer.
- Fuel consumption calculations are provided in Appendix E. A 30 second engine cooldown period was assumed to be required before shutting down the engines in the DBH configuration.
- For the life cycle cost analysis (LCCA), all costs were estimated as annual costs and inflation is accounted for in the net present value (NPV) calculation. The inflation rates are accounted for as follows:

$$Real\ Discount\ Rate = \frac{(1+nominal\ discount\ rate)}{(1+inflation\ rate)} - 1 \qquad [1]$$

  The discount and inflation rates shown in Table 3 were assumed for the LCCA estimate [4].

Table 3: Net Present Value Rates

Rate	Nominal (%)	Real (%)
Federal Discount Rate	2.75	
Inflation	2.10	0.64

- In the LCCA, the vessel capital cost was estimated parametrically in 2019 dollars [5]. The annual vessel maintenance (not including propulsion system maintenance or any contracted maintenance services needed for complex equipment) was assumed to be 2.25% of the capital cost. A larger vessel overhaul (again, not including propulsion system maintenance) was assumed to occur every 10 years for a cost of 7% of the capital cost[3].

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[3] The previous study [1] assumed a total vessel maintenance cost of 2.5% annually and 8% every ten years. In this study, these factors were reduced to 2.25% and 7% respectively to account for the separately calculated propulsion system maintenance costs.

4 DISCUSSION

4.1 Capital Cost

Table 4 summarizes the capital costs and scores of each propulsion system option. When comparing propulsion system machinery and equipment only, the DM option has the lowest capital cost. Appendix A contains a full break down of each option’s capital cost.

Table 4: Capital Cost Summary

Option	Cost	% Difference	Score
1 - DM	$1,124,000	-	1.00
2 - DBH	$2,082,000	85%	1.85
3 - DEH	$1,806,250	61%	1.61

4.2 Maintenance Cost

Table 5 provides a summary of the 40-year maintenance cost for each propulsion system option with values presented in 2019 dollars. Note that Table 5 does not summarize or represent maintenance costs for the entire vessel. This summary is only applicable to the major propulsion system components which (a) are significantly different between options and (b) are significant drivers of long-term maintenance costs. Two examples of both (a) and (b) above, are line shafts and line shaft bearings. With both the DM and DBH, there are assumed to be a total of four line shafts and four line shaft bearings; whereas the DEH is expected to have only two line shafts and no (0) line shaft bearings. From experience with similar vessel maintenance costs and from inspection, EBDG determined that line shafts and line shaft bearings are not significant enough drivers of long-term maintenance costs to be compared and factored into this analysis. Adding them into the analysis will not change the direction of the results or even meaningfully change the magnitude of the maintenance figures themselves so they are not considered.

When comparing major propulsion system components, the DEH has the lowest maintenance cost of any option because only one engine is operating at a time. With the DM and DBH options, both engines are typically in operation at the same time, resulting in greater engine maintenance costs, though the hybrid system does offer reduced main engine operating hours.

Table 5: Maintenance Cost Summary

Option	Maintenance Cost	% Difference	Score
1 - DM	$3,407,800	-	1.00
2 - DBH	$3,022,113	-11%	0.89
3 - DEH	$2,483,100	-27%	0.73

An annual breakdown of the estimated maintenance costs is provided in Appendix B.

4.3 Fuel Consumption and Emissions

The difference in annual fuel consumption and CO_2 emissions between the options is shown in Table 6. In hybrid mode, the DBH system has an estimated fuel savings of 8.0% compared to the DM system. Due to the limited shore power at either terminal, the DEH system gets all of its power by running diesel generators. Therefore, the DEH system has an estimated fuel savings of only 2.2% compared to the DM system. The DBH system has better fuel economy compared to the DEH system because it avoids the mechanical-electrical energy losses for the vessel propulsion loads during transit.

Table 6: Fuel Consumption Summary

Option	**Fuel Consumption**	**CO_2**	**% Difference**	**Score**
1 - DM	115,600 gal	1,163,000 kg	-	1.00
2 - DBH (Hybrid)	106,400 gal	1,070,400 kg	-8.0%	0.92
2 - DBH (Non-Hybrid)	115,600 gal	1,163,000 kg	0%	1.00
3 - DEH	113,100 gal	1,137,700 kg	-2.2%[4]	0.98

The diesel engine exhaust emissions for each option are presented below. The emissions can be considered to fall into two major categories: short term and long term. Short term emissions such as particulate matter (PM), oxides of nitrogen (NOx), hydrocarbons (HC), and carbon monoxide (CO) remain in the environment for a limited time but are known to cause health hazards. Short term emissions are currently regulated by the EPA for marine vessels and other emitters. Long term emissions are those characterized as greenhouse gas emissions such as carbon dioxide (CO_2). CO_2 is not currently regulated for marine vessels in the US but is receiving more attention and may be further scrutinized in the future.

Short term emissions have been addressed by the EPA for marine diesel engines by phasing in progressively more stringent "Tiers" of engine emission limits. This phasing of emission limits has occurred over the last fifteen years for marine diesels and they have effectively reached their final phase. The EPA requires the manufacturers of these engines to develop the technology required to meet the Tier requirements, and the operators are expected to maintain the equipment in functional status. For the propulsion configurations in this study (less than 800 hp per engine), the final EPA requirement is Tier 3.

Long term emissions, particularly CO_2, is directly related to the quantity of fuel burned. There are no currently feasible carbon capture devices or technology for marine diesels that would reduce CO_2 output for a given amount of fuel burned. The only existing technology options for reducing long term greenhouse gas emissions from marine diesels is to (a) burn less fuel either by operating less frequently (with a reduced sailing schedule) or (b) operate more efficiently.

The short-term emissions were estimated for the propulsion options using the EPA methodology found in [5]. The EPA's short-term emissions calculations use a method that accounts for engine

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[4] The previous study [1] assumed of 5% fuel savings with a DEH compared to a DM. This assumption was based on the average fuel savings from a range of sample vessels of various sizes. During the more detailed and specific analysis completed herein, the fuel savings on this specific vessel and route were calculated to be 2.2%.

power, loading, run time, and EPA engine Tier. CO_2 emissions were estimated using a simple formula that relates fuel burned to CO_2 produced.

The annualized short term, EPA regulated emissions are listed in Table 7. Note that the short term emissions are presented for reference, but only the fuel consumption and long term emissions (greenhouse gas emissions) are included in the scoring criteria (see Table 6).

Table 7: Annual Diesel Exhaust Emission Comparison

Option	**PM_{10} (kg)**	**NO_x (kg)**	**HC (kg)**	**CO (kg)**
1 - DM	84	6,489	138	1,522
2 - DBH (Hybrid)	90	6,938	148	1,627
2 - DBH (Non-Hybrid)	84	6,489	138	1,522
3 - DEH	88	6,789	145	1,592

4.4 Reliability

Table 8 provides a summary of the relative reliability calculations for the propulsion options. As the quantity of critical components or equipment increases, the reliability of the arrangement generally decreases because all critical components or equipment are required to be in an operable condition in order to prevent a system failure. The DM system has the fewest critical components and is therefore the most reliable. It is likely that a DM system on the new LIF would have a reliability similar to that of the WHATCOM CHIEF, i.e. few to zero failures preventing sailings annually.

Not considered in these calculations is the effect of added redundancy. For example, the DEH system could have significantly higher reliability if an additional generator was installed.

The reliability matrix uses weighting factors to account for the ease of repair in the event of a failure (failure in this case means preventing or delaying sailings). This is relevant to an operator as it shows that, although a failure event for one system may be more likely, if it is easy or quick to repair the consequence is not as bad compared to a system with a rare failure of a difficult or long lead time component.

The reliability scores presented in Table 8 are intended only to demonstrate the relative difference between the propulsion system options. As discussed, the DM reliability score of 18.0 is comparable to the reliability of the M/V WHATCOM CHIEF. For a complete breakdown of the reliability scoring, see Appendix C.

Table 8: Reliability Summary

Option	**Reliability Score**	**% Difference**	**Score**
1 - DM	18.0	-	1.00
2 - DBH (Hybrid)	31.0	72%	1.72
2 - DBH (Non-Hybrid)	18.0	0%	1.00
3 - DEH	20.5	14%	1.14

4.4.1 Hybrid Reliability

Traditional diesel mechanical systems are well understood and typically have the benefit of having many millions of hours of run time in other installations. While the state of the art in hybrid marine vessels is advancing rapidly, current installations are effectively prototypes and carry an element of risk due to their complexity and requirement for multiple systems from different vendors to work in harmony. One common theme of EBDG field engineers' recent experiences – across multiple clients and vessels utilizing either traditional diesel electric or a hybrid type of propulsion system – is that the software driving these hybrid control and power management systems cannot be fully tested and "de-bugged" prior to being installed. The results of this shortcoming are occasionally missed or delayed sailings and overall lower vessel reliability. This is particularly true in the first 1 to 2 years of service, while problems with software and other electrical componentry are worked out. The reliability presented in this report is intended to demonstrate the long-term reliability of the system after the initial de-bugging period is complete.

As introduced above, an important aspect of system reliability is the simplicity of repair and/or time required to repair. An owner of a diesel mechanical system, through benefit of widespread and long-term adoption, has multiple local options to call upon for emergency repair and parts supply. A hybrid vessel has components that may be sole source from overseas vendors that require specialist repair services and long lead times. This may be mitigated somewhat by the owner retaining backup system modules that could be replaced by their own maintenance crew with remote consultation from the propulsion system supplier. However, it is likely that annual maintenance and emergency repairs would need to be performed by a contracted service technician for some of the more complex components of the hybrid system.

4.4.2 DBH Reliability

As discussed, this study does not evaluate the impacts of adding additional equipment for greater redundancy and, therefore, improved reliability. However, the DBH option has inherent redundancy with the baseline equipment which needs to be considered and is presented in the scoring in Table 8. Should a failure occur in the batteries or electric drive components, the DBH system could still operate as a conventional DM system without impact to the sailing schedule, hence, no failure. While the fuel savings of the hybrid system would no longer be achieved, the vessel could still operate without any immediate repairs being required. This effectively gives the DBH option a reliability score equal to the DM option of 1.0.

5 CONCLUSIONS

The combined weighted scores are presented in Table 9. As discussed, a lower score represents a better evaluation result. Generally speaking, the hybrid options have higher capital costs and lower reliability but offer savings in maintenance cost and lower fuel consumption and greenhouse gas emissions.

Table 9: Scoring Matrix Results

Propulsion System Option	Reliability	Maintenance Cost	Capital Cost	Fuel Consumption & Emissions	Weighted Score
1 - DM	1.00	1.00	1.00	1.00	1.00
2 - DBH (Hybrid)	1.72	0.89	1.85	0.92	1.38
2 - DBH (Non-Hybrid)	1.00	0.89	1.85	1.00	1.16
3 - DEH	1.14	0.73	1.61	0.98	1.10
Weighting Factor	33%	27%	22%	18%	

Due to the reduced capital cost and a reliability similar to the M/V WHATCOM CHIEF, the DM system has the best score at 1.0. The DEH system scores second due to its lower maintenance cost and fair reliability (but note that this reliability is after the initial de-bugging time). The DBH option places third due to the low reliability score (but note this does not account for the redundancy of the non-hybrid mode). When the reliability in non-hybrid mode is included, the score is much closer to the DEH result.

In addition to the results of the scoring matrix, it is important to consider the overall vessel life cycle costs with each propulsion system option. The LCCA completed as part of the previous study [1] was updated to incorporate the propulsion system maintenance, capital costs, and fuel consumption contained herein (though the results of the LCCA should still be viewed as parametric). As demonstrated in Figure 4, the 40-year life cycle costs of each option are all comparable, with less than a 1% difference between the lowest and highest life cycle cost. This is because over a 40-year time frame, the fuel and maintenance savings of the hybrid configurations makeup for the higher initial capital costs. A full breakdown of the LCCA is included in Appendix D.

In addition to the life cycle costs, Figure 4 shows the reliability score. As discussed in Section 4.4.2, the DMH has the same reliability as the DM when operating as a conventional diesel but has the lowest reliability score when operating as a hybrid.

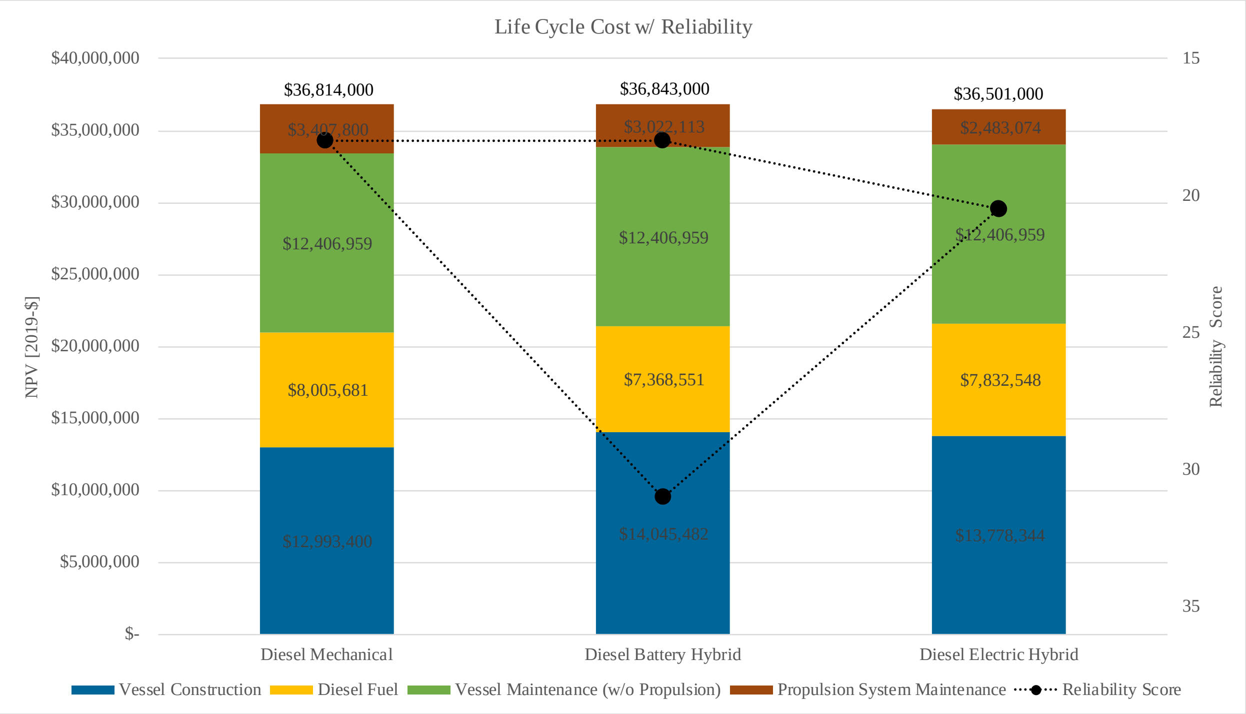

Figure 4: Life cycle cost analysis comparison

While the results presented in Table 9 and Figure 4 offer an evaluation of the quantifiable factors in propulsion selection, there are many other qualitative factors that must be considered. For example, of all the propulsion system options considered, the hybrid options are better suited to one day incorporate shore power charging to reduce or even eliminate diesel fuel consumption. Installation of properly sized shore power charging infrastructure would allow either hybrid system to utilize a cleaner energy source and burn less fuel. While the DM option could also be converted, the complexity and cost of doing so would be substantially greater than with either hybrid option. This improved flexibility for a "greener" vessel in the future may outweigh the higher initial capital cost and lower reliability of the current hybrid options.

Lastly, this report has focused on battery storage as the avenue for improving fuel economy and reducing emissions because it is the only technology that EBDG believes is currently feasible for immediate application on vessels such as the new LIF. However, there are emerging technologies which may eventually become viable alternatives to increased battery capacity and shore power charging. For example, liquified or compressed hydrogen gas with fuel cells for generating electricity may become a good option for generating propulsion power onboard the vessel. And while conversion to hydrogen fuel cell power would likely be a more expensive and longer vessel conversion, starting with a hybrid propulsion system would reduce the extent of such a conversion just as it does for shore power charging. Considering the speed of technological advances and the vessel's 40-year service life, conversion to what is currently an emerging alternative fuel source could someday become a viable option.

6 REFERENCES

[1] EBDG, "17098-04M, "Lummi Island Ferry System Task 4.3 - Alternative Fuel Analysis"," 2018.

[2] EBDG, "05017-5300-04, Rev. A, 17098-01M, "Lummi Island Ferry - Propulsion System Comparison"," 2005.

[3] EBDG, "17098-03M, "Lummi Island Ferry System Task 4.1 - Vessel Alternatives Analysis"," 2018.

[4] Federal Reserve System, "Current Interest Rates," [Online]. Available: https://www.frbdiscountwindow.org/. [Accessed 8 July 2019].

[5] EBDG, "17098.01-002-043-0, "Construction Cost Estimate"," Seattle, WA, 2020.

[6] United States Environmental Protection Agency, "EPA420-R-08-001a Regulatory Impact Analysis: Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression Ignition Engines Less than 30 Liters Per Cylinder," May 2008.

[7] EBDG, "17098-05M, "Lummi Island Verry System Task 4.4 - Vessel Costs"," 2018.

Appendix A

Capital Cost Data

Diesel Mechanical				
SWBS	**Item**	**Qty**	**Price / Ea**	**Total**
230	**Engines**			
	Propulsion Engines	2	$121,250	$242,500
241	**Reduction Gears / CPP System**			
	Hundested CPG 38 Gear (Standard Gear) w/MP 500 Propeller Units	2	$304,000	$608,000
243	**Shafting & Propeller**			
	Tail and Line Shafting	4	*	*
	Line Shaft Bearings	4	$4,375	$17,500
	Muff Coupling (between shafts)	2	*	*
	Torsional Couplings (Engine/Gear)	2	*	*
	Bulkhead Seals	4	$8,125	$32,500
	Misc. other couplings, bolts, nuts, chocks,	1	$25,000	$25,000
300	**Electrical**			
	Ship Service Generator	2	$37,250	$74,500
	Ship Service Switchboard	1	$65,000	$65,000
	Propulsion Control System	1	$35,000	$35,000
400	**Controls**			
	IMACS	1	$24,000	$24,000
*Costs are included in Reduction Gear/CPP cost				**$1,124,000**

Diesel Battery Hybrid				
SWBS	**Item**	**Qty**	**Price / Ea**	**Total**
230	**Engines**			
	Propulsion Engines	2	$121,250	$242,500
241	**Reduction Gears / CPP System**			
	Hundested CPG 38 Gear (Custom Gear) w/MP 500 Propeller Units	2	$338,500	$677,000
243	**Shafting & Propeller**			
	Tail and Line Shafting	4	*	*
	Line Shaft Bearings	4	$4,375	$17,500
	Muff Coupling (between shafts)	2	*	*
	Torsional Couplings (Engine/Gear)	2	*	*
	Bulkhead Seals	4	$8,125	$32,500
	Misc. other couplings, bolts, nuts, chocks, etc	1	$25,000	$25,000
300	**Electrical**			
	Ship Service Generator	2	$37,250	$74,500
	Ship Service Switchboard	1	$65,000	$65,000
	560 kWe Motor-Generators	2	$150,000	$300,000
	560 kWe AC motor drives	2	$75,000	$150,000
	237 kWH Battery Bank	1	$158,000	$158,000
	Propulsion Control System	1	$47,000	$47,000
	Battery Control Cabinet	1	$179,000	$179,000
400	**Controls**			
	IMACS	1	$34,000	$34,000
800/900	**Crew Training / Trials (Extended)**			
	Crew training, trials and commissioning	10	$8,000	$80,000
*Costs are included in Reduction Gear/CPP cost				**$2,082,000**

Diesel Electric Hybrid				
SWBS	**Item**	**Qty**	**Price / Ea**	**Total**
230	**Engines**			
	Propulsion Generators (Cummins/Stamford)	2	$172,500	$345,000
241	**Reduction Gears**			
	Twin Disc MGX5222DC	2	$48,000	$96,000
243	**Shafting & Propeller**			
	Line Shafts	2	$19,500	$39,000
	Mathers Shaft Brakes	2	$16,500	$33,000
	BulkHead Seals	2	$8,125	$16,250
	Torsional/Flex Couplings (Gear / Motor)	2	$17,500	$35,000
	Propellers (Fixed Pitch)	2	$17,500	$35,000
	Misc. other couplings, bolts, nuts, chocks, et	1	$25,000	$25,000
300	**Electrical**			
	Propulsion and Distribution Switchboard	1	$154,000	$154,000
	Battery Control Cabinet	1	$179,000	$179,000
	237 kW-hr Battery Bank	1	$158,000	$158,000
	Propulsion Control System	1	$47,000	$47,000
	***** 530 kWe AC motor drives	2	$75,000	$150,000
	***** 530 kWe Electric Motors	2	$150,000	$300,000
	Electrical Cabeling / Misc. Components	1	$80,000	$80,000
400	**Controls**			
	IMACS	1	$34,000	$34,000
800/900	**Crew Training / Trials (Extended)**			
	Crew training, trials and commissioning	10	$8,000	$80,000
				$1,806,250

Appendix B

Maintenance Cost Data

Diesel Mechanical									
Year	Engine Maintenance			Reduction Gear / CPP Maintenance			Generator Maintenance		
	Labor Hours	Material Cost	Total Cost	Labor Hours	Material Cost	Total Cost	Labor Hours	Material Cost	Total Cost
2024	89	$5,100	$12,220	40	$5,000	$8,200	88	$835	$7,875
2025	76	$4,560	$10,640	40	$5,000	$8,200	72	$668	$6,428
2026	80	$4,580	$10,980	40	$5,000	$8,200	76	$668	$6,748
2027	85	$5,080	$11,880	40	$5,000	$8,200	84	$835	$7,555
2028	80	$4,580	$10,980	40	$5,000	$8,200	100	$2,368	$10,368
2029	85	$5,080	$11,880	2	$220,000	$220,160	84	$835	$7,555
2030	480	$167,780	$206,180	40	$5,000	$8,200	76	$668	$6,748
2031	85	$5,080	$11,880	40	$5,000	$8,200	92	$835	$8,195
2032	80	$4,580	$10,980	40	$5,000	$8,200	340	$49,168	$76,368
2033	85	$5,080	$11,880	40	$5,000	$8,200	84	$835	$7,555
2034	80	$4,580	$10,980	40	$5,000	$8,200	76	$668	$6,748
2035	85	$5,080	$11,880	42	$5,002	$8,362	84	$835	$7,555
2036	80	$4,580	$10,980	2	$220,000	$220,160	76	$668	$6,748
2037	685	$231,880	$286,680	40	$5,000	$8,200	108	$2,535	$11,175
2038	80	$4,580	$10,980	40	$5,000	$8,200	76	$668	$6,748
2039	85	$5,080	$11,880	40	$5,000	$8,200	92	$835	$8,195
2040	80	$4,580	$10,980	40	$5,000	$8,200	76	$668	$6,748
2041	85	$5,080	$11,880	40	$5,000	$8,200	348	$49,335	$77,175
2042	80	$4,580	$10,980	40	$5,000	$8,200	76	$668	$6,748
2043	485	$168,280	$207,080	2	$220,000	$220,160	84	$835	$7,555
2044	80	$4,580	$10,980	40	$5,000	$8,200	76	$668	$6,748
2045	85	$5,080	$11,880	40	$5,000	$8,200	84	$835	$7,555
2046	80	$4,580	$10,980	40	$5,000	$8,200	100	$2,368	$10,368
2047	85	$5,080	$11,880	40	$5,000	$8,200	92	$835	$8,195
2048	80	$4,580	$10,980	40	$5,000	$8,200	76	$668	$6,748
2049	85	$5,080	$11,880	2	$220,000	$220,160	84	$835	$7,555
2050	680	$231,380	$285,780	40	$5,000	$8,200	340	$49,168	$76,368
2051	85	$5,080	$11,880	40	$5,000	$8,200	84	$835	$7,555
2052	80	$4,580	$10,980	40	$5,000	$8,200	76	$668	$6,748
2053	85	$5,080	$11,880	40	$5,000	$8,200	84	$835	$7,555
2054	80	$4,580	$10,980	40	$5,000	$8,200	76	$668	$6,748
2055	85	$5,080	$11,880	40	$5,000	$8,200	116	$2,535	$11,815
2056	80	$4,580	$10,980	2	$220,000	$220,160	76	$668	$6,748
2057	485	$168,280	$207,080	40	$5,000	$8,200	84	$835	$7,555
2058	80	$4,580	$10,980	40	$5,000	$8,200	76	$668	$6,748
2059	85	$5,080	$11,880	40	$5,000	$8,200	348	$49,335	$77,175
2060	80	$4,580	$10,980	40	$5,000	$8,200	76	$668	$6,748
2061	85	$5,080	$11,880	40	$5,000	$8,200	84	$835	$7,555
2062	80	$4,580	$10,980	40	$5,000	$8,200	76	$668	$6,748
2063	685	$231,880	$286,680	2	$220,000	$220,160	116	$2,535	$11,815

Diesel Battery Hybrid												
Year	Engine Maintenance			Reduction Gear / CPP Maintenance			SSG & M-Gen Maintenance			Battery Monitoring & Replacement		
	Labor Hours	Material Cost	Total Cost	Labor Hours	Material Cost	Total Cost	Labor Hours	Material Cost	Total Cost	Labor Hours	Material Cost	Total Cost
2024	30	$1,360	$3,760	40	$5,000	$8,200	88	$835	$7,875	2	$5,100	$5,260
2025	34	$1,860	$4,580	40	$5,000	$8,200	72	$668	$6,428	2	$5,100	$5,260
2026	40	$1,880	$5,080	40	$5,000	$8,200	76	$668	$6,748	2	$5,100	$5,260
2027	42	$2,280	$5,640	40	$5,000	$8,200	84	$835	$7,555	2	$5,100	$5,260
2028	42	$2,280	$5,640	40	$5,000	$8,200	100	$2,368	$10,368	2	$5,100	$5,260
2029	32	$1,360	$3,920	2	$220,000	$220,160	84	$835	$7,555	2	$5,100	$5,260
2030	42	$2,280	$5,640	40	$5,000	$8,200	140	$5,468	$16,668	2	$5,100	$5,260
2031	30	$1,460	$3,860	40	$5,000	$8,200	92	$835	$8,195	2	$5,100	$5,260
2032	42	$2,280	$5,640	40	$5,000	$8,200	340	$49,168	$76,368	2	$5,100	$5,260
2033	42	$2,280	$5,640	40	$5,000	$8,200	84	$835	$7,555	2	$5,100	$5,260
2034	30	$1,360	$3,760	40	$5,000	$8,200	76	$668	$6,748	16	$160,000	$161,280
2035	42	$2,280	$5,640	42	$5,002	$8,362	84	$835	$7,555	2	$5,100	$5,260
2036	30	$1,460	$3,860	2	$220,000	$220,160	76	$668	$6,748	2	$5,100	$5,260
2037	42	$2,280	$5,640	40	$5,000	$8,200	172	$7,335	$21,095	2	$5,100	$5,260
2038	42	$2,280	$5,640	40	$5,000	$8,200	76	$668	$6,748	2	$5,100	$5,260
2039	30	$1,360	$3,760	40	$5,000	$8,200	92	$835	$8,195	2	$5,100	$5,260
2040	442	$165,480	$200,840	40	$5,000	$8,200	76	$668	$6,748	2	$5,100	$5,260
2041	30	$1,460	$3,860	40	$5,000	$8,200	348	$49,335	$77,175	2	$5,100	$5,260
2042	42	$2,280	$5,640	40	$5,000	$8,200	76	$668	$6,748	2	$5,100	$5,260
2043	42	$2,280	$5,640	2	$220,000	$220,160	148	$5,635	$17,475	2	$5,100	$5,260
2044	30	$1,360	$3,760	40	$5,000	$8,200	76	$668	$6,748	16	$160,000	$161,280
2045	42	$2,280	$5,640	40	$5,000	$8,200	84	$835	$7,555	2	$5,100	$5,260
2046	30	$1,460	$3,860	40	$5,000	$8,200	100	$2,368	$10,368	2	$5,100	$5,260
2047	42	$2,280	$5,640	40	$5,000	$8,200	92	$835	$8,195	2	$5,100	$5,260
2048	42	$2,280	$5,640	40	$5,000	$8,200	76	$668	$6,748	2	$5,100	$5,260
2049	30	$1,360	$3,760	2	$220,000	$220,160	84	$835	$7,555	2	$5,100	$5,260
2050	42	$2,280	$5,640	40	$5,000	$8,200	404	$53,968	$86,288	2	$5,100	$5,260
2051	30	$1,460	$3,860	40	$5,000	$8,200	84	$835	$7,555	2	$5,100	$5,260
2052	42	$2,280	$5,640	40	$5,000	$8,200	76	$668	$6,748	2	$5,100	$5,260
2053	42	$2,280	$5,640	40	$5,000	$8,200	84	$835	$7,555	2	$5,100	$5,260
2054	30	$1,360	$3,760	40	$5,000	$8,200	76	$668	$6,748	16	$160,000	$161,280
2055	42	$2,280	$5,640	40	$5,000	$8,200	116	$2,535	$11,815	2	$5,100	$5,260
2056	30	$1,460	$3,860	2	$220,000	$220,160	76	$668	$6,748	2	$5,100	$5,260
2057	642	$229,080	$280,440	40	$5,000	$8,200	148	$5,635	$17,475	2	$5,100	$5,260
2058	42	$2,280	$5,640	40	$5,000	$8,200	76	$668	$6,748	2	$5,100	$5,260
2059	30	$1,360	$3,760	40	$5,000	$8,200	348	$49,335	$77,175	2	$5,100	$5,260
2060	42	$2,280	$5,640	40	$5,000	$8,200	76	$668	$6,748	2	$5,100	$5,260
2061	30	$1,460	$3,860	40	$5,000	$8,200	84	$835	$7,555	2	$5,100	$5,260
2062	42	$2,280	$5,640	40	$5,000	$8,200	76	$668	$6,748	2	$5,100	$5,260
2063	42	$2,280	$5,640	2	$220,000	$220,160	180	$7,335	$21,735	2	$5,100	$5,260

Diesel Electric Hybrid									
Year	Generator Maintenance			Reduction Gear			Battery Monitoring & Replacement		
	Labor Hours	Material Cost	Total Cost	Labor Hours	Material Cost	Total Cost	Labor Hours	Material Cost	Total Cost
2024	113	$2,500	$11,500	20	$2,500	$4,100	2	$5,100	$5,260
2025	114	$2,540	$11,660	20	$2,500	$4,100	2	$5,100	$5,260
2026	121	$2,560	$12,240	20	$2,500	$4,100	2	$5,100	$5,260
2027	136	$3,080	$13,920	20	$2,500	$4,100	2	$5,100	$5,260
2028	101	$2,060	$10,140	20	$2,502	$4,102	2	$5,100	$5,260
2029	126	$2,980	$13,020	2	$150,000	$150,160	2	$5,100	$5,260
2030	121	$2,560	$12,240	20	$2,500	$4,100	2	$5,100	$5,260
2031	136	$3,080	$13,920	20	$2,500	$4,100	2	$5,100	$5,260
2032	101	$2,060	$10,140	20	$2,500	$4,100	2	$5,100	$5,260
2033	126	$2,980	$13,020	20	$2,502	$4,102	2	$5,100	$5,260
2034	121	$2,560	$12,240	20	$2,504	$4,104	16	$160,000	$161,280
2035	576	$183,080	$229,120	20	$2,506	$4,106	2	$5,100	$5,260
2036	101	$2,060	$10,140	2	$150,000	$150,160	2	$5,100	$5,260
2037	126	$2,980	$13,020	20	$2,510	$4,110	2	$5,100	$5,260
2038	121	$2,560	$12,240	20	$2,512	$4,112	2	$5,100	$5,260
2039	136	$3,080	$13,920	20	$2,514	$4,114	2	$5,100	$5,260
2040	101	$2,060	$10,140	20	$2,516	$4,116	2	$5,100	$5,260
2041	126	$2,980	$13,020	20	$2,518	$4,118	2	$5,100	$5,260
2042	121	$2,560	$12,240	20	$2,520	$4,120	2	$5,100	$5,260
2043	136	$3,080	$13,920	2	$150,000	$150,160	2	$5,100	$5,260
2044	101	$2,060	$10,140	20	$2,524	$4,124	16	$160,000	$161,280
2045	126	$2,980	$13,020	20	$2,526	$4,126	2	$5,100	$5,260
2046	781	$246,560	$309,040	20	$2,528	$4,128	2	$5,100	$5,260
2047	136	$3,080	$13,920	20	$2,530	$4,130	2	$5,100	$5,260
2048	101	$2,060	$10,140	20	$2,532	$4,132	2	$5,100	$5,260
2049	126	$2,980	$13,020	2	$150,000	$150,160	2	$5,100	$5,260
2050	121	$2,560	$12,240	20	$2,536	$4,136	2	$5,100	$5,260
2051	136	$3,080	$13,920	20	$2,538	$4,138	2	$5,100	$5,260
2052	101	$2,060	$10,140	20	$2,540	$4,140	2	$5,100	$5,260
2053	126	$2,980	$13,020	20	$2,542	$4,142	2	$5,100	$5,260
2054	121	$2,560	$12,240	20	$2,544	$4,144	16	$160,000	$161,280
2055	136	$3,080	$13,920	20	$2,546	$4,146	2	$5,100	$5,260
2056	101	$2,060	$10,140	2	$150,000	$150,160	2	$5,100	$5,260
2057	566	$182,980	$228,220	20	$2,550	$4,150	2	$5,100	$5,260
2058	121	$2,560	$12,240	20	$2,552	$4,152	2	$5,100	$5,260
2059	136	$3,080	$13,920	20	$2,554	$4,154	2	$5,100	$5,260
2060	101	$2,060	$10,140	20	$2,556	$4,156	2	$5,100	$5,260
2061	126	$2,980	$13,020	20	$2,558	$4,158	2	$5,100	$5,260
2062	121	$2,560	$12,240	20	$2,560	$4,160	2	$5,100	$5,260
2063	136	$3,080	$13,920	2	$150,000	$150,160	2	$5,100	$5,260

Appendix C

Reliability Data

Component	Component Quantity	Probability of Failure	Complexity of Repair	Score
Option 1 (DM)			**Overall Score:**	**18.00**
Propulsion Engine	2.00	3.00	1.00	6.00
Hundested Pitch Integrated Reduction Gear	2.00	0.50	3.00	3.00
Hundested CPP	2.00	0.50	3.00	3.00
Ship Service Generator	1.00	3.00	1.00	3.00
Ship Service Switchboard	1.00	0.50	1.00	0.50
Propulsion Controls	1.00	0.50	1.00	0.50
Torsional Coupling (Engine/Gear)	2.00	0.50	2.00	2.00
Line Shaft Hydraulic Couplings	4.00	0.00	3.00	0.00
Bulk Head Seals	4.00	0.00	3.00	0.00
Option 2 (DBH)			**Overall Score:**	**31.00**
Propulsion Engine	2.00	3.00	1.00	6.00
Hundested Pitch Integrated PTO/PTI Reduction Gear	2.00	0.50	3.00	3.00
Hundested CPP	2.00	0.50	3.00	3.00
Ship Service Switchboard	1.00	0.50	1.00	0.50
Batteries	1.00	0.50	1.00	0.50
DMH Motor-Generators	2.00	0.50	3.00	3.00
Electric Motor Drive	2.00	1.00	2.00	4.00
Power Management System	2.00	2.00	1.00	4.00
Propulsion Controls	1.00	1.00	2.00	2.00
Torsional Coupling (Engine / Gear)	2.00	0.50	2.00	2.00
Bulk Head Seals	4.00	0.00	3.00	0.00
Ship Service Generator	2.00	0.50	1.00	1.00
Line Shaft Hydraulic Couplings	4.00	0.00	3.00	0.00
Torsional Coupling (Gear / Motor)	2.00	0.50	2.00	2.00
Option 3 (DEH)			**Overall Score:**	**20.50**
Propulsion Generator	1.00	3.00	1.00	3.00
Reduction Gear	2.00	0.50	3.00	3.00
Propulsion/Distribution Switchboard	1.00	0.50	2.00	1.00
Batteries	1.00	0.50	1.00	0.50
Electric Motor	2.00	0.50	3.00	3.00
Electric Motor Drive	2.00	1.00	2.00	4.00
Power Managment System	1.00	2.00	1.00	2.00
Propulsion Controls	1.00	1.00	2.00	2.00
Bulk Head Seals	2.00	0.00	3.00	0.00
Shaft Brake	2.00	0.00	1.00	0.00
Torsional Coupling (Gear / Motor)	2.00	0.50	2.00	2.00

Appendix D

LCCA

Diesel Mechanical

ASSUMPTIONS

Real Rate	0.64%	
Annual Fuel Consumption	115600	gal/yr
Fuel Cost	2.03	$/gal
Vessel Maintenance (Annual)	2.25%	of Capital Cost
Vessel Maintenance (10 years)	7%	of Capital Cost

	Vessel Construction	Diesel Fuel	Vessel Maintenance (w/o Propulsion)	Propulsion System Maintenance
NPV	$12,993,400	$8,005,681	$12,406,959	$3,407,800
2019	$0	$0	$0	$0
2020	$0	$0	$0	$0
2021	$0	$0	$0	$0
2022	$0	$0	$0	$0
2023	$13,412,300	$0	$0	$0
2024		$234,668	$301,777	$28,295
2025		$234,668	$301,777	$25,268
2026		$234,668	$301,777	$25,928
2027		$234,668	$301,777	$27,635
2028		$234,668	$301,777	$29,548
2029		$234,668	$301,777	$239,595
2030		$234,668	$301,777	$221,128
2031		$234,668	$301,777	$28,275
2032		$234,668	$301,777	$95,548
2033		$234,668	$938,861	$27,635
2034		$234,668	$301,777	$25,928
2035		$234,668	$301,777	$27,797
2036		$234,668	$301,777	$237,888
2037		$234,668	$301,777	$306,055
2038		$234,668	$301,777	$25,928
2039		$234,668	$301,777	$28,275
2040		$234,668	$301,777	$25,928
2041		$234,668	$301,777	$97,255
2042		$234,668	$301,777	$25,928
2043		$234,668	$938,861	$434,795
2044		$234,668	$301,777	$25,928
2045		$234,668	$301,777	$27,635
2046		$234,668	$301,777	$29,548
2047		$234,668	$301,777	$28,275
2048		$234,668	$301,777	$25,928
2049		$234,668	$301,777	$239,595
2050		$234,668	$301,777	$370,348
2051		$234,668	$301,777	$27,635
2052		$234,668	$301,777	$25,928
2053		$234,668	$938,861	$27,635
2054		$234,668	$301,777	$25,928
2055		$234,668	$301,777	$31,895
2056		$234,668	$301,777	$237,888
2057		$234,668	$301,777	$222,835
2058		$234,668	$301,777	$25,928
2059		$234,668	$301,777	$97,255
2060		$234,668	$301,777	$25,928
2061		$234,668	$301,777	$27,635
2062		$234,668	$301,777	$25,928
2063		$234,668	$938,861	$518,655
	LIFE CYCLE COST			**$ 36,813,840**

Diesel Battery Hybrid

ASSUMPTIONS

Real Rate	0.64%	
Annual Fuel Consumption	106400	gal/yr
Fuel Cost	2.03	$/gal
Vessel Maintenance (Annual)	2.25%	of Capital Cost
Vessel Maintenance (10 years)	7%	of Capital Cost

	Vessel Construction	Diesel Fuel	Vessel Maintenance (w/o Propulsion)	Propulsion System Maintenance
NPV	$14,045,482	$7,368,551	$12,406,959	$3,022,113
2019	$0	$0	$0	$0
2020	$0	$0	$0	$0
2021	$0	$0	$0	$0
2022	$0	$0	$0	$0
2023	$14,498,300	$0	$0	$0
2024		$215,992	$301,777	$25,095
2025		$215,992	$301,777	$24,468
2026		$215,992	$301,777	$25,288
2027		$215,992	$301,777	$26,655
2028		$215,992	$301,777	$29,468
2029		$215,992	$301,777	$236,895
2030		$215,992	$301,777	$35,768
2031		$215,992	$301,777	$25,515
2032		$215,992	$301,777	$95,468
2033		$215,992	$938,861	$26,655
2034		$215,992	$301,777	$179,988
2035		$215,992	$301,777	$26,817
2036		$215,992	$301,777	$236,028
2037		$215,992	$301,777	$40,195
2038		$215,992	$301,777	$25,848
2039		$215,992	$301,777	$25,415
2040		$215,992	$301,777	$221,048
2041		$215,992	$301,777	$94,495
2042		$215,992	$301,777	$25,848
2043		$215,992	$938,861	$248,535
2044		$215,992	$301,777	$179,988
2045		$215,992	$301,777	$26,655
2046		$215,992	$301,777	$27,688
2047		$215,992	$301,777	$27,295
2048		$215,992	$301,777	$25,848
2049		$215,992	$301,777	$236,735
2050		$215,992	$301,777	$105,388
2051		$215,992	$301,777	$24,875
2052		$215,992	$301,777	$25,848
2053		$215,992	$938,861	$26,655
2054		$215,992	$301,777	$179,988
2055		$215,992	$301,777	$30,915
2056		$215,992	$301,777	$236,028
2057		$215,992	$301,777	$311,375
2058		$215,992	$301,777	$25,848
2059		$215,992	$301,777	$94,395
2060		$215,992	$301,777	$25,848
2061		$215,992	$301,777	$24,875
2062		$215,992	$301,777	$25,848
2063		$215,992	$938,861	$252,795
LIFE CYCLE COST				**$ 36,843,104**

Diesel Electric Hybrid

ASSUMPTIONS			
	Real Rate	0.64%	
	Annual Fuel Consumption	113100	gal/yr
	Fuel Cost	2.03	$/gal
	Vessel Maintenance (Annual)	2.25%	of Capital Cost
	Vessel Maintenance (10 years)	7%	of Capital Cost

	Vessel Construction	Diesel Fuel	Vessel Maintenance (w/o Propulsion)	Propulsion System Maintenance
NPV	$13,778,344	$7,832,548	$12,406,959	$2,483,074
2019	$0	$0	$0	$0
2020	$0	$0	$0	$0
2021	$0	$0	$0	$0
2022	$0	$0	$0	$0
2023	$14,222,550	$0	$0	$0
2024		$229,593	$301,777	$20,860
2025		$229,593	$301,777	$21,020
2026		$229,593	$301,777	$21,600
2027		$229,593	$301,777	$23,280
2028		$229,593	$301,777	$19,502
2029		$229,593	$301,777	$168,440
2030		$229,593	$301,777	$21,600
2031		$229,593	$301,777	$23,280
2032		$229,593	$301,777	$19,500
2033		$229,593	$938,861	$22,382
2034		$229,593	$301,777	$177,624
2035		$229,593	$301,777	$238,486
2036		$229,593	$301,777	$165,560
2037		$229,593	$301,777	$22,390
2038		$229,593	$301,777	$21,612
2039		$229,593	$301,777	$23,294
2040		$229,593	$301,777	$19,516
2041		$229,593	$301,777	$22,398
2042		$229,593	$301,777	$21,620
2043		$229,593	$938,861	$169,340
2044		$229,593	$301,777	$175,544
2045		$229,593	$301,777	$22,406
2046		$229,593	$301,777	$318,428
2047		$229,593	$301,777	$23,310
2048		$229,593	$301,777	$19,532
2049		$229,593	$301,777	$168,440
2050		$229,593	$301,777	$21,636
2051		$229,593	$301,777	$23,318
2052		$229,593	$301,777	$19,540
2053		$229,593	$938,861	$22,422
2054		$229,593	$301,777	$177,664
2055		$229,593	$301,777	$23,326
2056		$229,593	$301,777	$165,560
2057		$229,593	$301,777	$237,630
2058		$229,593	$301,777	$21,652
2059		$229,593	$301,777	$23,334
2060		$229,593	$301,777	$19,556
2061		$229,593	$301,777	$22,438
2062		$229,593	$301,777	$21,660
2063		$229,593	$938,861	$169,340
	LIFE CYCLE COST			**$ 36,500,924**

Appendix E

Fuel Consumption Data

Diesel Mechanical

Loading Condition	Time (min)	Diesel Load (kW)	Eng. Load (%)	Aft Prop Load (%)	Fwd Prop Load (%)	BSFC (lb/hp-hr)	Fuel Rate (gal/trip)	Shore Power (kW)
Loading	4.10	112	10%	20%	0%	see	0.84	
Departure	0.95	615	55%	100%	10%	calcs	0.71	
Transit	3.30	503	45%	80%	10%	below	2.04	
Arrival	1.25	559	50%	50%	50%		0.90	
Unload	4.10	112	10%	20%	0%		0.84	
Slack (at dock)	1.30	28	3%	5%	0%		0.12	
SSDG	15.00	50	51%			0.408	0.99	
Trip Summary	**15.00**		**23%**				**6.42**	**0.00**

Loading Condition	bsfc aft	bsfc fwd	fuel rate aft	fuel rate fwd
Loading	0.451	0.576	0.67	0.17
Departure	0.365	0.479	0.62	0.08
Transit	0.369	0.479	1.75	0.28
Arrival	0.402	0.402	0.45	0.45
Unload	0.451	0.576	0.67	0.17
Slack (at dock)	0.5275	0.576	0.06	0.05

Diesel Battery Hybrid

Loading Condition	Time (min)	Diesel Load (kW)	Eng. Load (%)	Aft Prop Load (%)	Fwd Prop Load (%)	BSFC (lb/hp-hr)	Fuel Rate (gal/trip)	Shore Power (kW)
Loading	4.10	0	0%	0%	0%	see	0.00	
Departure	0.95	615	55%	100%	10%	calcs	0.71	
Transit	3.30	824	74%	80%	67%	below	3.27	
Arrival	1.25	559	50%	50%	50%		0.90	
Unload	4.10	0	0%	0%	0%		0.00	
Slack (at dock)	1.30	0	0%	0%	0%		0.00	
Engine Cooldown	0.50	56	5%			0.528	0.05	
SSDG	15.50	50	51%			0.408	0.99	
Trip Summary	**15.50**		**23%**				**5.91**	**0.00**

Loading Condition	bsfc aft	bsfc fwd	fuel rate aft	fuel rate fwd
Loading	0.576	0.576		
Departure	0.365	0.479	0.62	0.08
Transit	0.369	0.37782	1.75	1.51
Arrival	0.402	0.402	0.45	0.45
Unload	0.576	0.576		
Slack (at dock)	0.576	0.576		

Diesel Electric Hybrid

Loading Condition	Time (min)	Diesel Load (kW)	Eng. Load (%)			BSFC (lb/hp-hr)	Fuel Rate (gal/trip)	Shore Power (kW)
Loading	4.10	339	74%			0.383	1.72	
Departure	0.95	339	74%			0.383	0.40	
Transit	3.30	339	74%			0.383	1.38	
Arrival	1.25	339	74%			0.383	0.52	
Unload	4.10	339	74%			0.383	1.72	
Slack (at dock)	1.30	339	74%			0.383	0.54	
Trip Summary	**15.00**		**74%**				**6.28**	**0.00**

Appendix F

Battery Sizing Calculation

Diesel Battery Hybrid

Hybrid Battery Sizing Calcs

Trip Energy:	83.4 kWh	Battery Type:	NMC
Trip Duration:	0.25 hr	Charge C Rate:	1.5
Trip Average Power:	334 kW	Discharge C Rate:	3
Engine Size (kW):	460 kW	No Engines:	1

Loading Condition	Condition Load (kW)	Duration (min)	Aft Eng	Fwd Eng	Base Eng. Load (kW)	Shore Power (kW)	Battery Load (kW)	Energy Discharge Sizing (kWh)
Loading	112	4.10	0%	0%	0		117	8
Departure	615	0.95	100%	10%	615		0	
Transit	503	3.30	80%	67%	824		-302	
Arrival	559	1.25	50%	50%	559		0	
Unload	112	4.10	0%	0%	0		117	8
Slack (at dock)	28	1.30	0%	0%	0		29	1
						0.0		**17**

Additional Generator Load (chg/dischg losses): 3.3 kW

C-Rate Sizing

Max Charge Rate: 302 kW
Max Discharge Rate: 117 kW
Charge/Discharge Sizing: 201 kWh

Depth of Discharge Check

DOD for Initial Sizing: 8%
No. Cycles in 10 year cycle life: 115,500
Assumed cycle life at 80% DOD: 8,000
Desired IEEE Multiplier: 14.44
Max DOD (to achieve cycle life): 19%
Actual cycle life: 23.4 yr
Minimum Bank Size (to achieve cycle life): 201 kWh

Diesel Electric Hybrid

Hybrid Battery Sizing Calcs

Trip Energy:	83.4 kWh		Battery Type:	NMC
Trip Duration:	0.25 hr		Charge C Rate:	1.5
Trip Average Power:	334 kW		Discharge C Rate:	3
Engine Size (kW):	460 kW		No Engines:	1

Loading Condition	**Condition Load (kW)**	**Duration (min)**	**Base Gen. Load (kW)**	**Battery Load (kW)**	**Energy Discharge Sizing (kWh)**
Loading	173	4.10	334	-169	
Departure	718	0.95	334	405	6
Transit	597	3.30	334	277	15
Arrival	658	1.25	334	341	7
Unload	173	4.10	334	-169	
Slack (at dock)	82	1.30	334	-264	
					29

Additional Generator Load (chg/dischg losses): 5.7 kW

C-Rate Sizing

Max Charge Rate:	264	kW
Max Discharge Rate:	405	kW
Charge/Discharge Sizing:	176	kWh

Depth of Discharge Check

DOD for Initial Sizing:	16%	
No. Cycles in 10 year cycle life:	115,500	
Assumed cycle life at 80% DOD:	8,000	
Desired IEEE Multiplier:	14.44	
Max DOD (to achieve cycle life):	19%	
Actual cycle life:	11.8	yr
Minimum Bank Size (to achieve cycle life):	176	kWh