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4/22/2024

M/V EMERALD ISLE

PROPULSION EVALUATION

Prepared for: Beaver Island Transport Authority | Beaver Island, MI

Ref: 23085-894-1

Rev. A

April 19, 2024

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Revisions

REV	DESCRIPTION	DATE	APPROVED
-	Initial Release	1/30/24	LGB WA 51201
A	To comply with ADA requirements	4/19/24	LGB WA 51201

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1. Purpose

This report presents a review of alternative propulsion options and technologies for the M/V EMERALD ISLE in exclusive service from Beaver Island, Michigan to Charlevoix, Michigan. The M/V EMERALD ISLE is operated by Beaver Island Boat Company (BIBCO) under the Beaver Island Transportation Authority (BITA). The vessel is a 130-foot vehicle passenger ferry.

2. Procedure

2.1 Overview

Elliott Bay Design Group (EBDG) visited BITA and the M/V EMERALD ISLE on September 28th, 2023 to learn more about the vessel's operation and layout. BITA provided drawings of the vessel and a description of the typical operating conditions. EBDG used this information to create an operating profile using the existing equipment and proposed a variety of repower options to evaluate. These propulsion options were evaluated for feasibility, capital cost, operating cost, and emissions.

BITA and EBDG have previously designed a vessel to operate on this same route, but it has not yet been constructed. A review of possible propulsion systems for that new vessel will be provided in a separate report.

2.2 Candidate Propulsion Systems

EBDG proposed to evaluate five different propulsion systems. They are as follows:

2.2.1 Option 1: Tier IV Diesel Mechanical With Cat 3512e Engines

The first option is a repower of the vessel with replacement propulsion engines using the newest version of the existing engines, CAT 3512E Tier IV engines rated for 1649 horsepower. Per the Environmental Protection Agency (EPA) requirements, these engines require exhaust gas after-treatment via selective catalytic reduction (SCR). Caterpillar provides a Clean Emissions Module (CEM) and an associated urea dosing system to accomplish the aftertreatment. This option will utilize the existing reduction gear and propellers. No changes to the hotel generators or switchboard are required, though the after-treatment system will require power.

For this option, the following equipment was considered:

- CAT 3512E Tier IV 1649 HP @ 1800 RPM
- Addition of Clean Emissions Module (CEM)
- Addition of Urea Storage Tanks and Skid

2.2.2 Option 2: Tier IV Diesel Mechanical With Cat C32 Engines

The second option is a repower of the vessel with a different model of Caterpillar engines, The CAT C32 Tier IV engines rated for 1450 horsepower. The C32 engine has nearly the same horsepower rating as the existing engines; however, the footprint and weight of the C32 is significantly less than the 3512E engines proposed in Option 1. These engines will, likewise, require exhaust after-treatment via the approved CEM. The C32 engines are higher speed engines at 2150 RPM as compared to the existing engines at 1800 RPM. The engine speed difference will require an evaluation of the propellers and reduction gears.

For this option the following equipment was considered:

- CAT C32 Tier IV 1450HP @ 2150 RPM
- Addition of Clean Emissions Module (CEM)
- Addition of Urea Storage Tanks and Skid
- Change or modify reduction gear
- New propellers

2.2.3 Option 3: Parallel Diesel Hybrid Plant

The third option evaluated is the first battery hybrid option. This propulsion system is similar to a conventional diesel mechanical system with each diesel engine driving a propeller via a reduction gear and shafting. However, each reduction gear is also attached to a motor/generator which can be used to provide propulsion power or recharge an energy storage system (ESS). The ESS could be used for propulsion power or to meet hotel power demands.

This arrangement could be installed with the existing engines or upgraded Tier IV engines.

This arrangement assumes that the vessel operates on battery power while at the dock and maneuvering in/out of the terminal. The main engines will operate at a higher load during the transit time frame to charge the ESS.

EBDG consulted with two different vendors to develop this system for evaluation, Siemens and Twin Disc.

Siemens proposed their Blue ECO drive system which includes ESS, motor/generators, battery management and propulsion controllers. The Siemens quote did not include a gearbox with PTI/PTO. The Siemens system is sized to allow the vessel to maneuver in and out of the terminals completely on battery power.

Twin Disc proposed three different solutions using their EC600HC Hybrid System. This system includes ESS, motor/generators, Twin Disc gearbox, battery management and propulsion controllers.

2.2.4 Option 4: Serial Diesel Electric Hybrid Plant

The fourth option evaluated is also a battery hybrid option. In this option, electric motors drive the propellers, the diesel engines are replaced with diesel generators, and an ESS is added to store excess power produced by the diesel generators.

This option was deemed infeasible as there is limited available space in the machinery space to install the required equipment. Additionally, the hotel power system would need to be updated.

This option is also expected to be quite expensive and to deliver minimal emissions reductions.

2.2.5 Option 5: All Electric

The fifth option briefly considered was replacing the propulsion engines with a shore charged battery bank. Due to the duration of the voyage this was deemed infeasible. The transit is too long for this option to be considered. The cost, weight, and additional equipment to support a battery bank of this size would be substantially more expensive than the other options. In addition, this would be the longest known voyage for a pure battery vessel.

The following design constraints resulted in this option being disqualified:

- Length of route.
- Shorter layover time between transits on busy days.

- Estimated large battery bank required for transit.
- Estimated $7.4 million for the propulsion system and modifications.
- Estimated weight increase of 490 LT.

3. Given And Assumed Parameters

3.1 Vessel Operating Profile

The vessel transits between Beaver Island, MI and Charlevoix, MI a 32-statue mile transit taking approximately two hours and twenty minutes. The route is conducted approximately 700 times a year. The daily number of transits between Beaver Island and Charlevoix varies depending on the season and passenger traffic. The current engines operate approximately 1700-1800 hours a year. The typical lay period for back-to-back trips is 50 minutes. The typical transit speed is 13.5 knots with the engines at 70% load. The reduced speed is intended to conserve fuel. The available additional horsepower is used for ice breaking. Ice operations are rare but necessary to maintain the vessel's operational schedule in the early and late season.

The hotel generators typically operate well below their rated capacity during the summer months and at capacity during the winter months due to electric heaters for the passenger spaces.

Current Propulsion Equipment:

- Two CAT 3512B Propulsion Engines rated for 1500 HP.
- Two ZF Gearboxes Model BW750, Ratio 3.074:1,Light Duty, Max Power 2163 HP
- Fixed Pitch Propellers
- Two CAT 3304 100 ekW Generators at 208V
- One Bow Thruster with a CAT 3116 205hp engine

The two main propulsion engines and two generator sets are original to vessel.

3.2 Financial Assumptions

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

- For the life cycle cost estimate, all costs were estimated as annual costs. In most cases inflation was assumed to be 4%, a value that has generally aligned with maritime and marine related assets over time.
- The consumables in Table 1 were assumed for the life cycle and fuel cost comparisons.

Table 1: Cost of Consumables

Item	Cost	Units
Fuel (ULSD)	3.00	$/gal
Lube Oil	8.00	$/gal
Urea	2.15	$/gal

Major equipment manufacturers were contacted for rough order of magnitude (ROM) pricing for the propulsion equipment replacement. From the meeting between EBDG, BITA, and BIBCO, Caterpillar was chosen as the primary engine manufacturer. EBDG reached out to Siemens and Twin Disc for hybrid options.

Propulsion equipment installation affects all aspects of the vessel due to its complexity and size. EBDG performed a parametric cost estimate using the marine industry standard Ship Work Breakdown Structure (SWBS), as defined in Appendix A. Based upon EBDG previous vessel repower experience, the estimated cost for each SWBS was assumed to be a percentage of the propulsion equipment ROM.

4. Discussion

4.1 Feasibility

Options 1, 2, and 3 are discussed in terms of feasibility of successful installation and satisfactory operational capability.

4.1.1 Option 1: Tier IV Diesel Mechanical With Cat 3512e Engines

Replacing the current CAT 3512B Engines with CAT 3512E Tier IV engines is a very feasible option. The engine itself will mostly fit on the same engine space with the possibility of minor changes to the foundation. The engine control wires, and fuel lines would require minimal changes. The gearbox and driveline would require minimal upgrades if any.

This option will require the addition of the CEM. From the ship check, EBDG determined that the best location for this device would be on the main deck next the engine room entrance, see Figure 1. This would require relocation of several electrical boxes and an exhaust trunk extension to house the CEM. This modification would be required on each side of the vessel. This addition would lead to the partial loss of two large vehicle spaces on the main deck which currently used for loose freight.

Caterpillar offers the CEM in two styles, Z-flow and U-flow. The U-flow arrangement is recommended for this installation. The CEM requires urea, so a urea dosing system and an additional tank will be required. Urea is a generally a mild liquid that requires minimal special handling.

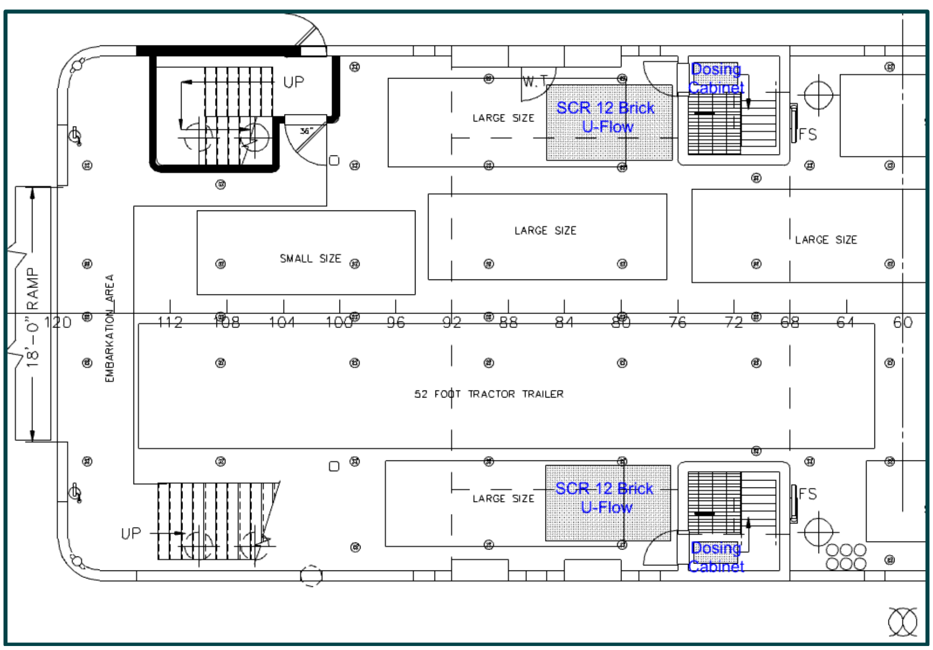

Figure 1: Recommended SCR Location

4.1.2 Option 2: Tier IV Diesel Mechanical With Cat C32 Engines

Replacing the current engines with C32 engines is a very feasible option as well. These engines have a smaller footprint and weight than the 3500 series Caterpillar engines while providing almost the same horsepower. These engines would likely require a change in engine foundations, fuel oil piping, engine control wires, and exhaust. This would free up twenty inches in front of the engine for other equipment. The C32 engine provides slightly less horsepower than the CAT 3500 series, but the operation does not use the full power of the installed engines.

The C32 engine is a higher speed engine than the CAT 3500 series engine, thus the gear box and propeller should be evaluated for replacement. The propellers are sized for a specific propeller shaft speed which will change with a faster spinning engine. The current gearbox ratio would provide a max propeller speed around 700 RPM which is undesirable. Further evaluation can be conducted to confirm the requirement for a new gear box. EBDG has spoken to ZF about the replacement options and gearbox cost. These costs are included in the capital expense evaluation.

The difference in weight between the CAT 3512B engines and a C32 is approximately 10,000 pounds per engine. EBDG recommends that if Option 2 is considered further, a new resistance curve be developed for the lighter vessel.

These engines are governed under the same EPA Tier IV rules as the CAT 3512E engines, so the addition of a Clean Emissions Module and Urea is required. It is recommended to place this equipment in the same location, on the main deck, as Option 1.

4.1.3 Option 3: Parallel Diesel Hybrid Plant

Parallel diesel hybrid options are feasible but would require extensive modification to the vessel. Both the Siemens and Twin Disc arrangements provide energy storage and delivery. The parallel diesel hybrid plants can deliver fuel savings through optimized power delivery, but they cannot reduce emissions to a level that is comparable to Options 1 and 2 without the installation of Tier IV engines.

Additionally, a hybrid plant will require systems that are not required of the existing propulsion system or Options 1 and 2. Batteries, for instance, must be installed in a separate protected compartment with its own HVAC, fire suppression, and cooling systems. From the ship check and discussion with the crew, there are void spaces forward and aft of the machinery space that could be utilized to house the required battery bank. Access to the battery bank for inspection and servicing has not been evaluated.

Figure 2 presents a potential equipment layout for a parallel hybrid system; note that that both Tier IV engine options are shown, but only one would be selected.

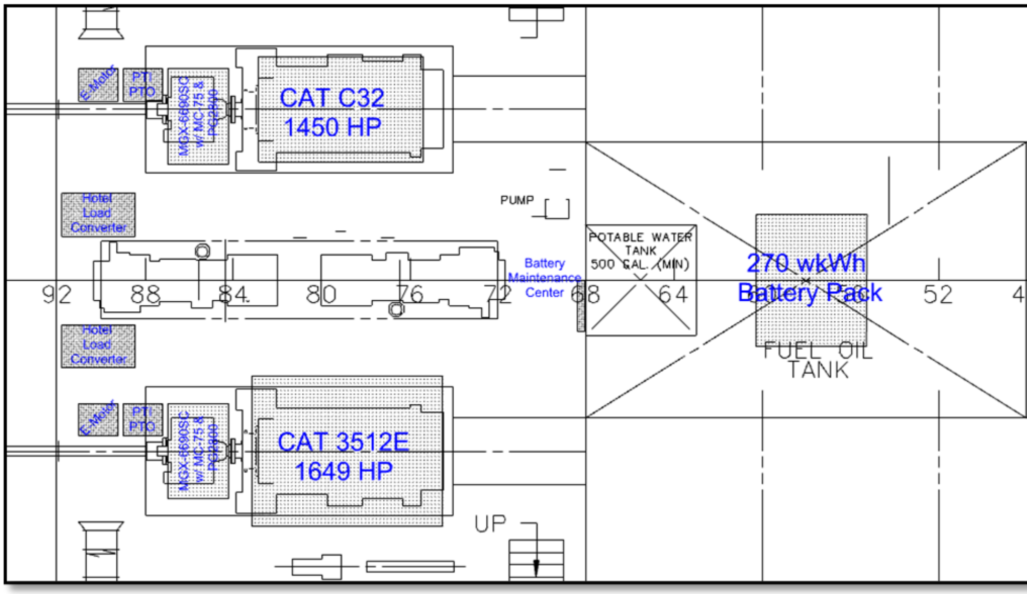

Figure 2: Parallel Hybrid Plant Options

The power management system provided by either vendor consists of several electrical components to transform power from the motor generators into stored energy or usable energy for various vessel loads. For example: the electricity generated by the motor generator is alternating current (AC) where lithium-ion batteries operate using direct current (DC), and the vessel hotel loads require AC. These electrical components would also need to be located in the machinery space, but not all are shown in Figure 2. It is likely the switchboard will need to be upgraded as well.

A primary component of the hybrid system is the electric motor/generator to transform the mechanical energy from the engine to electric energy for storage in the ESS. The 200 kW permanent magnet motors would typically be arranged on the after side of the gear boxes. At approximately 2 feet by 1.5 feet by 1.5 feet, these may be difficult to locate. As shown in Figure 3, these motors would essentially eliminate access around the after side of gear box due to the proximity of the aft bulkhead at Frame 92.

Both hybrid vendors proposed liquid cooled equipment: batteries, switchgear, inverters and converters. While water cooling can reduce the footprint of electrical components, additional cooling systems will need to be designed and located. It is possible that different components will require different coolant temperatures, so more than one system will be required.

Figure 3: Ship Check Picture-Gearbox proximity to Frame 92

4.2 Capital Cost

High-level capital cost assessments have been provided for the three feasible options, see Table 2. These cost estimates are based on previous EBDG projects of similar size and adjusted to accommodate the work necessary for each option.

Neither Twin Disc nor Siemens proposed to supply engines, so the capital cost of new Cat C32 engines is reflected in Table 2.

Table 2: Capital Cost Estimates

Propulsion Option	Propulsion Equipment Cost	Estimated Total Project Cost
Option 1 CAT 3512E Tier IV	$1,980,840	$4,338,000
Option 2 CAT C32 Tier IV	$1,161,600	$3,276,000
Option 3 Siemens w/o engine	$3,175,000	$6,342,000
Option 3 Siemens w/ C32	$4,336,600	$10,240,000
Option 3 Twin Disc w/o engine	$1,022,000	$4,472,000
Option 3 Twin Disc w/ C32	$2,183,600	$5,634,000

Using a series 3500 engine would result in less foundation and auxiliary modifications for the installation, but the 3500 series engine is more expensive than the C32 engine. The C32 engines will require structural, cooling, and fuel piping modifications. The hybrid option will require the most extensive vessel modifications in addition to having the highest upfront purchase price.

4.3 Operating Cost

EBDG considered fuel consumption, urea consumption and propulsion equipment maintenance costs when calculating the annual operating cost for each option. The fuel and urea are calculated from the engine load consumption rates provided by Caterpillar. The maintenance cost is assumed to be typical for engines of each type and is a product of the operating hours.

Table 3: Annual Operating Cost Summary

Annual Cost Item	Existing	Option 1 3512e	Option 2 C32	Option 3 Hybrid C32
Diesel	$777,000	$767,100	$854,300	$830,600
Urea	$0	$43,800	$25,200	$24,700
Lube Oil	$3,000	$3,000	$3,200	$3,200
Battery Maintenance	$0	$0	$0	$6,800
Engine Maintenance	$42,200	$42,200	$23,400	$23,400
Reduction Gear Maintenance	$4,000	$4,000	$4,000	$4,000
Generator Maintenance	$3,000	$3,000	$3,000	$3,000
Total Annual Cost	$829,200	$863,100	$913,100	$895,700

Table 3 demonstrates the fuel savings of upgrading to the CAT 3512E Engine over the existing CAT 3512B with Option 1. There is, however, an additional cost for the urea which makes Option 1 more expensive than the existing propulsion plant.

Option 2 appears, initially, to consume more fuel than Option 1 or Option 3 resulting in increased operating costs. The operating cost is primarily driven by fuel consumption. As discussed previously, the C32 engines offer significant weight savings over the 3500 series engines, so evaluation of this Option with revised resistance curves is advised.

To determine the operating cost over a 15-year life cycle EBDG calculated the present value of the annual operating costs from Table 3 over a 15-year period with an assumed 4% interest rate. The results are presented in Table 4.

Table 4: 15-Year Operating Cost

Life Cycle Cost Item	Existing	Option 1 3512e	Option 2 C32	Option 3 Hybrid C32
Diesel	$16,958,000	$16,742,000	$18,645,000	$18,128,000
Urea	$0	$956,000	$550,000	$540,000
Lube Oil	$66,000	$66,000	$70,000	$70,000
Battery Maintenance	$0	$0	$0	$149,000
Engine Maintenance	$921,000	$921,000	$511,000	$511,000
Reduction Gear Maintenance	$88,000	$88,000	$88,000	$88,000
Generator Maintenance	$66,000	$66,000	$66,000	$66,000
Total Life Cycle Cost	$18,099,000	$18,839,000	$19,930,000	$19,552,000

4.4 Emissions

The annual emissions are calculated by using the manufacturer's supplied engine exhaust information. The repower options are compared to the existing engines aboard the M/V EMERALD ISLE. The existing engines are not governed by any EPA Exhaust regulations while any replacement option will satisfy EPA Tier IV.

Table 5: Annual Emissions Summary

Emission	Existing	Option 1 3512e Tier Iv	Option 2 C32 Tier Iv	Option 3 Hybrid
CO2 (MT)	4.15	4.10	4.56	4.44
NOx (g)	86200	10800	8800	7700
CO (g)	5400	7200	4400	4400
HC (g)	3600	600	200	200
PM (g)	700	120	110	90

CO2 emissions are purely a function of the fuel burned. With further operational optimization, Option 2 and Option 3 could see a further reduction in all emissions. As the table above demonstrates, the Tier IV engines have a significant reduction in NOx, HC, and PM over the existing engines.

5. Conclusion

Table 6 is provided to demonstrate the total life cycle cost of the three feasible options. The lifecycle cost is the summation of the present value 15-year operating cost and the installation cost.

Table 6: Life Cycle Cost

Propulsion Option	Capital Cost	Operating Cost	Lifecycle Cost
Option 1 CAT 3512E Tier IV	$4,338,000	$18,839,000	$23,177,000
Option 2 CAT C32 Tier IV	$3,276,000	$19,930,000	$23,206,000
Option 3 Siemens w/o engine	$6,342,000	$19,952,000	$26,294,000
Option 3 Siemens w/ C32	$10,240,000	$19,952,000	$30,192,000
Option 3 Twin Disc w/o engine	$4,472,000	$19,952,000	$24,424,000
Option 3 Twin Disc w/ C32	$5,634,000	$19,952,000	$25,586,000

Option 1 and Option 2 are the most feasible and most practical solutions for repowering the M/V EMERALD ISLE. Option 1 with CAT3512E engines is more expensive up-front and will be marginally cheaper to operate over the 15-year period. Option 2 is less expensive up front and will be marginally more expensive to operate over 15 years. A revised speed and power curve should be evaluated to determine if the weight reduction of C32 engines could bring the fuel expenses down.

Option 3, the only feasible hybrid option for the M/V EMERALD ISLE, has serious installation constraints which would need to be addressed in future design phases. The emission improvements of the hybrid solution are nearly equivalent to Option 2 while the lifecycle cost well exceeds the lifecycle cost of Option 2. Any weight savings achieved by using C32 engines with the hybrid solution will likely be offset by the added hybrid components and supporting systems. The hybrid option, while intriguing, is ultimately not a great match for this vessel on this route.

6. References

[1] "BITA RFP #2023-4 - Consulting Firm to Evaluate Propulsion Systems," Beaver Island Transportation Authority , 2023.

[2] "3512E 1649 HP Performance Data [EM1779]," 10/27/2021.

[3] "C32 1450 HP Performance Data [32MP 404]," Caterplliar Inc., 10/27/2021.

[4] "3512 1500 HP Marine Engine Performance Data [4TN00169]," Caterpillar Inc. , 3/21/2012.

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[7] "Marine Power Solutions," Caterpillar Inc. , 2023.

[8] "CAT Marine Air-Assist Aftertreatment A&I Guide, U.S. EPA Tier 4 / IMO III/ EU Stage V," Caterpillar Inc, 2023.

Appendix A

SWBS Definitions

Code	Title	Descriptions
OFM	Owner Furnished Material	This category includes the major purchases outside of the shipyard or repair facility conducting engine repower work. These purchases are categorized separately to specify what arrangement is desired by the operator and to consider special savings from equipment manufacturers.
000	General	Typically covers items like, shipyard costs, Gas Freeing, tank cleaning, etc.
100	Structure	Includes cost associated with the ship's structure. In this project this will include the addition of the Urea tanks required for the Tier IV engines, addition of SCR on Car deck.
200	Propulsion Machinery	Includes removal of the existing Engines and Installation of the new engines. These factors are typically calculated as a function of engine horsepower thus representing the size and complexity of the tasks.
300	Electrical	Includes the changes to the main electrical system. For options 1 and 2 this should be modest. Option 3 will have substantial Electrical Work
400	Command and Surveillance/ Electronics	Includes cost associated with engine controls, engine monitors, and alarms.
500	Auxiliary Machinery	Includes cost for Auxiliary Machinery, steering pumps, compressors, HVAC systems. Again, this will be modest for options 1 and 2 but substantial for option 3.
600	Equipment and Outfit	Includes cost for painting, repairing passenger spaces that have been disturbed, reworking pilot house controls to accommodate new engine controls and monitors.
800	Integration & Engineering	Includes cost for engine technicians, equipment technicians, upfront engineering, detail engineering, and engineering support during the repower work.
900	Tests, Trials and Delivery	Includes engine startup tests, proving engine safety systems for regulatory bodies, Optional Sea trials, and delivery.