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NEW VEHICLE FERRY

Propulsion System Selection Study

Prepared for: Casco Bay Lines • Portland, Maine

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1 PURPOSE

This report presents a comparison of alternative propulsion options for the New Vehicle Ferry and recommends a propulsion configuration. The vessel will be 164 feet (length) x 40 feet (beam) x 12 feet (hull depth) passenger vehicle ferry intended for service between Portland, Maine and Peaks Island, Maine. The vessel will be operated by Casco Bay Lines (CBL).

As part of a previous study for this new vessel, EBDG determined that this route would be best served by a double-ended arrangement, [1].

2 PROCEDURE

2.1 Overview

Three different propulsion configurations were identified as options for this vessel. In order to compare these options, a scoring system consisting of six criteria and weightings were developed by EBDG and CBL. Each criterion was assigned a weighting factor to define its relative importance in the overall scoring. The criteria and respective weighting factors are:

- Capital Cost (10%)
- Operating Cost (20%)
- Serviceability (25%)
- Reliability (25%)
- CO_2 Emissions (10%)
- Port Noise/Exhaust Generation (10%)

Option 1, Diesel Mechanical, is considered the baseline and thus received a score of three for each criterion. Three is used for the baseline score to provide positive scores for all criteria. The other two options were scored relative to Option 1 with higher values representing better performance and lower values representing inferior performance.

The scores were then tabulated in a scoring matrix, weighting factors applied, and the weighted scores summed resulting in a total score for each option. The highest scoring configuration represents the optimal configuration for CBL. See Appendix A for the complete matrix.

2.2 Candidate Propulsion Systems

Preliminary discussions between EBDG and CBL led to the selection of three different propulsion arrangements for evaluation.

Based upon the speed and powering calculations from [1], the vessel will require about 400 hp delivered horsepower per end to maintain a cruising speed of 8 knots in various weather conditions. Additional power is recommended for maneuvering operations. Each propulsion arrangement will accomplish this in a different way. Caterpillar EPA Tier III propulsion engines would best match current fleet equipment. All arrangements will power two fixed pitch propellers, one per end.

Data supplied by vendors was used to estimate fuel consumption, capital costs, maintenance costs, reliability and CO2 emissions. The propulsion configurations are identified below as Option 1 thru Option 3.

2.2.1 Option 1: Diesel Mechanical

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

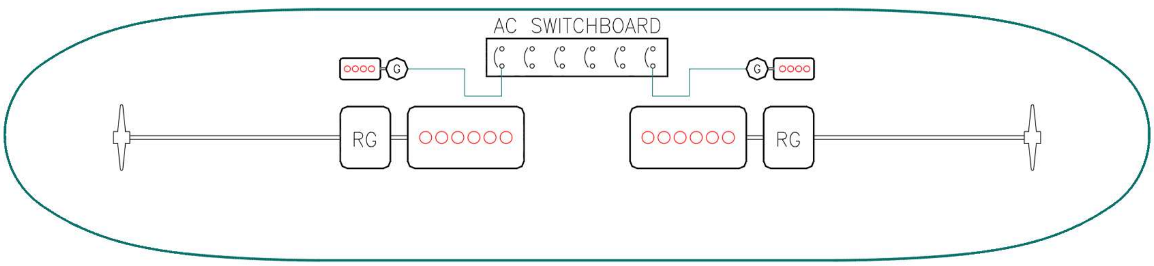

Figure 1: Diesel Mechanical System

For this option the following equipment was considered:

- Two propulsion engines rated for 715hp continuous duty
- Two reduction gears
- Two conventional shaft lines
- Two fixed pitch propellers
- Two 65 kW generators for ships service electrical loads

2.2.2 Option 2: Diesel Mechanical Hybrid

The second configuration, depicted in Figure 2, is a diesel mechanical propulsion system with the addition of a shaft generators and battery banks. The batteries are charged exclusively by onboard equipment; the shaft generators can be used to drive the propellers using power from the batteries or to charge the batteries using the propulsion engines. Electrical ship service power is provided by the battery bank and a ship service generator is on standby. The ship service generator is provided as a redundant source for hotel loads. Note that this arrangement is likely subject to more stringent USCG electrical requirements than is typically required for a vessel of this size due to its complexity.

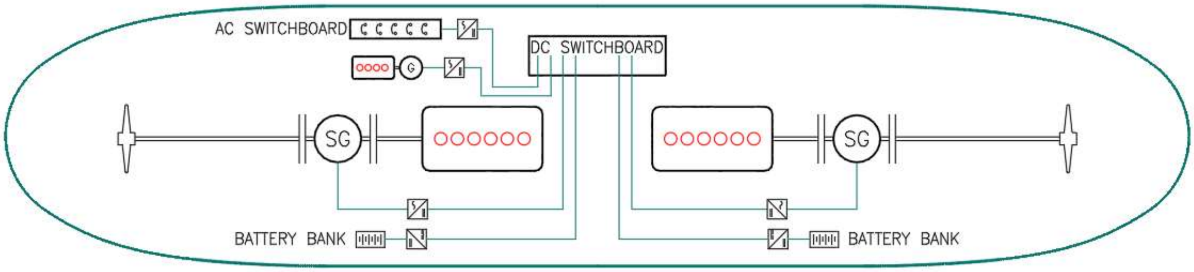

Figure 2: Diesel Mechanical Hybrid

For this option the following equipment was considered:

- Two propulsion engines rated for 469 hp continuous duty
- Two shaft generators
- One DC propulsion switchboard with all necessary converters and filters
- One AC switchboard for ship services
- Two battery banks with a total capacity of 287 kWh
- Two conventional shaft lines
- Two fixed pitch propellers
- One 65 kW generator (standby)

2.2.3 Option 3: Diesel Electric Hybrid with Shoreside Charging

This third propulsion option, depicted in Figure 3, is a diesel electric arrangement for full electric propulsion and hotel loads. Batteries are sized to target off peak / shoulder charging and to avoid costly peak charging. A high-speed diesel generator is provided to charge batteries or drive electric motors in the instance shore power is not available. Two variable speed propulsion motors, one at each end of the vessel, would then drive the propellers. The batteries would be charged on the Portland side of the route only. Note that this arrangement is likely subject to more stringent USCG electrical requirements than is typically required for a vessel of this size due to its complexity.

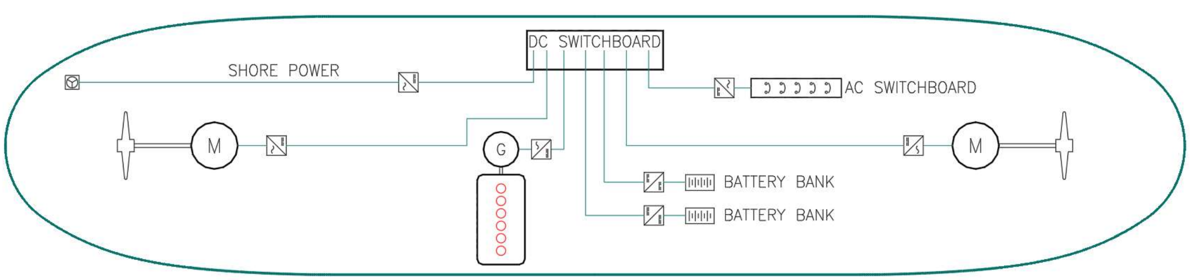

Figure 3: Diesel Electric Hybrid with Shoreside Charging

For this option the following equipment was considered:

- One generator rated for 528 ekW continuous duty (standby)
- One DC propulsion switchboard with all necessary converters and filters
- One AC switchboard for ship services
- Two battery banks with a total capacity of 1800 kWh
- Two propulsion motors
- Two variable speed drives
- Two fixed pitch propellers
- One shoreside connection and transformer

2.3 Evaluation Criteria

2.3.1 Capital Cost

Capital costs consist of the purchase price of all major equipment for each propulsion 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. Propulsion system integration costs are included. The options with the highest capital costs were scored the lowest.

Installation, shipyard, and engineering labor costs are not included. Installation materials such as structural steel, cables, system piping, and shafting are not included. These costs are expected to be similar across all options.

2.3.2 Operating Cost

The operating costs consist of 30-year life cycle maintenance and energy costs.

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 engine and gear operating hours. For the hybrid options, battery replacement is included and based upon a 10-year battery life. Maintenance cost for electrical equipment in the hybrid options was provided by a vendor as an annual estimate. Minimal maintenance costs for standby equipment is also included; annual time to verify the functionality of equipment and maintenance materials is estimated.

The energy cost is based upon an estimated annual fuel consumption and annual shoreside battery charging. Energy consumption is based upon the route profile described in [1]. Shoreside battery charging is based upon having power available on the Portland side only. There are potential cost efficiencies with the shoreside charging installation such as: off-peak charging and shore-side battery banks.

The options with the highest operating costs were scored the lowest.

2.3.3 Serviceability

Serviceability was determined by reviewing the geographic locations of the major equipment providers. Access to a supply of spare parts and skilled technicians for working on the equipment is critical for servicing the vessel. Systems were scored based upon the relative location of the nearest service providers. Arrangements that are likely to encounter delays while awaiting service were scored lowest. The ability of CBL employees to service the equipment was also considered.

2.3.4 Reliability

Reliability is the ability of a component or system to perform required functions under stated conditions for a stated period without failure.

For this study, a system or component failure is defined as a condition or issue that results in a cancelled or significantly delayed (>4 hours) scheduled sailing. EBDG considered the most likely type of failures, as seen and experienced by EBDG's field engineers, with similar propulsion systems, vessels, and vessel service. EBDG did not account for rare and/or extreme catastrophic failures that can occur.

The reliability score for each system is the inverse of the failure rates of all components in the system. The failure rate for each component is the product of the quantity of, probability of failure of, and complexity of repair of said components:

$$R = \frac{1}{\sum F} = \frac{1}{\sum (N * PoF * CoR)}$$

Probability of Failure (PoF) refers to a most typical type of failure that might occur on a given system, at any point in a 1-year time period. Each component was assigned a score from 0 to 3, representing extremely low probability of failure to high probability of failure.

Complexity of Repair (CoR) incorporates the anticipated cost of repair and time to repair, necessary to return the vessel to service. Each component was assigned a score from 0 to 3, representing extremely low complexity of repair to high complexity of repair.

System or component redundancy is included in this score by defining the quantity of components in the failure rate. For instance, for Option 2, the quantity of ship service generators is shown as zero as the normal operation for this arrangement provides hotel loads via the shaft generators and batteries.

The configuration with the highest level of reliability was scored the highest.

2.3.5 CO_2 Emissions

CO_2 emissions have a direct correlation with fuel consumption:

$$CO_2 = \frac{1}{99.4} \frac{metric\ ton}{gal\ of\ diesel}$$

Once annual fuel consumption for each arrangement is calculated the estimated annual CO_2 emissions can be calculated. Systems that generated a greater amount of CO_2 scored lower. This study only considered the vessel CO_2 emissions and does not account for offsite CO_2 emissions such as those associated with electrical power generation.

2.3.6 Port Noise & Exhaust Generation

Some arrangements can shut down engines while maneuvering in and out of port and while docked by relying on battery power thus reducing local noise and exhaust gas generation at the terminals. Options with reduced noise and exhaust generation received higher scores in this category.

3 GIVEN AND ASSUMED PARAMETERS

3.1 Vessel Route and Power Requirements

This vessel will operate on the Peaks Island route, approximately 2.2 nautical miles in length with water depths ranging from 35 to 50 feet. Operations on this route between Portland and Peaks Island continue year-round, with an average of 12.1 trips per day, 365 days per year. The powering requirements for this route are as described in [1].

3.2 Ships Service Electrical and HVAC Requirements

For the purpose of this study, the assumed ships service electrical load is 40 kW. This accounts for lighting, ventilation, fluid pumping, and other such normal operation loads. The ships service fuel consumption is calculated using published fuel consumption data provided by Caterpillar or by Northern lights, based upon the arrangement, [2] [3].

Because all arrangements assume heat is supplied by a hot water boiler system and the propulsion arrangement will not affect the heat required by the vessel, boiler fuel consumption is not included in the calculations.

3.3 Financial Assumptions

For the capital and operating cost estimates, the following assumptions were used:

- Shafting, bearing, and propeller maintenance is expected to be the same across all options, and as such is not considered in the operating cost analysis.
- No arrangement options will require more drydocking than any of the other arrangements, so dry docking expenses were not considered in the operating cost comparison.
- CBL stated that the rental fee for the barge utilized when the car ferry is out of service is $500 per trip with a minimum of 4 trips per day. This is included in the material cost for major overhaul maintenance activities for each option.
- Major equipment costs are based on vendor quotations.
- The cost of maintenance was estimated using a fully burdened labor rate of $126/hr.
- For the life cycle cost estimation all costs were estimated as annual costs and inflation is accounted for using a net present value (NPV) calculation. The inflation rates used in NPV calculations account for the federal discount rate as follows:

$$Real\ Discount\ Rate = \frac{(1+nominal\ discount\ rate)}{(1+inflatio\quad rate)} - 1$$

The discount and inflation rates shown Table 1 were assumed for the life cycle cost estimation.

Table 1: Inflation / Discount Rates

Rate	Nominal (%)	Real (%)
Federal Discount Rate	2.75	
General Inflation	2.10	0.64
Diesel Inflation	1.30	1.43
Electricity Inflation	0.00	2.75
Battery Inflation	0.00	2.75

- Electricity Rates were obtained from the Maine Public Utilities Commission website. Central Maine Power Company Large General Service Primary Time-Of-Use rates were used to estimate the cost to recharge batteries from shore for Option 3, [4].

- The consumable costs in Table 2 were assumed for life cycle and fuel cost comparisons.

Table 2: Cost of Consumables

Item	Cost	Units
Fuel (ULSD)	3.00	$/gal
Lube Oil	5.00	$/gal
Batteries	800	$/kWh

4 DISCUSSION

4.1 Capital Cost

As shown in Table 3, Option 1 is expected to have the lowest up-front capital cost.

Options 2 and 3 are expected to be the most expensive as they feature some of the newest marine hybrid technology. While Option 2 has the same quantity of traditional marine propulsion equipment as Option 1 it also includes much of the same electronic modules as Option 3.

Option 3 will require shoreside modifications to get the appropriate electrical service to the dock for shoreside charging; these costs are not reflected in the capital cost shown here. The shore charging davit is included in the capital cost for this option and is expected to cost $500,000 to $600,000.

For a full break down of each option's capital cost, see Appendix B.

Table 3: Capital Cost Summary

Capital Cost Estimate Summary				
Option	**Description**	**Cost**	**Cost Ratio**	**Score**
1	**Diesel Mechanical**	$694,000	100%	3.00
2	**Diesel Mechanical Hybrid** Onboard Charging	$1,849,000	266%	1.13
3	**Diesel Electric Hybrid** Shoreside Charging	$3,380,000	487%	0.62

4.2 Operating Cost

Table 4 provides a summary of the 30-year life cycle cost for the options with values presented in 2019 dollars. See Appendix C for a breakdown of each option's operating cost.

Option 1 has the highest operating cost. The maintenance cost is highest for this option because both propulsion engines are in operation the entire time the vessel is operating, and ship service generators are required for house electrical loads. This results in increased engine operating hours, increased engine maintenance costs, and the highest fuel consumption.

Options 2 benefits from reduced engine operating hours, reduced quantity of engines and reduced fuel consumption as compared to Option 1. However, there is still engine maintenance, electrical equipment maintenance, and the addition of battery replacement costs every 10 years. Minimal maintenance costs are included for the ship service generator as it is intended to be on standby.

Option 3 has the lowest operating cost. The normal operating condition for this arrangement is all electric, thus there are no fuel costs considered. The charging cost is predicated on charging batteries during the off-peak or shoulder portion of the day. The arrangement has larger battery banks to account for this charging time frame which increases the capital cost and battery replacement costs but allows CBL to avoid costly peak charge demand costs. Minimal maintenance costs are included for the onboard generator as it is intended to be on standby.

Table 4: Operating Cost Summary

Operating Cost Estimate				
Option	**Description**	**Cost**	**Cost Ratio**	**Score**
1	**Diesel Mechanical**	$6,990,191	100%	3.00
2	**Diesel Mechanical Hybrid** Onboard Charging	$6,473,326	93%	3.24
3	**Diesel Electric Hybrid** Shoreside Charging	$6,078,254	87%	3.45

4.3 Serviceability

All equipment utilized in this study is available in the United States with many of the same local service providers already utilized by CBL. However, both Options 2 and 3 incorporate electrical equipment that will be unique to this vessel when compared to the rest of the fleet. If Option 2 or 3 is selected CBL will require different service providers and the employed staff will require different knowledge than is currently required. Options 2 and 3 received slightly lower serviceability scores to account for the increased requirements. The serviceability scores are summarized in Table 5.

Table 5: Serviceability Summary

Serviceability		
Option	**Description**	**Score**
1	**Diesel Mechanical**	3.00
2	**Diesel Mechanical Hybrid** Onboard Charging	2.50
3	**Diesel Electric Hybrid** Shoreside Charging	2.50

4.4 Reliability

Table 6 provides a summary of the reliability calculations for each of the propulsion arrangements.

Generally speaking, Options 2 and 3 require more equipment and thus have higher opportunity for failure resulting in reduced reliability. See Appendix D for the full assessment of each option's reliability score.

Table 6: Reliability Summary

Reliability				
Option	**Description**	**Reliability**	**Percent**	**Score**
1	**Diesel Mechanical**	0.06	100%	3.00
2	**Diesel Mechanical Hybrid** Onboard Charging	0.05	85%	2.55
3	**Diesel Electric Hybrid** Shoreside Charging	0.05	85%	2.55

4.5 CO2 Emissions

Table 7 displays the calculated CO_2 emissions for each of the propulsion arrangements. These calculations only account for the CO_2 emissions created by the vessel during operation; they do not account for any emissions that may occur upstream of the vessel. For example, if the power plant is generating emissions to power the electrical grid which provides shore power to vessel, that is not considered here.

Because Option 3 is designed to run on electric battery power for all normal transit operations, it will not require fuel for propulsion, thus it offers a 100% improvement over the baseline diesel mechanical system. Option 2 will have reduced emissions by utilizing batteries and excess power from the propulsion engines to provide hotel loads. This will be a more efficient operation of the propulsion engines and eliminate the use of ship service generators.

Table 7: CO2 Emissions Summary

CO2 Emissions				
Option	**Description**	**CO2 Emissions (mt/yr)**	**% Reduction**	**Score**
1	**Diesel Mechanical**	700	0%	3.00
2	**Diesel Mechanical Hybrid** Onboard Charging	653	7%	3.20
3	**Diesel Electric Hybrid** Shoreside Charging	0	100%	6.00

4.6 Port Noise and Exhaust Production

Because Options 2 and 3 can use battery power for maneuvering into dock on either side of the route the propulsion engines will not be in operation during this time. As a result, these two options offer a 100% improvement over the baseline diesel mechanical system with regard to in port noise and exhaust generation. This will create a quieter, cleaner local neighborhood.

Table 8 summarizes the port noise and exhaust scores for each of the propulsion arrangements.

Table 8: Port Noise and Exhaust Generation Summary

Port Noise and Exhaust Generation			
Option	**Description**	**Noise & Exhaust In Port**	**Score**
1	**Diesel Mechanical**	Y	3.00
2	**Diesel Mechanical Hybrid** Onboard Charging	N	6.00
3	**Diesel Electric Hybrid** Shoreside Charging	N	6.00

5 CONCLUSIONS

After considering several criteria for the three different propulsion arrangement options and their relative importance to CBL, the recommended propulsion arrangement for the vessel is Option 3, a diesel electric hybrid system. While this arrangement will incur the greatest upfront cost, it offers significant savings over the life of the vessel eliminating propulsive fuel consumption and engine hours if the proper shore charging arrangements are available. The battery sizing for this arrangement is flexible and should be further optimized as the design continues. The battery cost is a significant portion of the capital cost; thus, the scalability of the battery capacity could be employed to reduce the upfront cost for this system. Future vessel modifications could then include increasing the battery capacity to recognize the full benefits of the battery electric arrangement.

Option 3 represents the cutting edge of marine hybrid technology. There are several vessels operating worldwide with this type of propulsion system, and system failures have been minimal, but the true success of this technology remains to be fully realized. Moving to a battery electric propulsion system will require CBL's operating and maintenance staff to learn and adapt to new technology. Crew training and vendor support after construction should be carefully planned to minimize operational risks.

Although there are several international examples of battery hybrid propulsion systems, there are few examples of these systems operating in the United States. There is, therefore, limited US shipbuilder experience with battery hybrid integration during construction. Option 3 offers significant operational and environmental improvements over the diesel mechanical propulsion system and system integration risks can be mitigated during the final design and construction with attention to detail during the design and contracting processes.

Option 1, a diesel mechanical arrangement, is the second-place recommendation. It is the simplest installation and it aligns well with the existing fleet of vessels. This option would deliver the same reliability and serviceability to which CBL is accustomed and CBL could expect similar parts and service availability. This choice would likely offer an improved environmental impact over the existing vessel based solely on improved engine technology. However, when compared to the hybrid options, it will still generate noise and exhaust in the terminals and produce more emissions.

Option 2, a diesel mechanical hybrid system is nearly equivalent to Option 1 in the weighted scores. However, the increased capital cost, reduced serviceability and reliability offset the lifecycle cost and environmental improvements. There is emerging technology from a few reduction gear vendors that could allow for standard diesel mechanical operation in the event of a battery system failure. The capital costs of such an option were not well known at the writing of this report.

Table 9 provides the weighted final scores for the propulsion arrangement options. See Appendix A for the full weighted matrix.

Table 9: Weighted System Score Summary

Weighted System Scores		
Option	**Description**	**Score**
1	**Diesel Mechanical**	3.00
2	**Diesel Mechanical Hybrid** Onboard Charging	2.94
3	**Diesel Electric Hybrid** Shoreside Charging	3.21

6 REFERENCES

[1] Elliott Bay Design Group, 18045-070-0, Vessel Configuration Comparison.

[2] Caterpillar, "LEHM0215-00c9.3 ACERT Marine Generator Set Package," 2015.

[3] Northern Lights, "M65C13 Specifications and Dimensions," Seattle, WA, 2017.

[4] Central Maine Power Company, "Electric Delivery Rate Schedule: Large General Service-Primary-Time Of Use," 7/1/2019.

Appendix A

Comparison Matrix

Option	Propulsion System Description	Capital Cost	Operating Cost	Serviceability	Reliability	CO2 Emmisions	Port Noise / Exhaust Generation	Weighted Score	Rank
1.00	Diesel Mechanical	3.00	3.00	3.00	3.00	3.00	3.00	3.00	2.00
2.00	Diesel Mechanical Hybrid	1.13	3.24	2.50	2.55	3.20	6.00	2.94	3.00
3.00	Diesel Electric Hybrid	0.62	3.45	2.50	2.55	6.00	6.00	3.21	1.00
	Weighting Factor	10%	20%	25%	25%	10%	10%	100%	

Appendix B

Capital Cost

Diesel Mechanical				
SWBS	**Item**	**Qty**	**Price / Ea**	**Total**
230	**Engines**			
	Propulsion Engines	2	$105,000	$210,000
241	**Reduction Gears**			
	Twin Disc MGX522DC	2	$53,000	$106,000
300	**Electrical**			
	Ship Service Generator	2	$49,000	$98,000
	Ship Service Switchboard	1	$45,000	$45,000
400	**Controls**			
	IMACS	1	$35,000	$35,000
800	**Integration**	1	$200,000	$200,000
				$694,000

Diesel Mechanical Hybrid with Onboard Charging				
SWBS	**Item**	**Qty**	**Price / Ea**	**Total**
230	**Engines**			
	Propulsion Engines	2	$105,000	$210,000
241	**Reduction Gears / Clutches**			
	Clutches on either side of shaft Generator	2	$55,000	$110,000
300/400	**Electrical**			
	Ship Service Generator	1	$49,000	$49,000
	Integrator Package	1	$1,480,000	$1,480,000
	400 kW shaft generator	2		
	Transformers	2		
	AC Switchboard(s)	2		
	DC Switchboard with rectifiers, inverters, converters	1		
	287 kwh batteries	1		
	Power and Energy Management System			
	Remote Diagnositcs			
				$1,849,000

Diesel Electrical Hybrid Shoreside Charging				
SWBS	**Item**	**Qty**	**Price / Ea**	**Total**
230	**Engines**			
	Propulsion Generator	1	$105,000	$105,000
300/400	**Electrical**	1	$3,275,000	$3,275,000
	AC switchboard(s)			
	Transformers			
	DC Switchboard with rectifiers, inverters, converters			
	1800 kwh batteries			
	Electric motors			
	Remote Diagnostics			
	Power and Energy Management System			
	Shore charging connection & transformer			
				$3,380,000

Appendix C

Operating Cost

Life Cycle Cost Estimate Summary

Year	Option 1 - DM			Option 2 - Mechanical Hybrid Onboard Charging				Option 3 - Diesel Electric Hybrid			
	Maintenance Cost	Diesel Cost	Charging Cost	Maintenance Cost	Batteries	Diesel Cost	Charging Cost	Maintenace Cost	Batteries	Diesel Cost	Charging Cost
2022	$26,176	$208,782	$0	$24,659		$194,653	$0	$23,059		$0	$131,167
2023	$28,108	$208,782	$0	$28,943		$194,653	$0	$23,059		$0	$131,167
2024	$118,219	$208,782	$0	$28,691		$194,653	$0	$23,059		$0	$131,167
2025	$28,108	$208,782	$0	$113,602		$194,653	$0	$23,059		$0	$131,167
2026	$138,219	$208,782	$0	$28,691		$194,653	$0	$23,059		$0	$131,167
2027	$28,108	$208,782	$0	$28,943		$194,653	$0	$23,059		$0	$131,167
2028	$114,867	$208,782	$0	$30,371		$194,653	$0	$23,059		$0	$131,167
2029	$29,528	$208,782	$0	$109,318		$194,653	$0	$23,059		$0	$131,167
2030	$32,140	$208,782	$0	$28,943		$194,653	$0	$23,059		$0	$131,167
2031	$135,195	$208,782	$0	$28,691		$194,653	$0	$23,059		$0	$131,167
2032	$32,140	$208,782	$0	$28,943	$231,616	$194,653	$0	$23,059	$1,455,040	$0	$131,167
2033	$113,019	$208,782	$0	$113,350		$194,653	$0	$23,059		$0	$131,167
2034	$31,376	$208,782	$0	$28,943		$194,653	$0	$23,059		$0	$131,167
2035	$132,767	$208,782	$0	$30,371		$194,653	$0	$23,059		$0	$131,167
2036	$33,560	$208,782	$0	$24,659		$194,653	$0	$23,059		$0	$131,167
2037	$112,767	$208,782	$0	$113,602		$194,653	$0	$23,059		$0	$131,167
2038	$33,560	$208,782	$0	$28,691		$194,653	$0	$23,059		$0	$131,167
2039	$28,108	$208,782	$0	$28,943		$194,653	$0	$23,059		$0	$131,167
2040	$130,835	$208,782	$0	$28,691		$194,653	$0	$23,059		$0	$131,167
2041	$34,568	$208,782	$0	$113,602		$194,653	$0	$23,059		$0	$131,167
2042	$112,767	$208,782	$0	$30,371	$231,616	$194,653	$0	$23,059	$1,455,040	$0	$131,167
2043	$33,560	$208,782	$0	$24,659		$194,653	$0	$23,059		$0	$131,167
2044	$132,767	$208,782	$0	$28,943		$194,653	$0	$23,059		$0	$131,167
2045	$32,392	$208,782	$0	$113,350		$194,653	$0	$23,059		$0	$131,167
2046	$112,003	$208,782	$0	$28,943		$194,653	$0	$23,059		$0	$131,167
2047	$32,140	$208,782	$0	$28,691		$194,653	$0	$23,059		$0	$131,167
2048	$29,528	$208,782	$0	$28,943		$194,653	$0	$23,059		$0	$131,167
2049	$136,799	$208,782	$0	$115,030		$194,653	$0	$23,059		$0	$131,167
2050	$30,536	$208,782	$0	$24,659		$194,653	$0	$23,059		$0	$131,167
2051	$116,799	$208,782	$0	$28,943		$194,653	$0	$23,059		$0	$131,167

Main. Cost PV	Diesel Cost PV	Charging Cost PV	Main. Cost PV	Batteries PV	Diesel Cost PV	Charging Cost PV	Main. Cost PV	Batteries PV	Diesel Cost PV	Charging Cost PV
$1,927,010	$5,063,180	$0	$1,307,985	$444,801	$4,720,541	$0	$627,910	$2,794,294	$0	$2,656,050
Total Lifecycle Cost PV		$6,990,191				$6,473,326				$6,078,254

Life Cycle Cost Estimate Worksheet

Option 1 Diesel Mechancial: (2) Cat C18 Engines, (2) Twin Disc Gears, (2) SS Generators

Year	Engine Maintenance			Reduction Gear Maintenance			SS Generator Maintenance			Annual Fuel Consumption		
	Labor Hours	Material Cost	Total Cost	Labor Hours	Material Cost	Total Cost	Labor Hours	Material Cost	Total Cost	Gallons	Price/gal	Total Cost
2022	104	$3,360	$16,464	0	$0	$0	72	$640	$9,712	69594	$3.00	$208,782
2023	112	$3,780	$17,892	0	$0	$0	76	$640	$10,216	69594	$3.00	$208,782
2024	286	$70,799	$106,835	0	$0	$0	84	$800	$11,384	69594	$3.00	$208,782
2025	112	$3,780	$17,892	0	$0	$0	76	$640	$10,216	69594	$3.00	$208,782
2026	286	$70,799	$106,835	0	$20,000	$20,000	84	$800	$11,384	69594	$3.00	$208,782
2027	112	$3,780	$17,892	0	$0	$0	76	$640	$10,216	69594	$3.00	$208,782
2028	276	$70,379	$105,155	0	$0	$0	72	$640	$9,712	69594	$3.00	$208,782
2029	114	$3,780	$18,144	0	$0	$0	84	$800	$11,384	69594	$3.00	$208,782
2030	144	$3,780	$21,924	0	$0	$0	76	$640	$10,216	69594	$3.00	$208,782
2031	254	$70,799	$102,803	0	$20,000	$20,000	92	$800	$12,392	69594	$3.00	$208,782
2032	144	$3,780	$21,924	0	$0	$0	76	$640	$10,216	69594	$3.00	$208,782
2033	254	$70,799	$102,803	0	$0	$0	76	$640	$10,216	69594	$3.00	$208,782
2034	136	$3,360	$20,496	0	$0	$0	80	$800	$10,880	69594	$3.00	$208,782
2035	252	$70,799	$102,551	0	$20,000	$20,000	76	$640	$10,216	69594	$3.00	$208,782
2036	146	$3,780	$22,176	0	$0	$0	84	$800	$11,384	69594	$3.00	$208,782
2037	252	$70,799	$102,551	0	$0	$0	76	$640	$10,216	69594	$3.00	$208,782
2038	146	$3,780	$22,176	0	$0	$0	84	$800	$11,384	69594	$3.00	$208,782
2039	112	$3,780	$17,892	0	$0	$0	76	$640	$10,216	69594	$3.00	$208,782
2040	244	$70,379	$101,123	0	$20,000	$20,000	72	$640	$9,712	69594	$3.00	$208,782
2041	146	$3,780	$22,176	0	$0	$0	92	$800	$12,392	69594	$3.00	$208,782
2042	252	$70,799	$102,551	0	$0	$0	76	$640	$10,216	69594	$3.00	$208,782
2043	146	$3,780	$22,176	0	$0	$0	84	$800	$11,384	69594	$3.00	$208,782
2044	252	$70,799	$102,551	0	$20,000	$20,000	76	$640	$10,216	69594	$3.00	$208,782
2045	146	$3,780	$22,176	0	$0	$0	76	$640	$10,216	69594	$3.00	$208,782
2046	244	$70,379	$101,123	0	$0	$0	80	$800	$10,880	69594	$3.00	$208,782
2047	144	$3,780	$21,924	0	$0	$0	76	$640	$10,216	69594	$3.00	$208,782
2048	114	$3,780	$18,144	0	$0	$0	84	$800	$11,384	69594	$3.00	$208,782
2049	284	$70,799	$106,583	0	$20,000	$20,000	76	$640	$10,216	69594	$3.00	$208,782
2050	114	$3,780	$18,144	0	$0	$0	92	$800	$12,392	69594	$3.00	$208,782
2051	284	$70,799	$106,583	0	$0	$0	76	$640	$10,216	69594	$3.00	$208,782

Life Cycle Cost Estimate Worksheet															
Option 2 Diesel Mechancial Hybrid: (2) Cat C18 Engines, (2) Shaft Generators, (1) SS Generator, (2) Battery Banks															
Year	Engine Maintenance			Electrical Eqpt Maintenance			SS Generator Maintenance			Battery Replacement			Annual Fuel Consumption		
	Labor Hours	Material Cost	Total Cost	Labor Hours	Material Cost	Total Cost	Labor Hours	Material Cost	Total Cost	Labor Hours	Material Cost	Total Cost	Gallons	Price/gal	Total Cost
2022	44	$2,100	$7,644	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2023	78	$2,100	$11,928	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2024	76	$2,100	$11,676	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2025	218	$69,119	$96,587	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2026	76	$2,100	$11,676	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2027	78	$2,100	$11,928	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2028	86	$2,520	$13,356	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2029	184	$69,119	$92,303	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2030	78	$2,100	$11,928	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2031	76	$2,100	$11,676	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2032	78	$2,100	$11,928	0	$0	$11,979	36	$500	$5,036	16	$229,600	$231,616	64884	$3.00	$194,653
2033	216	$69,119	$96,335	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2034	78	$2,100	$11,928	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2035	86	$2,520	$13,356	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2036	44	$2,100	$7,644	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2037	218	$69,119	$96,587	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2038	76	$2,100	$11,676	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2039	78	$2,100	$11,928	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2040	76	$2,100	$11,676	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2041	218	$69,119	$96,587	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2042	86	$2,520	$13,356	0	$0	$11,979	36	$500	$5,036	16	$229,600	$231,616	64884	$3.00	$194,653
2043	44	$2,100	$7,644	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2044	78	$2,100	$11,928	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2045	216	$69,119	$96,335	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2046	78	$2,100	$11,928	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2047	76	$2,100	$11,676	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2048	78	$2,100	$11,928	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2049	226	$69,539	$98,015	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2050	44	$2,100	$7,644	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653
2051	78	$2,100	$11,928	0	$0	$11,979	36	$500	$5,036	0			64884	$3.00	$194,653

Life Cycle Cost Estimate Worksheet

All Electric w/ Shoreside Charging; Electric Drives, Batteries

Year	Engine Maintenance			Electrical Equipt Maintenance			Battery Replacement			Annual Fuel Consumption			Annual Electric Consumption		
	Labor Hours	Material Cost	Total Cost	Labor Hours	Material Cost	Total Cost	Labor Hours	Material Cost	Total Cost	Gallons	Price/gal	Total Cost	kW	kWh	Annual Cost
2022	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2023	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2024	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2025	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2026	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2027	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2028	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2029	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2030	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2031	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2032	80	$1,000	$11,080	0	$0	$11,979	40	$1,450,000	$1,455,040		$3.00	$0	1200	117261	$131,167
2033	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2034	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2035	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2036	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2037	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2038	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2039	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2040	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2041	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2042	80	$1,000	$11,080	0	$0	$11,979	40	$1,450,000	$1,455,040		$3.00	$0	1200	117261	$131,167
2043	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2044	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2045	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2046	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2047	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2048	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2049	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2050	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167
2051	80	$1,000	$11,080	0	$0	$11,979	0				$3.00	$0	1200	117261	$131,167

Appendix D

Reliability

Component	Component Quantity (N)	Probability of Failure (PoF)	Complexity of Repair (CoR)	Failure Rate (F)
Option 1 (DM)				
Propulsion Engine	2.00	3.00	1.00	6.00
Reduction Gear	2.00	1.00	2.00	4.00
Ship Service Generator	2.00	1.00	2.00	4.00
Ship Service Switchboard	1.00	1.00	1.00	1.00
Propulsion Controls	1.00	1.00	2.00	2.00
			Sum of Failure Rate:	**17.00**
			System Reliability:	**0.059**
Option 2 (DMH)				
Propulsion Engine	2.00	3.00	1.00	6.00
Reduction Gear	2.00	1.00	2.00	4.00
Shaft Generator	2.00	1.00	2.00	4.00
Ship Service Generator	0.00	1.00	2.00	0.00
DC Switchboard	1.00	1.00	1.00	1.00
AC Ship Service Switchboard	1.00	1.00	1.00	1.00
Propulsion Controls	1.00	1.00	2.00	2.00
Battery Banks	2.00	1.00	1.00	2.00
			Sum of Failure Rate:	**20.00**
			System Reliability:	**0.050**
Option 3 (DEH)				
Propulsion Generator	0.00	2.00	1.00	
DC Propulsion Switchboard	1.00	1.00	1.00	1.00
AC Distribution Switchboard	1.00	1.00	2.00	2.00
Battery Banks	2.00	1.00	1.00	2.00
Electric Motor	2.00	1.00	3.00	6.00
Electric Motor Drive	2.00	3.00	1.00	6.00
Propulsion Controls	1.00	1.00	2.00	2.00
Shorecharger	1.00	1.00	1.00	1.00
			Sum of Failure Rate:	**20.00**
			System Reliability:	**0.050**

$$R = \frac{1}{\sum F} = \frac{1}{\sum(N * PoF * CoR)}$$

Appendix E

Fuel and Emissions

Increment	Loading Condition	Load (hp)	Time (min)	Eng MCR (%)	Fuel Consumption (gal/hr)	Fuel per Trip (gal/trip)	Annual Fuel (gal/year)	CO^2 Emissions (mt/year)	Annual Fuel (gal/year)	CO^2 Emissions (mt/year)	Fuel Savings (gal/year)	CO^2 Reduction (mt/year)
Aft Diesel Mech 715 hp	Load	27	6.00	4%	1.609	0.161	1,422	14	69,594	700	0	0
	Maneuver	260	1.13	36%	13.518	0.255	2,249	23				
	Transit	310	15.48	43%	16.068	4.146	36,617	368				
	Maneuver	260	0.89	36%	13.518	0.201	1,771	18				
	Tie Up	27	0.50	4%	1.609	0.013	118	1				
	Unload	27	6.00	4%	1.609	0.161	1,422	14				
Fwd Diesel Mech 715hp	Load	27	6.00	4%	1.609	0.161	1,422	14			0%	0%
	Maneuver	260	1.13	36%	13.518	0.255	2,249	23				
	Transit	30	15.48	4%	1.788	0.461	4,074	41				
	Maneuver	260	0.89	36%	13.518	0.201	1,771	18				
	Tie Up	27	0.50	4%	1.609	0.013	118	1				
	Unload	27	6.00	4%	1.609	0.161	1,422	14				
Genset	Normal Load	40	30.00	62%	3.383	1.691	14,939	150				

Increment	Loading Condition	Load (hp)	Time (min)	Eng MCR (%)	Fuel Consumption (gal/hr)	Fuel per Trip (gal/trip)	Annual Fuel (gal/year)	CO^2 Emissions (mt/year)	Annual Fuel (gal/year)	CO^2 Emissions (mt/year)	Fuel Savings (gal/year)	CO^2 Reduction (mt/year)
Aft Diesel Mech Hybrid 469 hp	Load	0	6.00	0%	0.000	0.000	0	0	64,884	653	4,710	47
	Maneuver	260	1.13	55%	13.583	0.256	2,260	23				
	Transit	310	15.48	66%	16.143	4.165	36,789	370				
	Maneuver	260	0.89	55%	13.583	0.201	1,780	18				
	Tie Up	0	0.50	0%	0.000	0.000	0	0				
	Unload	0	6.00	0%	0.000	0.000	0	0				
Fwd Diesel Mech Hybrid 469 hp	Load	0	6.00	0%	0.000	0.000	0	0			7%	7%
	Maneuver	260	1.13	55%	13.583	0.256	2,260	23				
	Transit	166	15.48	35%	8.783	2.266	20,017	201				
	Maneuver	260	0.89	55%	13.583	0.201	1,780	18				
	Tie Up		0.50	0%	0.000	0.000	0	0				
	Unload		6.00	0%	0.000	0.000	0	0				
Genset	Normal Load	0	0.00	0%	3.383	0.000	0	0				

Increment	Loading Condition	Load (kW)	Time (min)	Gen Loading (%)	BSFC (lb/kW-hr)	Fuel per Trip (gal/trip)	Annual Fuel (gal/year)	CO^2 Emissions (mt/year)	Annual Fuel (gal/year)	CO^2 Emissions (mt/year)	Fuel Savings (gal/year)	CO^2 Reduction (mt/year)
All Electric	Load	0	6.00	0%	0.000	0.000	0	0	0	0	**69,594**	**700**
	Maneuver	0	1.13	0%	0.000	0.000	0	0				
	Transit	0	15.48	0%	0.000	0.000	0	0				
	Maneuver	0	0.89	0%	0.000	0.000	0	0			**100%**	**100%**
	Tie Up	0	0.50	0%	0.000	0.000	0	0				
	Unload	0	6.00	0%	0.000	0.000	0	0				
	-	-	-	-	-	-	-	-				

Appendix F

Charging Cost

Period	Charge	Fee		Power (kW)	Energy (kWh)	Fee (USD)	Frequency per year	Subtotal Cost
July/August	Demand - On-Peak	$ 14.24	per kw	0	-	$ -	2	0
	Demand - Shoulder	$ 2.67	per kw	1186	-	$ 3,166.21	2	6,332
	Supply Charge	$ 0.073829	per kWh	-	133	$ 9.79	1,472	14,412
	Delivery Charge	$ 0.004008	per kWh	-	133	$ 0.53	1,472	782
	Service Charge	$ 592.06		-	-	$ 592.06	2	1,184
September-June	Demand - On-Peak	$ 13.81	per kw	0	-	$ -	10	0
	Demand - Shoulder	$ 2.24	per kw	1186	-	$ 2,656.29	10	26,563
	Supply Charge	$ 0.073829	per kWh	-	133	$ 9.79	7,361	72,061
	Delivery Charge	$ 0.004008	per kWh	-	133	$ 0.53	7,361	3,912
	Service Charge	$ 592.06		-	-	$ 592.06	10	5,921
							Total Annual Cost	131,167