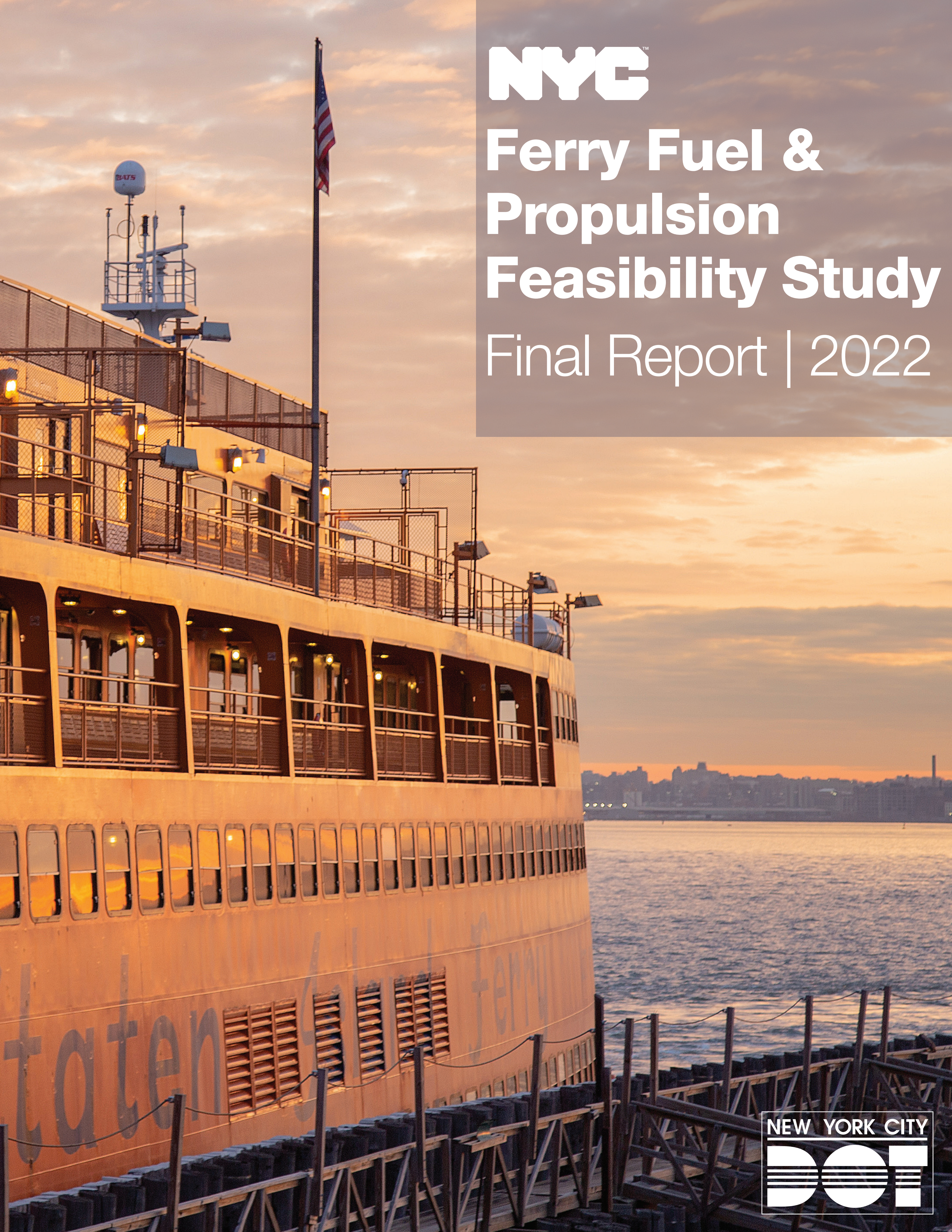

NYC

Ferry Fuel & Propulsion Feasibility Study

Final Report | 2022

NEW YORK CITY DOT

Prepared for the NYC Department of Transportation by Glosten, Inc.

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List of Definitions

Term	Definition
ABS	American Bureau of Shipping
AC	Alternating Current
AEO	Annual Energy Outlook
AFE	Active Front End
ASTM	American Society for Testing and Materials
BSEF	Brake Specific Emissions Factors
Bunkering	Transferring fuel to or from a ship
CARB	California Air Resources Board

CFPP	Cold Filter Plugging Point
CFR	Code of Federal Regulations
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DC	Direct Current
DCAS	Department of Central Administrative Services
DGB	Dynamic Gas Blending
DIG	Direct Injected Gas
DNV-GL	Det Norske Veritas – Germanischer Lloyd
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
EEDI	Energy Efficiency Design Index
EIA	US Energy Information Administration
EISA	Energy Independence and Security Act
EPA	Environmental Protection Agency
FAME	Fatty Acid Methyl Ester
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
GWP	Global Warming Potential
HC	Hydrocarbons
HVAC	Heating, Ventilation, and Air Conditioning
IGF	International Code of Safety for Ships Using Gases or other Low Flashpoint Fuels
IMO	International Maritime Organization
LCFS	Low Carbon Fuel Standard
LFL	Low Flashpoint Liquid
LNG	Liquefied Natural Gas
LTFT	Low Temperature Flow Test
MARPOL	International Convention on the Prevention of Pollution from Ships
MCR	Maximum Continuous Rating
NMC	Nickel Manganese Cobalt Oxide
NPV	Net Present Value
NYC DOT	New York City Department of Transportation
NYCF	New York City Ferries
OCMI	Officer in Charge, Marine Inspection

PM	Particulate Matter
PUD	Public Utility District
RGGI	Regional Greenhouse Gas Initiative
SCR	Selective Catalytic Reduction System
SEEMP	Ship’s Energy Efficiency Management Plan
SFC	Specific Fuel Consumption
SIF	Staten Island Ferries
SOLAS	International Convention for the Safety of Life at Sea
SOx	Sulfur Oxide
ULSD	Ultra-Low Sulfur Diesel
UPS	Uninterruptible Power Supply
USCG	United States Coast Guard
WSF	Washington State Ferries
ZEV	Zero Emission Vehicle

Revision History

Section	Rev	Description	Date	Approved
All	P0	Preliminary release	4/19/19	DWL
All	P1	Second draft release	6/19/19	DWL
All	-	Original release	10/31/19	DWL
Exec. Sum. 6.1.11, Appendix A	A	Added new SIF option, T3 Diesel Molinari Hybrid II	6/6/22	DWL
Cover page, Release notes	B	Final release	7/29/22	DWL

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2022 Release Notes

This report was originally released in late 2019 and the state of technology and cost estimates are based on this reporting year. Several factors have delayed the final report release, including the COVID-19 outbreak in New York City in early 2020. Marine emissions are a sharp global focus, and the industry has seen several major changes since 2019. Those changes are discussed below.

During the release delay, an option was added discussing new assumptions for a diesel-battery hybrid conversion of the SIF Molinari Class. This new option uses the same 2019-vintage data as the original to ensure a fair comparison.

Costs

Diesel fuel was $2.40/gallon based on the city's fuel contract in 2018. This baseline was used for comparison throughout the report. Fuel pricing is currently at record highs.

Budgetary pricing for equipment was collected between 2017 and 2019. Supply shortages, foreign import tariffs, political sanctions, and inflation have all increased prices of manufactured goods since 2019.

Construction cost estimates were based on 2019 data. Shipyard conversion costs have increased significantly since 2019, driven by both the cost of steel and labor. Steel has increased in price by roughly three times since 2019 and the consumer price index for goods and services has increased 8% in the last year alone.

Battery Technology

Battery technology is advancing at an amazing rate. New battery chemistries are emerging, reducing battery bank size, increasing battery life, and increasing charging rates. This only improves the case for battery hybrid conversions recommended in this report. Some details of battery system capabilities are no longer current, however.

Alternative Marine Fuels

Popularity of some alternate marine fuels has fallen while others are emerging. There is less focus on natural gas due to rising gas prices and a subsequent change in economics. Additionally, methane slip (unburned natural gas) from reciprocating engines is more widely seen as a significant emission contributor.

Methanol is emerging as a potential low-carbon solution for medium- and high-speed reciprocating engines. Methanol-fueled engines are now commercially available from some manufacturers in the appropriate size range for SIF vessels. Like hydrogen, the carbon reduction potential of methanol is dependent on the fuel production pathway and feedstocks.

Recommendation Validity

Though costs have increased, the above industry changes have little impact on the overall recommendations made in this report. Electrification is still seen as the long-term path ahead for significant emissions reductions in both the SIF and NYCF ferry fleets. Hydrotreated renewable diesel (HRD) is still seen as an effective near-term solution.

Executive Summary

For the past fifteen years, New York City's ferry system has been a leader in evaluating and implementing new fuels and technologies. Past efforts have included voluntary early adoption of ultra-low sulfur diesel fuel, upgrading engines to exceed EPA requirements for emissions performance, exploring natural gas fuel feasibility, and trialing biodiesel. This moment is a critical juncture for further evaluating marine propulsion technologies: 2019 has seen the first all-electric ferry enter service in the US, new low-sulfur fuel regulations that take effect in 2020 are changing the global maritime industry, battery technology is advancing rapidly, and across industries, intense focus is being placed on environmental impacts. The NYC Department of Transportation is continuing its historic leadership by conducting the present fuel and propulsion feasibility study. Numerous alternative fuel and propulsion technologies are currently available or are quickly developing to a commercial scale, and careful consideration is warranted to capitalize on these opportunities.

This study investigates the feasibility of using alternative fuels and propulsion technologies in the ferries the City of New York owns and operates and recommends options for near-term and long-term implementation. While the specific fleets considered are the Staten Island Ferry (SIF) and the New York City Ferry (NYCF), many of the conclusions are broadly applicable to other ferries operated around the city.

The study has two goals for the operation of the City's ferry fleets:

- Reduce the amount of emissions generated
- Reduce the cost of fuel consumed

In some cases, these are complementary goals. Some technologies presented in this report simply make ships more efficient. When less power is required to propel a ship, fuel cost and emissions are both reduced. In other cases, these goals are competing; some of the options explored in this study minimize emissions but increase fuel costs. Many options also provide emissions and/or fuel cost benefits but require expensive capital investments or result in increased operational complexity, and these considerations must be weighed against the benefits provided.

The study considered six fuels and compared them to the current benchmark fuel, ultra-low sulfur diesel:

- Biodiesel (B5 – B20)
- Renewable Diesel
- Methanol
- Liquefied Natural Gas
- Compressed Natural Gas
- Hydrogen

Four alternative propulsion systems were evaluated against the existing fleets' systems:

- Variable speed diesel-electric
- Plug-in hybrid battery-electric
- Non-plug-in hybrid diesel-electric
- Fuel cell-electric

The study also considered several efficiency options that either directly reduce emissions or hydrodynamic resistance or empower operators to better manage fuel consumption:

- Emissions upgrades
- Optimizing double-ended ferry propulsion
- Low friction hull coatings
- Fuel flow monitoring

Results

Table 1 and Table 2 summarize the expected changes to capital and operating costs, fuel consumption, carbon dioxide (CO_2), and various regulated local emissions for select fuels and technologies investigated in this study. Some fuels and technologies listed above were not analyzed quantitatively for reasons summarized below in the “Not Recommended” section. Additional details can be found in Section 5.

Table 1 SIF recommendations and capital and operating cost metrics

Option	Capital Cost	Operating Cost	Fuel	CO_2	NO_X	HC	PM	CO	SO_2
Emission Control Upgrades	$2,200,000	-	-	-	-4%	-	-37%	-	-
B20 Biodiesel	$390,000	+4%	+1%	-11%	+2%	-15%	-11%	-15%	-20%
R50 Renewable Diesel	$0	+26%	-	-33%	-2%	-15%	-11%	-15%	-49%
DGB LNG Molinari	$30,000,000	-9%	-	-	-	-	-	-	-18%
DIG LNG Ollis/Midsize	$48,000,000	-17%	-8%[1]	-8%	-	-	-	-	-41%
Low Friction Hull Coatings	$0	-	-2%	-2%	-2%	-2%	-	-1%	-1%
Integrated Bus Molinari	$6,800,000	-	-1%	-2%	-8%	-4%	-	-1%	-1%
Int Bus & Var Spd Molinari	$33,000,000	-4%	-5%	-6%	-6%	-	-9%	-1%	-5%
Diesel Hybrid Molinari	$37,000,000	-4%	-5%	-5%	+6%	+4%	-10%	-1%	-4%
Plug-in Electric Operation	$160,000,000	-9%	-89%	-64%	-75%	-84%	-70%	-72%	*
Power Split Molinari	$11,000	-4%	-4%	-5%	-4%	-6%	-	-4%	-4%
T3 Diesel Hybrid Molinari II	$15,165,000	-0%	-4%	-5%	-17%	-57%	-45%	-93%	-4%

[1] *Based on lower heating value of fuel compared to baseline.*

**The theoretical SO_2 emissions rate is dramatically influenced by the few remaining coal plants in New York. The remaining coal plants are likely to be decommissioned by 2021, reducing SO_2 emissions to approximately zero.*

Table 2 NYCF recommendations and capital and operating cost metrics

Option	Capital Cost	Operating Cost	Fuel	CO_2	NO_X	HC	PM	CO	SO_2
Emission Control Upgrades	$3,800,000	-2%	-8%	-8%	-80%	-	-75%	-	-7%
B10 Biodiesel	$0	+2%	+1%	-6%	+1%	-8%	-5%	-8%	-10%
R50 Renewable Diesel	$0	+21%	-	-33%	-2%	-13%	-13%	-16%	-50%
Natural Gas[1]	$31,300,000	-38%	-10%[2]	-9%	-	-	-	-	-100%
Plug-in Electric[1]	$43,100,000	-38%	-100%	-73%	-96%	-90%	-91%	-83%	*

[1] *Neither all-gas conversion nor a plug-in electric fleet for NYCF are currently technically feasible. These options were evaluated to estimate the long-term benefits of a theoretical fleetwide conversion in the future.*

[2] *Based on lower heating value of fuel compared to baseline.*

**The theoretical SO_2 emissions rate is dramatically influenced by the few remaining coal plants in New York. The remaining coal plants are likely to be decommissioned by 2021, reducing SO_2 emissions to approximately zero.*

Based on the findings presented in Table 1 and Table 2, this study developed a series of immediate, short-term, long-term, and future fleet recommendations for the SIF and NYCF fleets. These findings are summarized below.

Immediate Recommendations

The following items require minimal or no capital investment and planning and are recommended for immediate implementation.

→ SIF & NYCF: Use hydrotreated renewable diesel fuel in all vessels

Hydrotreated Renewable Diesel (HRD) is the best immediate option to reduce each ferry fleet's global warming potential with potential reduction of one third.

The refining process used to produce HRD results in a fuel that is chemically similar to petroleum diesel, eliminating the risks associated with biodiesel. A 50% blend of HRD with petroleum diesel is assumed in this study for conservatism, but higher blends may be possible.

Benefits to local air quality may also result, but the research on this topic is inconclusive. HRD is also quite flexible. Varying quantities could be purchased as budgets dictate with negligible overhead costs required to increase or decrease HRD usage periodically. The City should compare the cost of using renewable diesel on the ferries with other green initiatives and utilize as much renewable diesel as is financially feasible.

This option applies to both SIF and NYCF. If a combined fuel contract were negotiated, it could also be the only option that achieves synergies between the fleets.

→ SIF: Apply low-friction hull coatings to SIF vessels at the next scheduled drydocking

Two areas researched during this study warrant implementation as soon as is practical. The first is to begin using low-friction hull coating systems on SIF vessels. The newer NYCF ferries were constructed with advanced coatings and gain little from additional coating improvements.

Low friction coating systems carry a small increase in lifetime maintenance costs that is repaid 20 times over by decreased fuel consumption. Advanced coatings could be applied during the SIF ferries' next regularly scheduled drydocking period.

→ SIF: Modify Molinari class fwd/aft power distribution to improve propulsion efficiency

Adjustment of the power distribution between the forward and aft end propellers on the Molinari class SIF is an easy way to reduce fuel consumption on the Molinari class vessels. This has already been trialed on the *John J. Marchi* and was found to offer as much as 15% fuel savings.

→ SIF: Install fuel flow meters on one Molinari class vessel and one VSP vessel to monitor real time fuel consumption and improve operations

Monitoring real time fuel consumption can be a valuable tool for driving fleetwide fuel efficiency. Flow meters installed on both the supply and return piping at the main engines are a simple and cost-effective way to better inform captains how their handling of a vessel affects fuel consumption. This collection of data coupled with an incentive program could provide modest reductions in fuel use and associated emissions.

Short-Term Recommendations

The following items require some capital investment and planning and are recommended for short-term implementation.

→ SIF: Upgrade Barberi and Molinari class propulsion engines to improve EPA tier ratings

Further emissions upgrades to the existing propulsion engines on both the Barberi and Molinari class ferries would reduce particulate emissions up to 40% and NOx by 3%.

These upgrades could qualify for Volkswagen NOx abatement funding, and the Governor's strategy document for using these funds noted a need to identify appropriate ferry projects.

→ SIF: Investigate hybrid technology strategies for the Molinari class vessels

The load profile and power train architecture of the Molinari class vessels make them possible candidates for a series diesel-battery hybrid conversion. Using batteries to absorb excess power while maneuvering and passenger loading could allow for lower power plant output during transit. This has potential to put onboard combustion engines at a more efficient and cleaner load point through the vessel's operating profile. Combined with new, more powerful ship service diesel generators and propulsion engine emissions upgrades, this option could provide significant criteria emissions reductions, modest fuel consumption savings, and reduced maintenance.

A diesel-hybrid Molinari conversion, combined with EPA Tier 3 upgrades, could reduce fuel consumption, particulates, and NOx up to 4%, 45%, and 17% respectively. Reduced engine hours also provide a reduction in maintenance burden.

The feasibility of hybridization depends on validating several assumptions made in this study. Follow on engineering work is required to confirm feasibility of the concept and evaluate details of the best hybrid architecture. Gaining experience with battery technologies now is also valuable for a future fleet of plug-in electric ferries and provides a stepped approach towards that goal. Cost of the first hybrid option (Section 6.1.6) is based on a budgetary proposal from Siemens for a hybrid upgrade that involved complete replacement of the ship's electrical system (including new propulsion alternators). The second option (Section 6.1.11) assumes that comparatively minor modifications can be made to the existing 4160V switchboards and propulsion drive electronics. This second concept has not yet been reviewed by Siemens.

Long-Term Recommendations

The following items require modest capital investment and planning and are recommended for long-term implementation.

→ SIF: Investigate propulsion optimization options for Barberi, Austen, and Ollis class ferries

The Barberi, Austen, and Ollis class vessels use Voith-Schneider propellers (VSP). Less data is available on optimizing VSP propulsion compared to the Molinari fwd-aft power distribution, but tank test results from the new Ollis class ferries suggest that some gains are possible. Compared to the Molinari class, greater engineering effort would be required and less benefit expected.

A sustained 5% reduction in fuel usage could potentially be achieved with a careful full-scale study of optimized VSP power split.

→ NYCF: Upgrade to Tier 4 concurrent with planned main engine replacements

The propulsion engines on the NYCF fleet have a finite service life. The hulls will likely last longer and a mid-life engine replacement is currently estimated at roughly 10-years. Preliminary sizing and arrangement information from the engine manufacturer suggests that a Tier 4 retrofit is feasible even though not required by the EPA. However, the number of components requiring replacement and the resulting cost means this option is not practical until the planned engine replacement. If no preferred alternative (such as an electric or alternative fuel) is identified before this scheduled replacement, a Tier 4 upgrade would offer a significant local emissions reduction over the baseline fleet.

NYCF has unique circumstances resulting in a viable Tier 3 to Tier 4 upgrade.

Future Fleet Recommendations

The following items require significant capital investment and/or planning and are recommended for future consideration. Recommendations are focused on achieving the City's goal to reduce greenhouse gas emissions 80% by the year 2050 (80x50).

→ SIF & NYCF: Invest in plug-in electric infrastructure to leverage green grid technologies

Incremental upgrades to the existing fleet architecture discussed above will provide subsequent incremental improvements to the fleet's emissions profile. In order to achieve the goal of 80x50, a fundamentally different approach is required, however.

The blueprint for an environmentally friendly City ferry fleet is electrification.

Today, electric power in New York is 50% carbon free. This is the lowest-carbon energy source that can feasibly be used to power ferries with today's technologies. Environmental initiatives such as the Regional Greenhouse Gas Initiative will inevitably result in further improvements to regional electric power's carbon performance. A large ferry can be in service for as much as 50 years, and as this report will show, it is typically very expensive to make major changes to the propulsion system during this long lifetime. Even if an alternative fuel were cost effective, the strict regulatory process applied to ensure ship safety makes it challenging to implement new technologies, even when they have been successfully demonstrated on land. Electrification would allow the ferry systems to leverage incremental improvements in land-based green power generation, where the dramatically larger market provides greater incentive for advanced research.

The path to large scale emissions reduction begins with embracing electric propulsion.

There are numerous technological challenges to overcome before the ferry systems can provide reliable service using only grid-based electrical power. Section 7 of this report lays out a roadmap to achieving electrification incrementally while mitigating the risk of required new technologies. A formal Preliminary Design Investigation into the use of electric ferries to achieve 80x50, including the associated shoreside infrastructure, should be initiated without delay.

→ NYCF: Continue using hydrotreated renewable diesel fuel for vessels on long routes

Considering today's technologies, several of NYCF's routes are likely not feasible for electric ferries due to infrequent stops, long distances and a weight-sensitive vessel design. The absence of a viable plug-in solution means energy will need to be developed onboard for the immediate future. Using HRD is more expensive than continuing to burn ULSD but offers a potential one-third reduction in greenhouse gas (GHG) emissions.

The most effective future option for NYCF's longest routes is a switch to hydrotreated renewable diesel.

Not Recommended

The following items are not technically feasible with current technology or will not provide a reasonable benefit for the capital investment required. They are not recommended at this time for use on the ferries.

Some fuels' potential environmental benefits are overcome by the carbon intensive processes used to produce them. This is true of hydrogen and methanol.

Although advocates for these fuels may appeal to alternative production processes that use renewable electricity, the limited sources of renewable electricity are better left on the power grid. In theory, an excess of renewable electricity could allow environmentally beneficial production of hydrogen, but complete replacement of the electric energy sector with renewable power is not likely to occur in the next fifty years.

Some fuels required closer investigation but were ultimately not recommended. Natural gas offers marginal environmental benefits but promises 40% lower fuel costs. Sections 5.4, 6.1.3, and 6.2.9 examine these factors and ultimately find that the SIF route is too short and average fuel consumption too low to offset the high capital costs associated with adoption of a natural gas fuel system. For NYCF, the only marine certified gas engines currently available in the power range needed are physically too large for the existing hulls. Numerous technological and regulatory challenges also exist for burning natural gas in either ferry fleet.

Although natural gas is still a promising fuel for many marine applications, neither LNG nor CNG is recommended for SIF or NYCF at this time.

Traditional biodiesel is discussed in Sections 5.2, 6.1.1, and 6.2.1. Utilizing B20 offers a slight improvement in global warming potential, but there is insufficient evidence to be confident of local emissions improvements. Generous federal subsidies and tax benefits make B20 available at a very minor price premium compared to diesel. However, biodiesel presents some undesirable operational risks. The manufacturer of the main propulsion engines for the SIF fleet only certifies performance for biodiesel blends up to B5 and the NYCF main propulsion engine manufacturer limits biodiesel blends to B10. Operating with biodiesel blends above those limits recommended by the engine manufacturers would be done at the City's risk. There is little demand in the maritime industry to prompt engine manufacturers to resolve these technical questions or provide better support for biodiesel.

Balanced against the risks, biodiesel's benefits are marginal, and a shift to biodiesel is not recommended.

Section 1 Introduction to the Study

The New York City Department of Transportation (NYC DOT) commissioned a feasibility study (the “Study”) under an on-call contract with Glosten to investigate possible changes to fuel type and propulsion systems used in the ferries owned by or operated on behalf of the City of New York (the “City”), with the primary goals of reducing emissions generated in the operation of its ferry fleets and the total cost of fuel consumed in the operation of its ferry fleets.

This study evaluates fuel and propulsion alternatives to determine their technical and operational feasibility, costs, and potential benefits. Benefits are narrowly defined as reduced emissions or fuel costs. The emissions portion of the benefits considers both local and upstream emissions back to the Public Utility District (PUD). For example, for a battery propulsion system that might have zero local stack emissions, this study accounts for emissions produced by the PUD when generating the electrical power that charges the batteries on the ferries.

Ferries subject to this study include the Staten Island Ferry (SIF) fleet and the New York City Ferry (NYCF) fleet. This study recommends immediate-, near-, and mid-term changes to the existing fleets and designs for future vessel construction. Recommendations vary by vessel class for both ferry fleets due to differences in size, existing propulsion machinery configurations, and operating profile.

Section 2 Emissions Regulations & Goals

2.1 Background

Internal combustion engine emissions are becoming ever more regulated at the international, federal, state, and local levels. This evolving regulatory framework has the potential to change the actual, projected, and assessed costs of fuels used for combustion and their post-combustion byproducts. As a result, it has become increasingly important for transportation agencies to assess possible alternatives to their existing fuel regimes from a cost perspective, in addition to the air quality benefits these alternatives may provide.

It is convenient to divide emissions into two categories: greenhouse gas (GHG) emissions and criteria pollutants. Discussions of GHG emissions tend to focus on carbon dioxide (CO_2), but other gases also contribute to global warming effects. A complete analysis will include the global warming potential (GWP) contribution of all relevant gases, with results most frequently reported in terms of “equivalent CO_2,” also referred to in this report as “CO_2e.” Depending on the methods used, reported equivalent CO_2 rates may include contributions from various phases of the fuel lifecycle, sometimes including removal of CO_2 from the atmosphere by plant-based fuels during plant growth. As all combustion fuels involve oxidizing hydrocarbons, any such fuel will produce CO_2 as a byproduct. Although there are modest differences in equivalent CO_2 emissions at the stack from different types of combustion fuel, a vessel burning any fuel can reduce GHG emissions by increasing vessel efficiency and therefore reducing the amount of fuel burned. Alternatively, the lifecycle GHG emissions of some fuels may offer substantive improvements over others.

Criteria pollutants are regulated by both domestic and international agencies. Whereas greenhouse gases have come under scrutiny due to their global effects, criteria pollutants are typically regulated to improve local air quality and achieve corresponding benefits for health. To cover the wide range of engine power levels available, criteria pollutants are typically regulated through limits on emission rates per unit power such as grams per kilowatt-hour (g/kWhr). In some cases, pollution totals are reported, such as metric tons (MT) per year. New York County is an EPA nonattainment zone for ozone and particulate matter, meaning it is currently exceeding allowed limits. As ferries emit both NOx (a key component for forming ozone) and particulate matter, reductions in these emissions are desirable.

2.2 OneNYC

In the absence of comprehensive carbon pricing either at the state or national levels, many cities have taken up independent initiatives to reduce their carbon footprint. New York City has adopted a goal of 80% reduction in GHG emissions by 2050, including an interim target of 40% reduction by 2030 (Reference 1). While the 80x50 Roadmap acknowledges limited opportunities to reduce marine GHG emissions, it does make a commitment to explore carbon reduction technologies for the marine sector. The present study significantly advances the goal to identify applicable low-emission technologies.

2.3 Current Emission Regulations

Vessels operating in New York City are subject to regulations at the national (EPA), state, and potentially the local level.

2.3.1 Environmental Protection Agency

Several criteria pollutants produced by marine diesel engines are regulated by the EPA under 40 CFR §1042. EPA limits are separated into different tiers, with increasingly strict standards depending on when the engines were manufactured. Tier 1 and 2 limits were phased in over engine model years 2004-2006. Tier 3 and 4 emissions standards were established in 2008 and entered in to force from 2009 to 2017. All EPA tiers regulate carbon monoxide (CO) and oxides of nitrogen (NOx). Limits on hydrocarbons (HC), and particulate matter (PM) were introduced at Tier 3. Limits are specified on a unit energy basis in grams emitted per kilowatt-hour of energy produced (g/kWhr). Manufacturers must test engines across a range of engine loading conditions to achieve compliance. A weighted average emissions level is determined for each pollutant that must meet the applicable limit. These weighting factors emphasize high-power operations, and emissions at power levels below 25% are not regulated.

Engine manufacturers can only supply engines that meet the applicable tier standard when providing equipment for new vessels. Separately, remanufacturing engines can trigger requirements under 40 CFR §1042 Subpart I to upgrade engines to meet higher tier limits. Remanufacturing is defined as replacing all cylinder liners, which is usually done during major engine overhauls. Since Tier 4 performance generally requires the use of large aftertreatment systems, EPA regulations assume that it is not practical to retrofit these aftertreatment systems into existing ships. For other tiers, manufacturers must document space or performance constraints that prevent meeting higher tier requirements and remanufacture the engine to meet the highest tier possible.

Limits imposed by 40 CFR §80 reduced the acceptable concentration of sulfur in marine diesel fuel, with a current limit of 15 ppm (parts per million). Fuel formulated to this standard is known as Ultra-Low Sulfur Diesel (ULSD) as defined in ASTM D975 (*Standard Specification for Diesel Fuel Oils*). This limit serves a dual purpose – first, limiting sulfur in fuel limits the amount of sulfur oxide pollutants (SOx) produced by the engine. Second, sulfur poisons the catalytic reactions used in current exhaust aftertreatment technologies that reduce other pollutants such as NOx. Requiring low-sulfur fuel assures engine manufacturers that a compatible fuel supply will be used.

There are no current EPA regulations limiting greenhouse gas emissions from marine engines. The Regional Greenhouse Gas Initiative (RGGI) is a regional cap and trade system (New York is a member) to reduce greenhouse gas emissions within the power sector. However, it does not affect the sale or distribution of carbon-based fuels outside the sector and does not directly affect the marine industry.

2.3.2 International Maritime Organization

Vessels operating exclusively on domestic voyages, such as all the City’s ferries, are not subject to international regulations. However, many vessels in NYC waterways are on international voyages, and their engine emissions are regulated by the International Maritime Organization (IMO). International limits on marine engine emissions are established by the International Convention on the Prevention of Pollution from Ships, known as MARPOL. Emissions limits similar to EPA Tier 1 entered force in 2005, while stricter limits similar to EPA Tiers 3 and 4 entered in to force from 2011-2016. Unlike the EPA regulations, IMO standards do not limit hydrocarbons or particulate matter. This means that some engine technologies can be used to achieve low NOx limits under IMO regulations but are not capable of achieving the combined NOx and PM limits established by EPA rules.

2.3.3 California Air Resources Board (CARB)

Although not directly relevant to this study, regulations in California have prompted a number of analyses that are helpful for evaluating fuel alternatives. One such regulation is the Low Carbon Fuel Standard (LCFS). The goal of this regulation is to promote the use of fuels with lower lifecycle equivalent CO_2 emissions. In support of this, fuels are assigned a “carbon intensity” (CI) score, reported in equivalent grams of CO_2 per megajoule. Although these scores include various factors such as transportation distances and electricity production that are specific to consuming the subject fuels in California, these carbon intensity scores nevertheless offer a helpful comparative tool to assess differences between fuels. Note that the energy values in these CI scores are based on the energy content (higher heating value) of the fuel and are not directly comparable with energy figures elsewhere in this report, which are generally for energy produced by engines. Not all of the chemical energy in the fuel is converted to useful work due to inefficiencies in the combustion process. Finally, although CI scores for a wide variety of fuels are available through the CARB, no data is provided about the available volume of such fuels. Some fuels, such as those produced from used cooking oil, achieve extraordinarily low CI scores, but likely cannot be produced in sufficient quantities to be of broad commercial use. More details on this regulation and the CI scores and methodologies are available in Reference 35.

2.4 Future Regulations

2.4.1 Carbon Tax

A carbon tax of some kind will likely be enacted in the future. Many countries have introduced some form of carbon pricing, and several US states have attempted this. While most efforts have originated in western states (Washington State’s third attempt at carbon pricing failed in November 2018), now a number of eastern states, including New York, are taking carbon pricing efforts seriously. In January, legislation was introduced in New York that would impose a carbon tax of no less than $35 per ton for distribution or sale of carbon-based fuels. This would increase by $15 per ton up to a maximum of $185. Unlike the RGGI, a carbon tax would affect vessels that use carbon-based fuels such as the City’s ferries. Beyond the state level, there is also a possibility of a national carbon tax passing in the future. On January 24th, a bipartisan bill was introduced in the house of representatives. HR 763, The Energy Innovation and Carbon Dividend Act of 2019 would put a price on carbon starting at $15 per ton and going up by $10 per ton per year. All of these efforts indicate a growing movement to regulate carbon emissions in the United States and point to the question of not *if*, but *when* such laws will be passed.

A future carbon tax would financially incentivize low carbon fuels and change the cost-benefit analysis provided in Section 6. If such legislation passes, the results of this study should be re-evaluated considering this new economic environment.

2.4.2 Marine Energy Efficiency Regulation

Several aspects of marine propulsion emissions seem likely to come under increased regulation in the future. First, improving vessel efficiency offers a nearly direct emissions benefit to both regulated and unregulated pollutants. The Energy Efficiency Design Index (EEDI) requires new ships to gradually improve their energy efficiency and is applicable to many cargo ships. This approach depends on establishing a baseline for similar ships and therefore can’t be easily applied to unique ferry operations – domestic ships are already excluded from EEDI regulations.

The EPA has taken this approach for road vehicles by establishing increasingly stringent gas mileage targets. Although this type of regulation will continue to be employed for cars and cargo ships, it is unlikely that it will be applied to ferries in the near future.

2.4.3 Limits on Methane Emissions

Natural gas, as a relatively new marine fuel, is also likely to experience increased regulation. Methane, the primary component of natural gas, is a powerful greenhouse gas. A significant issue facing natural gas-powered engines is methane slip, in which some of the fuel is not combusted and exits the engine with the exhaust gases. Methane can also escape during fueling evolutions. Although not yet regulated by the EPA or IMO, some natural gas engine technologies already achieve minimal methane slip. It is not clear that new regulations limiting methane slip would result in significant changes to the marine gas fuel market, although future regulations limiting leakages in production or storage could raise natural gas prices. Methane slip is discussed in more detail in Section 5.4.

Section 3 Fleet Background

3.1 Staten Island Ferry

3.1.1 History

Staten Island Ferry (SIF) has operated in some capacity since its inception as a private company in 1817. The ferry service was acquired by the city in the early 1900’s and is now run by the New York City Department of Transportation. While initially comprised of many routes, the current route has withstood the test of time as the only direct connection between Staten Island and Lower Manhattan. This allowed it to survive the rapid construction of bridges and subways in the sixties that led to the demise of all other ferry routes in the New York harbor for many years. In 1997, the ferries’ historically low fare was eliminated completely. Following the 9/11 attack in 2001, new cost-prohibitive security laws permanently discontinued car service on the route. However, ferries with a car deck still carry state emergency vehicles as needed.

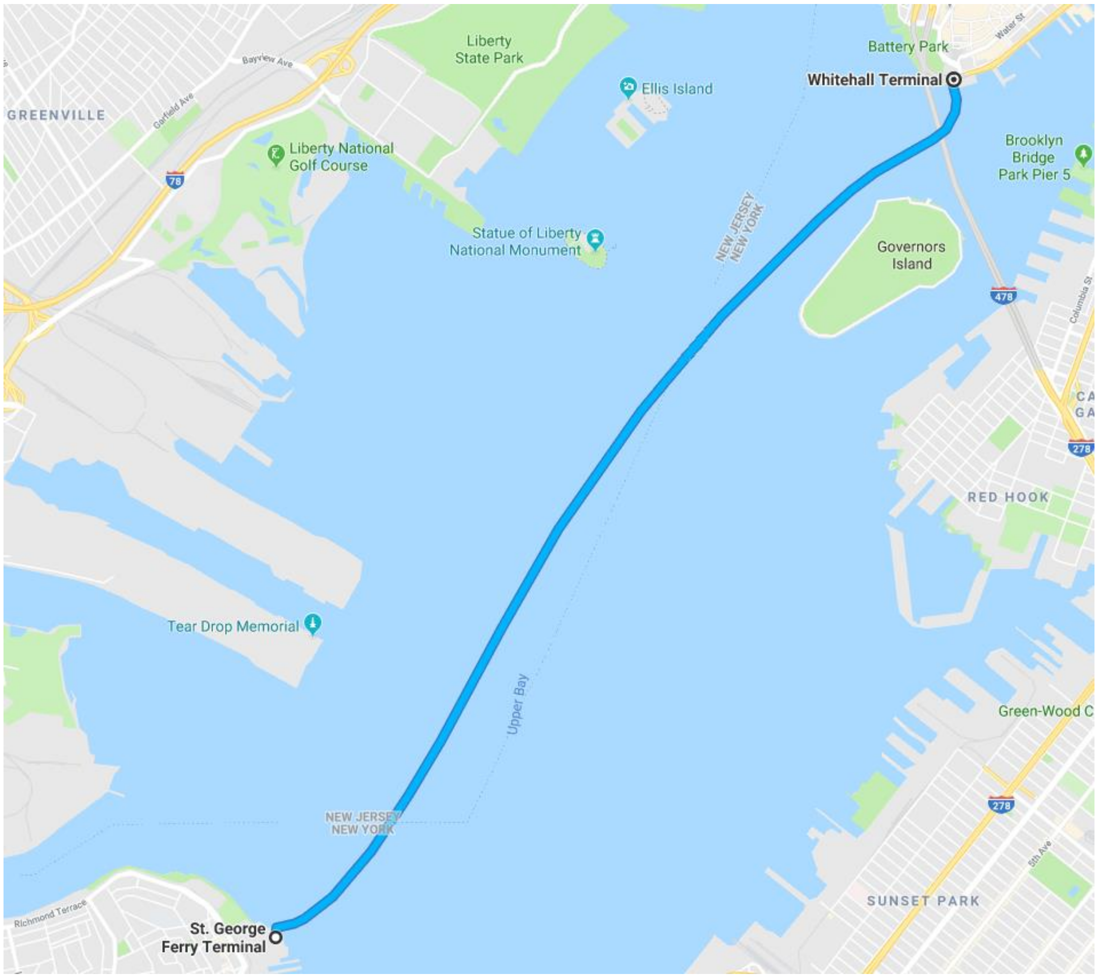


Figure 1 Staten Island Ferry Route (source: Google Maps)

3.1.2 Operational Overview

The Staten Island Ferry (SIF) service operates 24 hours per day, 365 days per year and transports over 24 million passengers annually. The fleet consists of eight vessels providing service between the St. George Terminal on Staten Island and the Whitehall Terminal in Lower Manhattan. The 5.2-mile voyage, shown in Figure 1, takes a total of 30 minutes, with 22 minutes of travel time and 8 minutes for loading/unloading.

Four of the six large ferries are required during peak commuting hours when vessels depart each terminal every 15-20 minutes. During off-peak times, vessels operate on a 30-minute schedule and two are required. Two large ferries run during the day and typically both small Austen class ferries run overnight. During a given day, six of the eight ferries are available to provide service while two undergo repairs, maintenance or inspections. Ferries are rotated in and out of service to meet usage demand and distribute operating hours among the fleet.

3.1.3 Terminal Descriptions

3.1.3.1 St. George Terminal

Located on the northeastern shore of Staten Island, the St. George terminal has served the ferry system since its construction in 1950. It was renovated in 2005 into the modern transportation hub that it is today. It has four bow loading slips used for normal ferry operations along with several mooring locations for vessel maintenance. The terminal serves SIF vessels exclusively.

Figure 2 St. George terminal, Staten Island (source: Google Earth)

3.1.3.2 Whitehall Terminal

Located on the southern shore of Manhattan, the Whitehall ferry terminal opened its doors in 2005, replacing the century-old terminal lost to a fire in 1991. It features three bow loading ferry slips and connection to prominent modes of transportation in lower Manhattan. Due to the short barrier noted in Figure 3, SIF does not use Slip 2 and Slip 3 concurrently. Docking capacity for two ferries is therefore available at any one time. The terminal serves SIF vessels exclusively.

Figure 3 Whitehall terminal, lower Manhattan (source: Google Earth)

3.1.4 Vessel Descriptions

The Staten Island Ferry fleet consists of four current vessel classes and two future classes. All vessels are U.S. Coast Guard (USCG) inspected and adhere to rules of the American Bureau of Shipping (ABS) for classification. The fleet composition is summarized in Table 3 and further described below.

Table 3 SIF fleet composition

Class	Passenger Capacity	Propulsion Drive Train	Vessel	Service Timeline	EPA Certification[1]
Kennedy	4,500	Diesel Electric (fixed-speed, segregated)	*John F. Kennedy*	1965 – 2021	[Tier 1] / [Tier 2]
Barberi	6,000	Diesel Mechanical (VSP[2])	*Andrew J. Barberi* *Samuel I. Newhouse*	1981 – 2022 1982 – 2030	[Tier 1] / [Tier 2]
Austen	1,280	Diesel Mechanical (VSP[2])	*Alice Austen* *John A. Noble*	1986 – 2030 1986 – 2031	[Tier 3]
Molinari	4,400	Diesel Electric (fixed speed, segregated)	*Guy V. Molinari* *John J. Marchi* *Spirit of America*	2004 – Future 2005 – Future 2005 – Future	Tier 2
Ollis	4,500	Diesel Mechanical (VSP[2])	*Michael H. Ollis* *Sandy Ground* *(Not yet named)*	2021 – Future 2022 – Future 2022 – Future	Tier 4
Future	3,000	(Not yet determined)	*(Not yet named)* *(Not yet named)*	2030 – Future 2031 – Future	Tier 4[3]

[1]Diesel engines on all existing vessels have been voluntarily fitted with upgrade kits to bring exhaust emissions below modern US EPA limits, equivalent emissions are noted with brackets [Tier 2]; [2]Voith-Schneider Propellers; [3]Or higher future requirement

3.1.4.1 Kennedy Class

The last remaining vessel in the Kennedy class is the M/V *John F. Kennedy*, which was delivered in 1965. It is the oldest vessel in the fleet and is scheduled for decommissioning by 2021 and will be replaced by a new Ollis class vessel. As such, it will not be evaluated in this study. The *Kennedy* is capable of carrying 4,500 passengers. The *Kennedy* has a segregated diesel electric propulsion system with dedicated propulsion and ship service diesel generators. Each of four propulsion diesel generators have been retrofitted to meet equivalent EPA Tier 1 standards for NO_x emissions and Tier 2 standards for PM emissions. The propulsion generators supply up to 7,000 hp to eight electric motors, four per end. At each end of the vessel, these four motors are mounted through a reduction gear which drives a fixed-pitch propeller. Ship service electrical power is provided by two smaller, dedicated diesel generator sets. All engines are fueled by ultra-low sulfur diesel (ULSD).

Figure 4 M/V *John F. Kennedy* (source: SIF)

3.1.4.2 Barberi Class

The Barberi class consists of the M/V *Andrew J. Barberi* and the M/V *Samuel I. Newhouse,* which were delivered in 1981 and 1982 respectively. As the second oldest vessel in the fleet, the *Barberi* is scheduled for decommissioning by 2022 and replacement by a new Ollis class vessel. After delivery of the third Ollis class vessel, the *Newhouse* may shift to reduced service as an auxiliary vessel for the foreseeable future. The Barberi class vessels are each capable of transporting 6,000 passengers. The Barberi class vessels have diesel mechanical propulsion and Voith-Schneider propellers. Each of four propulsion diesel engines have been retrofitted to meet equivalent EPA Tier 1 standards for NO_x emissions and Tier 2 standards for PM emissions. Combined the propulsion plant outputs up to 7,000 hp. Two of these engines are used at each end of the vessel to mechanically drive a single Voith-Schneider propeller through a combining gear. Ship service electrical power is provided by two small diesel generator sets. All engines are fueled by ULSD.

Figure 5 M/V *Andrew J. Barberi* (source: SIF)

3.1.4.3 Austen Class

The Austen class consists of the M/V *Alice Austen* and the M/V *John A. Noble*, which were delivered in 1986. These vessels, primarily used for night service, are considerably smaller than the other ferries, with a capacity of just 1,280 passengers. The Austen class vessels have diesel mechanical propulsion and Voith-Schneider propellers. The two propulsion diesel engines have been retrofitted to meet equivalent EPA Tier 3 standards using exhaust after treatment and provide a combined output of 3,100 hp. At each end, one engine mechanically drives a Voith-Schneider propeller. Ship service electrical power is provided by two small diesel generator sets. All engines are fueled by ULSD.

Figure 6 M/V *John A. Noble* (source: SIF)

3.1.4.4 Molinari class

The Molinari class consists of the M/V *Guy V. Molinari*, the M/V *John J. Marchi*, and the M/V *Spirit of America*, which were delivered between 2004 and 2005, making them the newest vessels currently serving in the fleet. They are each capable of carrying 4,400 passengers. The Molinari class vessels are segregated diesel electric with dedicated propulsion and ship service diesel generators. Each vessel is powered by three propulsion diesel generators supplying up to 10,800 hp to four electric propulsion motors. Each propulsion diesel generator has been retrofitted to meet equivalent EPA Tier 2 standards. At each end of the vessel, two propulsion motors are attached in series to a propulsion shaft which drives a fixed-pitch propeller. Under typical operation, only two propulsion generators are running, resulting in a combined operating power of 7,200 hp. Three small diesel generator sets provide ship service electricity, with two running whenever the ferry is in service. All engines are fueled by ULSD.

Figure 7 M/V *Guy V. Molinari* (source: SIF)

3.1.4.5 Ollis Class

The Ollis class is currently under construction, with three new vessels set to be delivered between 2021 and 2022. Each vessel is designed to carry 4,500 passengers. The Ollis class vessels will have diesel mechanical propulsion and Voith-Schneider propellers. Each Ollis class vessel will be powered by four EMD 12-710 propulsion diesel engines with a combined 9,980 hp. At each end of the vessel, two of these engines will mechanically drive a Voith-Schneider propeller through a combining gear. Ship service electrical power will be provided by two small diesel generator sets. All engines will be fueled by ULSD.

All diesel engines installed on Ollis class vessels will meet current EPA emissions limits, known as Tier 4. To meet these limits, diesel engines on the Ollis class vessels require an exhaust gas aftertreatment technology known as selective catalytic reduction (SCR). This technology uses diesel exhaust fluid (DEF) and a catalyst bed to reduce NO_x in the exhaust gas. EPA emissions regulations are explained in detail in Section 2.3.1.

Figure 8 Ollis class rendering (source: SIF)

3.2 New York City Ferry

3.2.1 History

New York City Ferry (NYCF) was started in 2017 as a means to provide transit access to under-served waterfront communities throughout New York City. It was designed to work alongside existing New York Waterway and New York Water Taxi services to provide commuters in waterfront communities another transportation option. The NYCF vessels are owned by the New York City Economic Development Corporation (NYC EDC) and operated by Hornblower Cruises and Events.

3.2.2 Operational Overview

The NYCF system currently has six routes connecting 21 terminals across the city of New York, and three additional routes are planned. The existing routes and terminals are shown below in Figure 9. Service is provided half-hourly or hourly on all routes. Ridership greatly exceeded the expected 4.6 million annually, spurring additional vessel orders and use of charter vessels during peak periods. NYCF has plans for three expansion routes by 2021 to serve St. George, Coney Island and Throgs Neck.

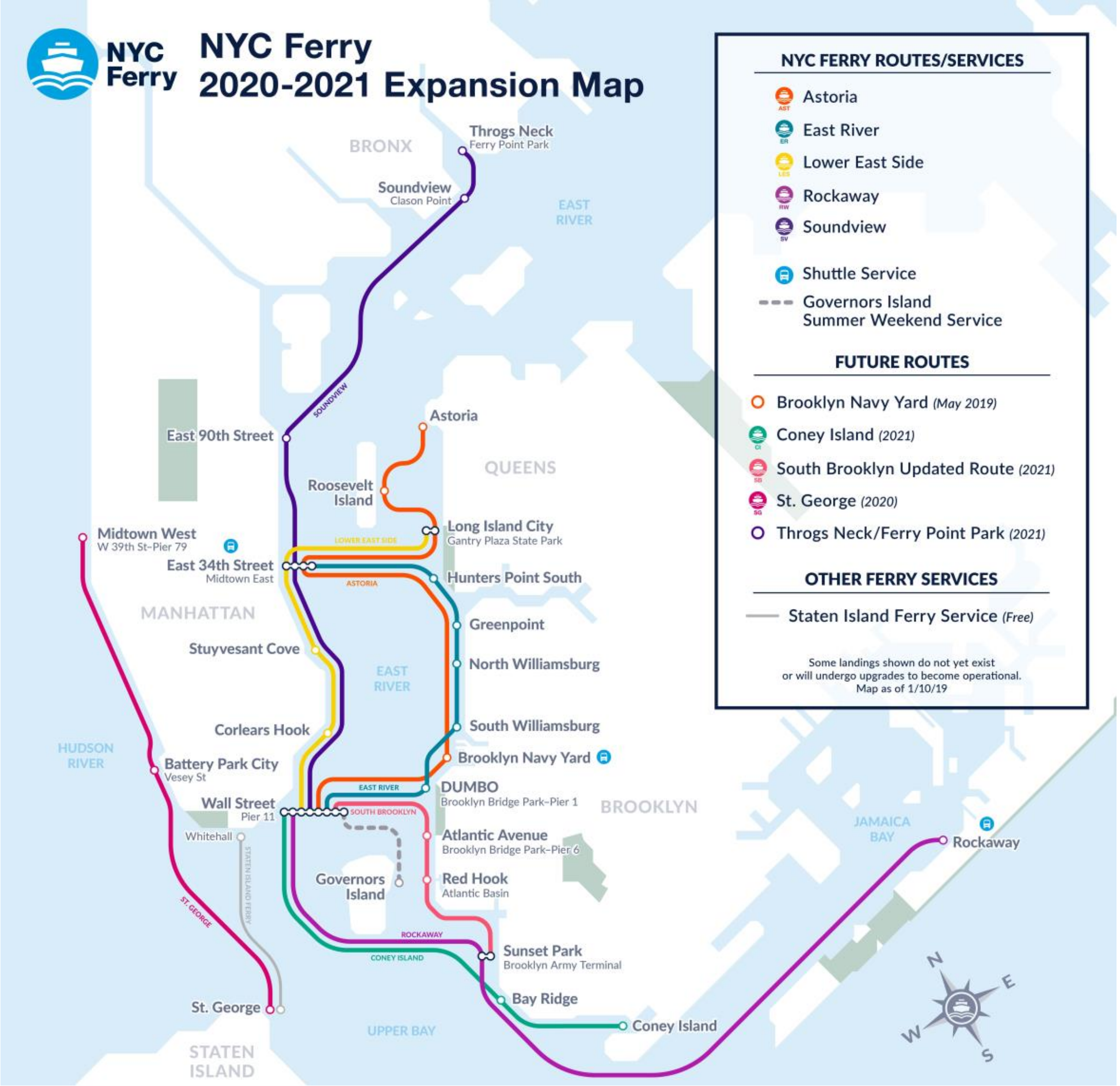


Figure 9 NYCF routes (source: www.ferry.nyc)

3.2.3 Terminal Descriptions

Most terminals in the system serve one or two NYCF routes. Wall Street and East 34th Street are the major destination hubs for the system, serving eight and four routes respectively. The typical ferry terminal, example shown in Figure 10, is a floating dock accessed from shore or another pier via a long gangway. All terminals except Wall Street are able to serve two bow loading vessels simultaneously. Pier 11 at Wall Street, shown in Figure 11, is shared with other ferry services and has ten berthing areas.

Figure 10 East 34th Street terminal (source: Google Earth)

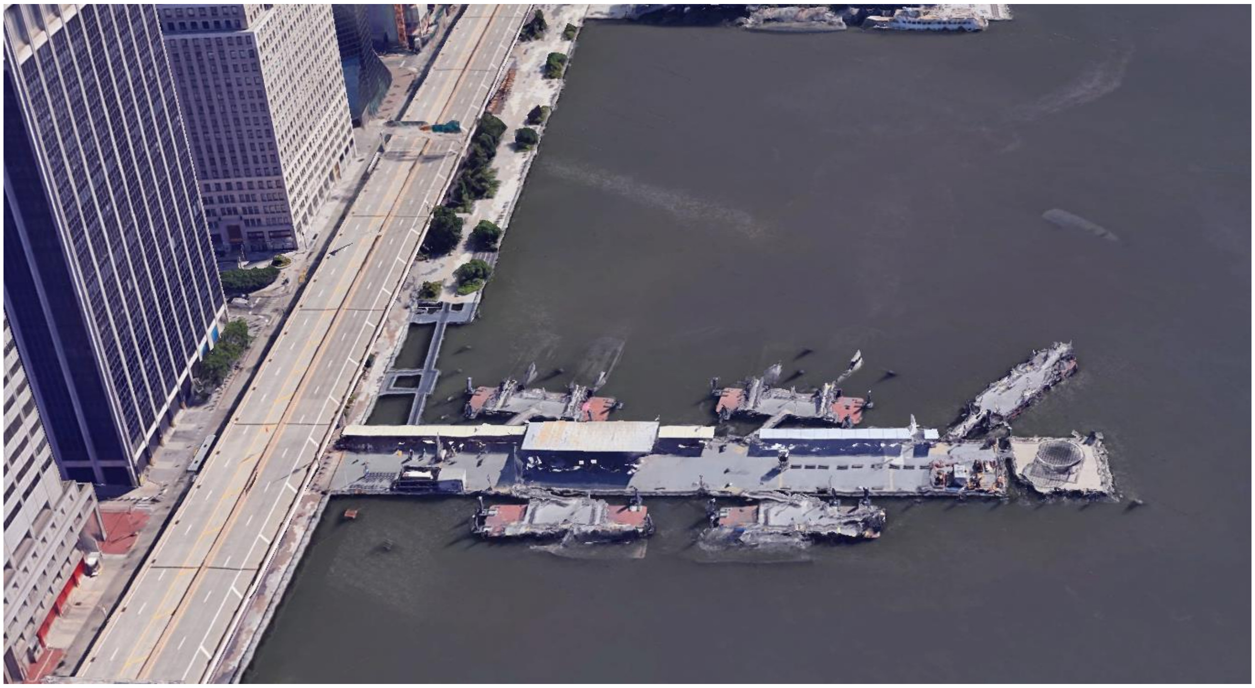


Figure 11 Pier 11 at Wall Street, lower Manhattan (source: Google Earth)

3.2.4 Vessel Descriptions

The New York City Ferry fleet consists of three classes of vessels, all of which are U.S. Coast Guard (USCG) inspected. The fleet composition is summarized in Table 4 and further described below.

Table 4 NYCF vessel description

Class	Passenger Capacity	Length (m)	Beam (m)	Installed Power Capacity (hp)	Operating Speed (knots)	EPA Tier
150 River	149	26	8	1606	25	3
150 Rockaway	149	26	8	2760	25	3
350 Rockaway	354	29.6	8.5	2760	24	3

Regardless of class, each vessel has two Baudouin engines that each independently drive a fixed-pitch propeller through a gearbox. Two small diesel generator sets provide ship service electricity. All engines are fueled by ULSD.

The NYCF fleet is largely new, with most of the vessels constructed in the last three years. NYCF vessels' onboard technology is correspondingly new, with EPA Tier 3 engines and modern low-friction hull coatings.

As the ferry service has established itself in the City, it has seen a surge in ridership. To respond to the higher than anticipated demand, NYCF is expanding its fleet with additional 150- and 350-passenger vessels.

Figure 12 150-passenger River class vessel M/V *Lunch Box* (source: NYC Ferry)

Section 4 Baseline Fleet Performance

4.1 Summary

This section evaluates the baseline performance of each fleet and subsequent vessel class, providing a comparative basis for the fuel costs and emissions impacts of the alternative fuels and propulsion technologies introduced in Section 5. The baseline evaluation includes the current annual fuel consumption and emissions profile for each class and the fleetwide totals over a 20-year period, summarized in Table 5 and Table 6, respectively. Fleetwide totals given in Table 6 consider the changing fleet composition during this time period. Section 4.3 describes analysis methods and presents the baseline performance of each fleet in detail.

All vessels in the SIF and NYCF fleets meet or exceed current EPA exhaust emission regulations. EPA requirements for a specific vessel are based on the build date and become steadily more stringent as build dates approach the present. In SIF's case, significant reductions (above what is required) in exhaust emissions have been achieved through voluntary engine and exhaust system modifications.

Table 5 Individual baseline performance per one-way trip for SIF fleet

Class	Fuel (gal)	NO_x (kg)	PM (kg)	CO (kg)	HC (kg)	CO_2 (kg)
Barberi[2]	113	14.5	0.39	1.2	0.33	1165
Molinari	109	10.8	0.25	1.6	1.08	1130
Ollis	114	2.3	0.04	0.6	0.08	1180
Austen	45	5.0	0.06	0.5	0.53	470
Future[3]	48	1.2	0.02	1.2	0.32	495

[1] *John F. Kennedy* was not considered in the SIF baseline.
[2] Barberi vessels will be replaced by Ollis vessels beginning in 2021, see Table 3.
[3] Austen class vessels will be replaced by Future Midsize vessels beginning in 2030, see Table 3.

Table 6 Individual baseline performance per round trip for NYCF fleet

Route	Fuel (gal)	NO_x (kg)	PM (kg)	CO (kg)	HC (kg)	CO_2 (kg)
East River - Weekday	36	3.2	0.1	0.5	0.1	385
East River - Weekend	52	4.3	0.1	0.7	0.2	555
Rockaway	115	8.8	0.2	1.4	0.2	1255
South Brooklyn - Weekday	37	3.2	0.1	0.5	0.1	395
South Brooklyn Weekend - Governor's Island	47	3.9	0.1	0.6	0.1	505
Astoria – Weekday	38	3.3	0.1	0.5	0.1	450
Astoria – Weekend	38	3.3	0.1	0.5	0.1	450
Soundview – Weekday	63	4.7	0.1	0.7	0.1	690
Soundview – Weekend	63	4.7	0.1	0.7	0.1	690
Lower East Side – Weekday	29	2.6	0.1	0.4	0.1	335
Lower East Side - Weekend	31	2.8	0.1	0.4	0.1	345

Route	Fuel (gal)	NO_x (kg)	PM (kg)	CO (kg)	HC (kg)	CO_2 (kg)
Future Routes						
St Georges	44	3.8	0.1	0.6	0.1	385
Coney Island	36	3.1	0.1	0.5	0.1	380

Table 7 Total 20-year baseline performance for SIF and NYCF fleets

Fleet	Round Trips	Fuel (gal)	CO_2 (MT)	NO_x (MT)	PM (MT)	HC (MT)
SIF	8200	82M	850K	5,300	110	470
NYCF	N/A	65M	657K	4977K	113	104

4.2 Compression Ignition Engines

4.2.1 Background

The SIF and NYCF fleets utilize a variety of propulsion system technologies. These technologies, described in more detail below, center around the use of compression ignition engines (diesel engines) burning ultra-low sulfur diesel (ULSD) fuel. All the City's ferries use either:

1. Medium-speed diesel-driven mechanical propulsion with controllable pitch propellers (Voith Schneider) (SIF),
2. Diesel electric propulsion with fixed-pitch propellers (SIF), or
3. High-speed diesel-driven mechanical propulsion with fixed-pitch propellers (NYCF).

All ship service electrical power on SIF and NYCF ferries is developed using high speed diesel engine-driven generators burning ULSD.

4.2.2 Engine Performance Metrics

4.2.2.1 Specific Fuel Consumption

Specific fuel consumption (SFC) is a performance metric associated with diesel engine fuel efficiency across engine loading conditions. SFC is often measured in terms of grams of fuel burned per kilowatt-hour of power produced (g/kWh). Whereas an engine producing more energy will always consume more fuel, the fuel consumed per unit of energy will vary with engine loading. SFC is usually lower at higher power, as shown in Figure 13. Accordingly, ship operations at lower engine loading carry a fuel consumption penalty and have the potential to be optimized using certain alternative propulsion technologies. For ferry operations, the time spent pushing against the dock during loading and unloading is spent with the engines very lightly loaded. Additionally, depending on how the size of the engines compares to the power needed to achieve transit speeds, there may be potential savings during transit. For example, the Molinari class Staten Island Ferries typically transit with the engines at approximately 60% load. The SFC at this operating point is 213 g/kwh, 7% higher than the fuel consumption at the engine's most efficient loading. In theory, if the Molinari class ferries could consume all fuel at optimum loading, this would translate to a 15% fuel savings, or 80,000 gallons per ship per year with corresponding reductions in fuel cost and CO_2 emissions. Realizing all this potential savings is not feasible, but several of the options in this report realize some of the savings by shifting operations from the baseline to a better point on the SFC curve.

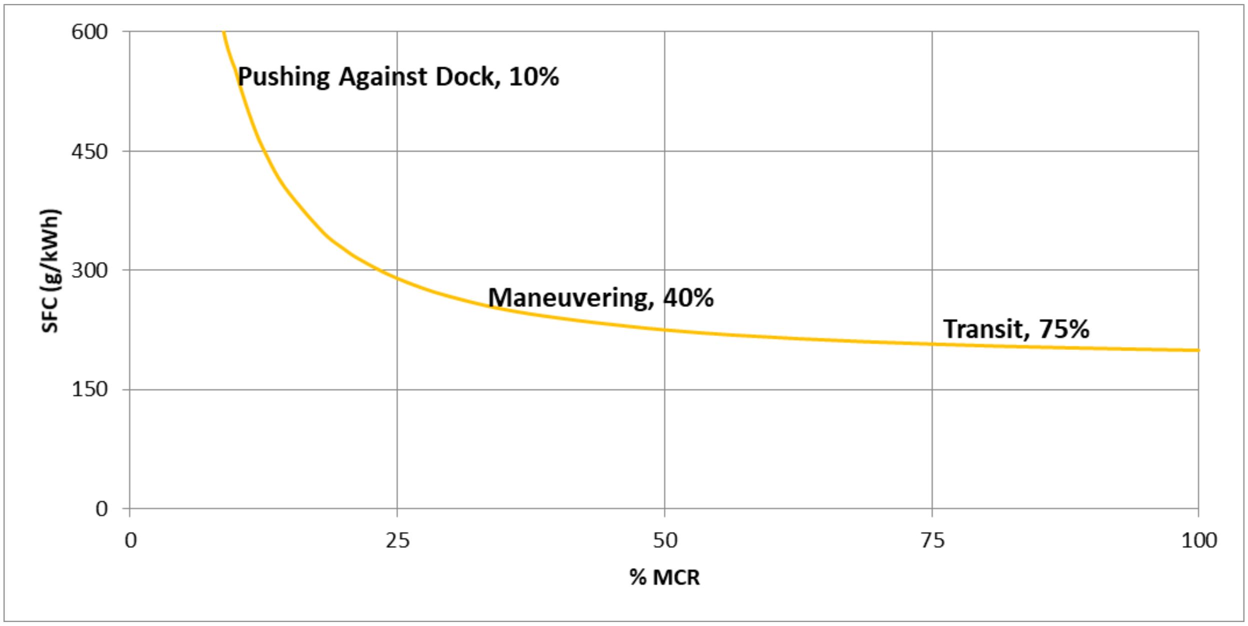


Figure 13 Typical diesel engine specific fuel consumption curve showing reduced engine efficiency at low load

4.2.2.2 Brake Specific Emissions Factors

Engine emissions factors also vary with load. Section 2.3.1 discussed the EPA emissions limits and weighting factors used during engine testing. Like fuel consumption, emission rates per kilowatt-hour of power produced (brake-specific emissions factors or BSEF) generally increase at low engine load. This can partly be attributed to increased fuel consumption but changing combustion conditions such as cylinder temperature and air concentration also play a significant role in emissions rates. Representative curves are shown in Figure 14. Since manufacturer's data sheets generally do not include BSEF data below 25% load, this study uses values estimated based on the shape of the curves. Further detail on the determination of BSEF values can be found in Appendix A.2.

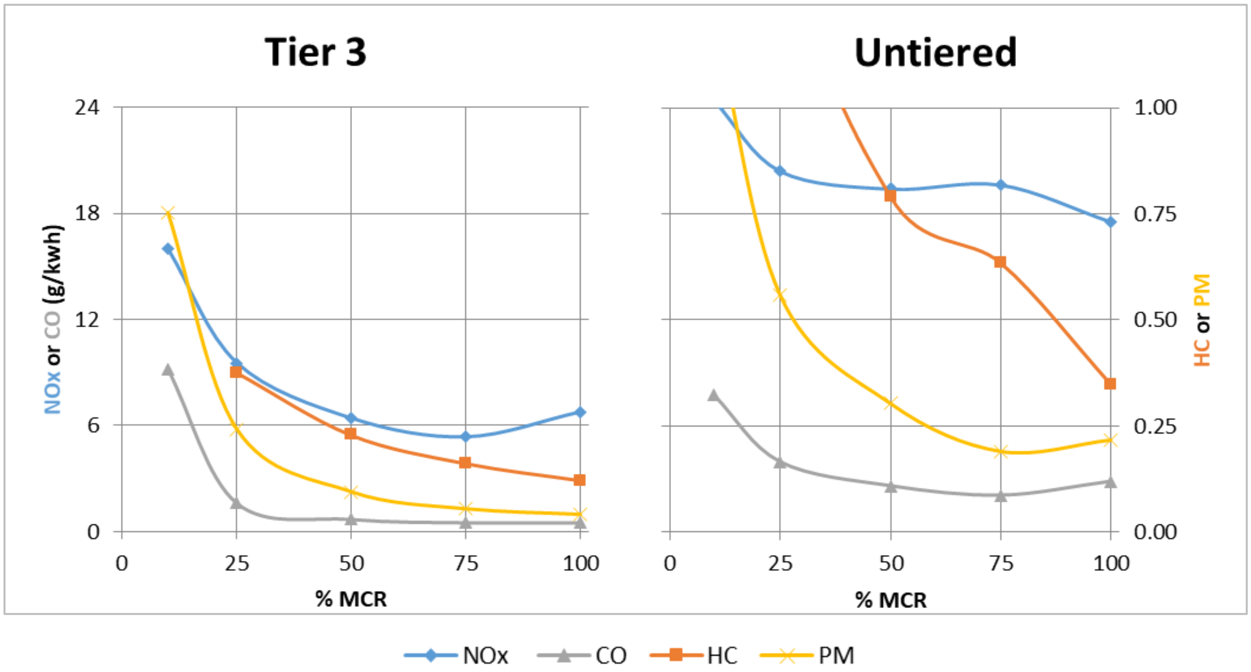


Figure 14 Brake specific emissions factors for two diesel engines (same model, different years)

4.2.3 Emissions Control

Emissions from diesel engines are addressed using one or more technologies, depending on the age of the engine and the tier of emissions standards targeted. Combustion conditions factor significantly in the formation of NO_x and PM; some changes to emissions profiles can be achieved through changes to engine controls to optimize cylinder conditions for minimum emissions. This might come at the expense of fuel efficiency (and therefore CO_2 production). Equipment can also be added to the exhaust system to clean up combustion byproducts. This equipment includes diesel particulate filters (DPF's), which mechanically remove particulate matter from the exhaust, and selective catalytic reduction systems (SCR's), which actively remove NO_x by reaction with an ammonia solution called urea that is injected into the exhaust. Compared to other technologies, SCR's require significantly more vessel modification because they are large and require storage and handling systems for the urea solution and integration with the engine control system. Diesel oxidation catalysts (DOC's), which passively oxidize NO to NO_2, are also used to support the performance of other systems such as DPF's and SCR's that require certain ratios of exhaust products to operate effectively.

In general, available manufacturer's information only addresses upgrades that achieve certified compliance with an EPA tier level. For SIF's untiered engines, voluntary upgrades would not need to be certified at an improved tier. Some improvements to criteria emissions might be possible using non-certified changes or by adding additional aftertreatment devices that achieve "equivalent tier" emissions. The existing upgrades to the Kennedy, Barberi, and Austen class ferries were achieved in this manner. Pursuing such upgrades would require a concerted research and engineering effort by the City – manufacturers have little incentive to design non-certified aftertreatment options, especially for older model engines, where an engine upgrade would provide the greatest emissions benefit.

As discussed in Section 2.3.1, current environmental regulations applicable to all ships in the City's ferry fleet require using diesel fuel with a maximum sulfur content of 15 ppm, resulting in low SO_x emissions. Emission levels of other pollutants for the existing fleet vary based on year of construction and exhaust treatment technologies utilized. Even the worst emission performers, the *Kennedy* and *Barberi*, have been retrofitted to EPA Tier 1. The newer Austen class SIF and NYCF ferries are certified to EPA Tier 3. The Ollis class and any future NYCF expansion vessels will meet EPA Tier 4.

4.2.4 Ultra-low sulfur diesel (USLD)

4.2.4.1 Background

Diesel fuel is the standard against which other fuel options are evaluated. ULSD is in widespread use in the marine industry, which gives it several advantages. Of the fuels and propulsion technologies in this report, the ULSD powered diesel engine is easily the most mature. Both manufacturers and operators have extensive experience with the diesel supply chain, and operational and maintenance considerations for diesel engines are well understood. Although all fuels must meet sulfur requirements, in this report, ULSD refers to diesel produced from traditional petroleum-based sources. The ULSD supplied to ships is typically grade #2 per ASTM D975 (*Standard Specification for Diesel Fuel Oils*, reference 85). It is common practice to mix some #1 ULSD during cold weather, creating a “winterized” diesel fuel.

4.2.4.2 Operational Considerations

Both SIF and NYCF have well established ULSD refueling routines. Ship and shore personnel are well-versed in the bunkering process (the process of transferring fuel to the ship). It is straightforward to receive small or large quantities of ULSD as operational requirements dictate. The capacity of existing diesel storage tanks along with diesel's excellent energy density results in comfortable operating margins with large fuel reserves easily achievable.

Diesel has several uses on board the ferries that would make it difficult to replace completely. In addition to providing fuel for propulsion and electrical generator engines, most SIF vessels also burn diesel in boilers to provide steam for heating. Diesel fuel is also used for routine maintenance items such as cleaning lubricating oil purifier bowls. Finally, some alternative fuel technologies are available in the power range needed to replace the main propulsion engines, but not the ship service generator engines. Diesel fuel would still be required in this case for shipboard electrical power generation.

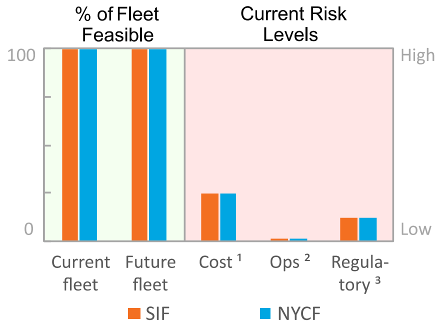
One difference in ULSD's properties compared to other marine fuels is reduced lubricity, in part because the refinery process for desulfurization removes some compounds that contribute to lubricity. Lubricity is a measure of how well the fuel lubricates moving engine fuel system components. Low lubricity can lead to increased wear on components in the fuel system such as fuel pumps, fuel injectors, and valves. ASTM D975 governs ULSD and includes a minimum lubricity requirement. The lubricity of commercially available ULSD is therefore not a concern for engine manufacturers, as current engine designs and maintenance practices are based on these fuel properties. However, some sources suggest that maintenance intervals could be extended if an alternate fuel with more lubricity was used.

ULSD at a Glance

Baseline option, fuel and emissions improvements sought

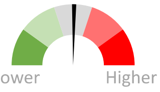
- Standard & proven marine fuel, but:
- Can emissions be improved?
- Can costs be reduced?

Recommendation

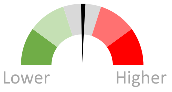


[1] Cost rises high and unpredictable
[2] Minimal operational risk
[3] Future carbon tax possible

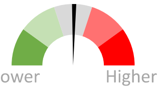
Feasibility and Risk Areas



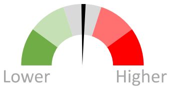
Capital Cost



Criteria Emissions



Fuel Cost



CO2e Emissions

4.2.4.3 Cost

Prices for ULSD are volatile, tracking with broader trends in the worldwide oil market. ULSD contracts are negotiated by the NYC Department of Citywide Administrative Services for delivery by bunker barge directly to the ferry piers. As of November 2018, NYC DOT's rate for ULSD is approximately $2.40/gal. Fuel costs for the NYCF are negotiated separately. Although there may be small differences from the government price, the general trends will be similar, especially over the 20-year time frame used for analysis in this study.

4.2.5 Diesel-Mechanical Propulsion

The baseline propulsion technology for the SIF Barberi, Austen, and Ollis class ferries is diesel mechanical with controllable pitch Voith Schneider propellers (VSP's). One diesel engine (Austen class) or two diesel engines (Barberi and Ollis class) are connected to a single VSP at each end of the ferry. All main engines are running whenever the ferry is in service. The propulsion load is split relatively evenly between the bow and stern VSP's when the vessel is underway. All three SIF classes with diesel mechanical propulsion have two small ship service diesel generators. One ship service diesel generator is running whenever the ferry is in service.

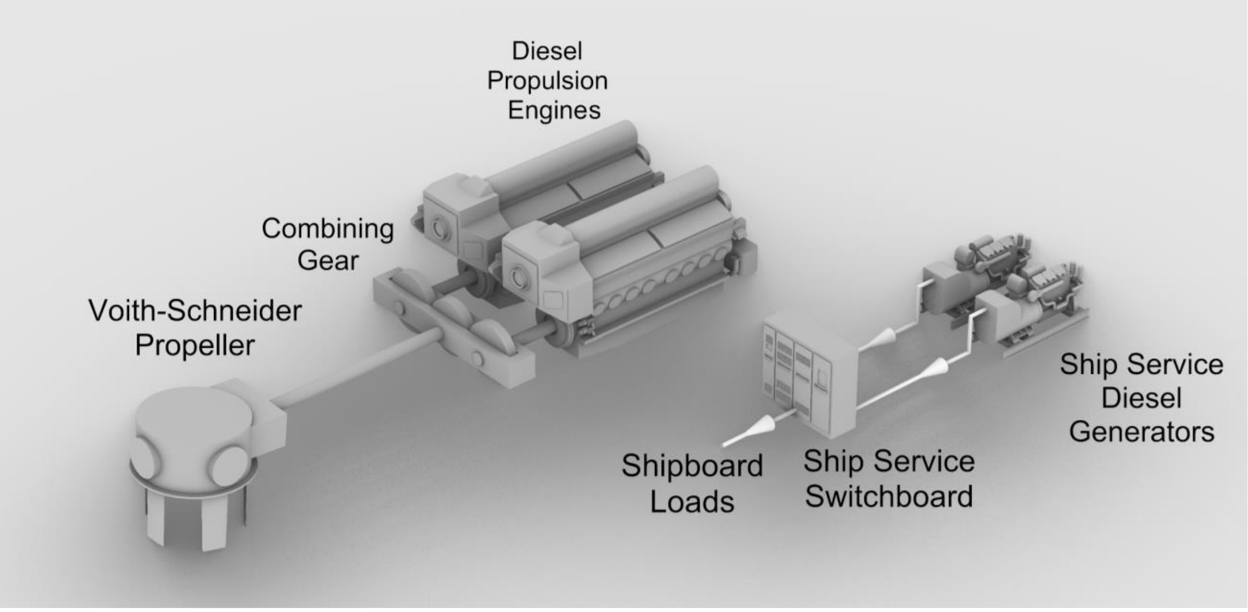


Figure 15 Diesel mechanical propulsion plant with Voith-Schneider propeller as used on Ollis class; Barberi and Austen plants similar

The baseline propulsion technology for all NYCF classes is diesel mechanical with fixed-pitch propellers. One diesel engine is connected via a reduction gear to a single propeller in each hull of the catamaran ferries. Both engines and propellers are running whenever the ferry is in service. All three NYCF classes of ferries have two small ship service diesel generators. One ship service diesel generator is running whenever the ferry is in service.

Advantages of diesel mechanical propulsion over other propulsion system configurations include:

- High propulsion transmission efficiency from the engine output to the propeller input
- Vessel range
- Variable engine speed to match engine load resulting in improved low load efficiency

Disadvantages of diesel mechanical propulsion relative to other propulsion system configurations include:

- The need to power ship service electrical loads with separate diesel generators
- Inability to readily use alternate energy storage systems
- Lack of redundancy for primary power generation components

4.2.6 Diesel-Electric Propulsion

The baseline propulsion technology for the Molinari and Kennedy classes is a constant-speed diesel-electric plant with segregated propulsion and ship service power systems (a segregated system is also referred to as “split bus”). The Molinari class has three propulsion diesel generators (EMD 16-710) operating at 900 rpm and two ship service diesel generators (CAT 3408) operating at 1800 rpm synchronous speed to produce 60 Hz frequency for each power system. The propulsion generating plant provides electric power to two variable speed propulsion motors (per end) that drive a fixed-pitch propeller. Two propulsion diesel generators and one ship service diesel generator are normally running.

The Molinari class carries an additional temporary generator. This allows one generator to be out of service for maintenance. Without the temporary generator, USCG redundancy rules preclude operating with one genset out of service. SIF has conducted some feasibility and design work to install a 3rd permanent generator. Some of the options in this study provide an alternative means to accomplish the goals of a 3rd genset upgrade.

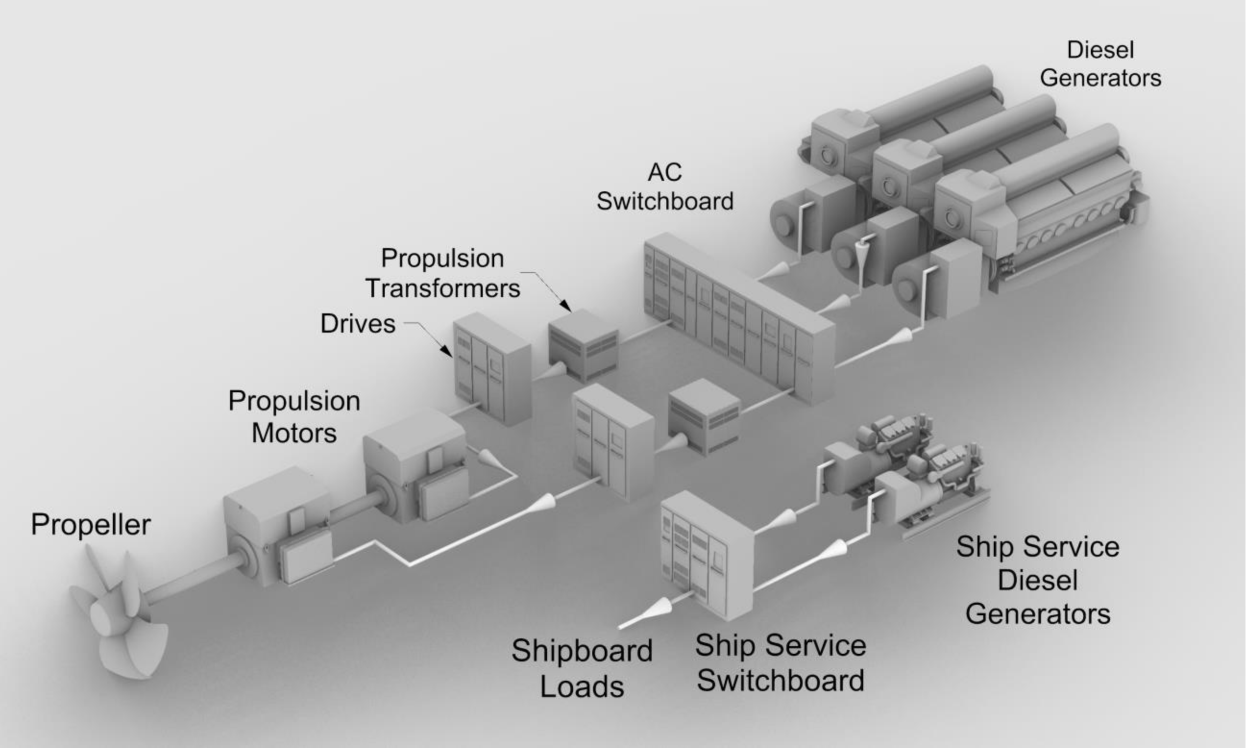


Figure 16 Segregated ship’s service/propulsion diesel electric plant as used on the Molinari class (Kennedy similar); propulsion transformers to propeller shown for one end

Synchronous generators cannot vary their speed to match power demand like propulsion engines. A typical fixed-speed generator operates at peak efficiency above 80% load, and the efficiency quickly decreases as the load falls below 50%. The resulting high mechanical losses when operating at low power levels result in lower efficiency and higher wear compared to engines in mechanical propulsion systems.

The SIF diesel-electric plants have several advantages relative to other propulsion system configurations, including:

- Higher reliability and operational flexibility through engine/generator redundancy

- Higher arrangement flexibility as engine location is not limited by the propulsion shaft line
- Lower noise and vibrations than mechanical drive systems
- Higher torque at low propulsion power levels

The SIF diesel-electric plants also have several disadvantages relative to other propulsion system configurations, including:

- Lower efficiency because split bus operation requires ship service diesel generators
- Inability to readily use alternate energy storage systems
- Poor part load efficiency due to constant speed of diesel generators (to maintain 60 Hz power)
- Propulsion system weight
- Propulsion system space requirements

4.3 Current Emissions Profiles and Fuel Usage

4.3.1 SIF

4.3.1.1 Methodology

Fuel Consumption per Trip

Each trip of the Staten Island ferries can be broken down into 6 parts: departing the slip, accelerating to transit speed, transiting, slowing, maneuvering to enter the slip, and pushing against the dock during loading and unloading. To model energy consumption for current and alternative technologies, the trip was simplified into three phases: maneuvering, transiting, and pushing. Based on observed trips documented in reference 81, each trip is divided into 3-4 minutes of maneuvering, 18-19 minutes of transit, and 8 minutes of pushing time at the dock. Average power levels while maneuvering ranged from 15-30% depending on the ship class. Transit power is approximately 70%. During loading and unloading, the Captain pushes against the dock at approximately 10% power to prevent the ferry from drifting away from the dock.

SFC at each power level was derived from engine manufacturer data sheets. Additional data on Molinari class SFC was available from past work performed for DOT (Reference 65) and was used to supplement and validate the manufacturer’s curves. Multiplying SFC, power level, and time for each phase of the ship yields fuel consumption, as shown in Table 8 for a typical Molinari class one-way trip.

Table 8 Molinari class baseline fuel consumption, typical one-way trip

Phase	Power (kw)	SFC (g/kWh)	Time (min)	Fuel (gal)
Transit	3640	213	19	80
Maneuvering	1943	254	3	8
Pushing Dock	729	447	8	14
Ship Service Diesel Generators	170	269	30	8
			Total Fuel	109

Model Validation

Fuel usage predicted by this approach was validated through comparison to historical fuel consumption records. Weekly fuel usage calculated from the trips alone is approximately 15% lower than the historical average. Schedule information (Reference 86) indicates that each ship spends an average of 1.5 hours/day on "layover" without tying up. Accounting for this time spent pushing the dock, generator operations, and assuming 100 gallons per day for miscellaneous uses like operating the boilers gives a weekly total within 5% of historical average use.

Separately, fuel data collected from the *Marchi* during a past study (Reference 65) was reviewed. Fuel usage was measured with fuel flowmeters over the course of several days of operation. The average fuel usage per one-way trip measured with flowmeters agrees within 3 gallons of the fuel usage predicted by the operating profile and SFC curves described above.

Emissions Per Trip

Emissions factors for NOx, PM, HC, and CO were estimated using a fit curve, as with fuel consumption. Values from this curve were utilized with EPA calculation methods to verify that the average engine emissions were consistent with the manufacturer's data sheets or applicable EPA tier limit. Further details on this derivation can be found in Appendix A.2. CO_2 and SO_2 emissions were estimated based on the chemical composition of ULSD and mass of fuel burned. NOx, PM, and CO_2 emissions for the typical Molinari class one-way trip are given in Table 9. HC, CO, and SO_2 emissions were determined in a similar manner.

Table 9 Selected Molinari class baseline emissions, typical one-way trip

Phase	BSEF (g/kwh)		Actual Emissions (kg)		CO_2 Rate	Actual CO_2
	NOx	PM	NOx	PM		(kg)
Transit	5.9	0.2	7.0	0.18	3.206 (kg CO_2 per kg diesel)	821
Maneuvering	7.9	0.2	0.8	0.02		82
Pushing Dock	10.7	0.3	1.1	0.03		145
SSDG's	20.2	0.2	1.9	0.02		80
	Totals		10.8	0.2		1,128

Trips per week and per year

The weekly ferry schedule requires 592 daytime trips by the large ferries and 190 nighttime trips by the small ferries. Normal operations at SIF utilize four large ferries for daytime service. Executing the weekly schedule requires each large ferry to make an average of 21.1 trips per day. The nighttime trips are split equally between the small ferries. Over the course of the year, each individual ferry will periodically be out of service for inspections or preventative and corrective maintenance. Although on some days SIF may utilize five large ferries or cover nighttime service with a large ferry, a consistent schedule has been assumed in this analysis for simplicity.

It was assumed that each large ferry is out of service equally, resulting in each running an equal number of trips throughout the year.

Planned Changes to Fleet Composition

Three new Ollis class ferries will enter into service in the next few years. The first two will replace the *Kennedy* and *Barberi*. This will represent a significant upgrade in NOx and PM emissions performance, as the Ollis class main propulsion engines will be certified to EPA Tier 4, replacing the mixed Tier 1 and 2 engines currently in service. Based on discussions with SIF, the Barberi class ferry *Frank Newhouse* will remain in service when the third Ollis class ferry is commissioned. The *Newhouse* will provide added operational flexibility when needed but is assumed to only run half as many trips as the other six ferries (three Molinari and three Ollis).

The Austen class are the next ferries scheduled for replacement, starting in approximately 2030. Design of this class of replacement ferries has not begun. Based on discussions with SIF management, the replacement ferries may be larger than the existing Austen class. This would allow those ships to supplement daytime service as required while still minimizing fuel used in nighttime service. For the purposes of this study, these vessels are assumed to have the relevant particulars given in Table 10 and will be assumed to replace the Austen class and be used only for nighttime service. Although alternative options for future ferries are discussed in Section 7, the midsize ferries are assumed to be diesel-powered in the baseline case to establish a "business as usual" reference case for comparing options in this report.

Table 10 Particulars for SIF "Future Midsize" ferries

Displacement (LT)	1300
Draft (ft)	10.4
Length (ft)	260
Beam (ft)	53
Transit Speed (kts)	15.5
Brake Horsepower at Transit Speed	3100

Propulsion: (2) EMD 8-710 diesel engines, rated for 900 rpm/2000 hp, driving (2) VSP's

The assumed fleet composition over time is summarized in Table 11. Year-by-year details can be found in Appendix A.1. Note that this composition is common to the baseline profile and all options evaluated in this report.

Table 11 SIF Fleet composition over time

Year	Fleet Composition
2020	F/B *Kennedy*, (2) Barberi class, (3) Molinari class, (2) Austen class
2025	F/B *Newhouse*[1], (3) Molinari class, (3) Ollis class, (2) Austen class
2035	(3) Molinari class, (3) Ollis class, (3) Future midsize class

[1] F/B Newhouse utilized half as much as the other 6 large ferries

Costs

Options evaluated quantitatively in this report are compared to the baseline case using a net present value Lifecycle Cost Analysis (LCCA), modified from the NIST Lifecycle Cost Handbook (Reference 87). To simplify the analysis, costs are only included where they vary between options and a basis is available to estimate a difference. Some examples of included and excluded costs are given in Table 12.

Table 12 Examples of costs included and excluded from LCCA

Cost	Included?	Reason
Propulsion Fuel	Yes	Key difference for some options, estimated using input from industry experts and government reports
Boiler Fuel	No	No options make changes to boilers
Hull Paint	Yes	Required to evaluate cost effectiveness of advanced hull coatings
Drydocking Fees	No	No options change the frequency of drydocking
Routine Maintenance (non-overhaul)	No	Although some options (e.g. gas engines or biodiesel) might have different maintenance periodicities and costs, insufficient data was available to estimate these differences

Changes to fuel and electrical energy costs over time were estimated using the 2019 Annual Energy Outlook (AEO) published by the US Energy Information Administration (EIA), Reference 88. Cost factors were based on the reference case using prices for the Middle Atlantic region (region 1-2). Sensitivity analyses using alternative price projections from the AEO, including the "high oil price" and "low oil price" cases are used where appropriate, with results discussed in Section 6. It is notable that the AEO does not include separate projections for biofuels. The price projections for biofuels in this report are based on fixed offsets from diesel. If a carbon tax such as that described in 2.4 were implemented, the market value of low-carbon biofuels would increase accordingly and drive prices up. No fuel price forecasts were available to evaluate these effects.[1]

4.3.1.2 SIF Baseline Performance

The baseline performance of the SIF fleet using the above methodology is summarized in Table 13.

Table 13 20-year performance of baseline SIF fleet

Net Present Value Cost, diesel gallons consumed and Metric Tons emitted, 2020-2040							
	Cost	Fuel	CO_2	NOx	HC	PM	CO
SIF Baseline	$240M	83M gal	859,000	6100	710	180	2610

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[1] The 2017 AEO had two side cases that included a carbon tax. These cases were used for more in-depth analysis of future nuclear power plant construction possibilities. The tax was only applicable to utility scale electrical power generation and the main result was to change the mix of fuels used in electrical power generation. These cases did not result in any fuel price forecasts that provide meaningful insight for this study. See Reference 70.

4.3.2 New York City Ferries

4.3.2.1 Methodology

The New York City Ferries operate on a constrained schedule, ferrying passengers from as far north as Soundview, down through the East River, and out east to Rockaway. These ferries make many stops, with central hubs at Wall Street, Pier 11 and East 34th Street. The ferries' demanding schedules have them in transit, typically, for 50% or more of their operational day. The ferries' short loading and unloading times are punctuated by quick, high-powered transits between docking jetties.

A baseline fuel consumption and emissions profile was developed to compare propulsion alternatives. This study builds an operational profile for each ferry, on each existing route, using the daily transit, dwell, layover, and deadheading times listed in the NYCF schedules (Reference 80). The route-specific arrival and departure times are used to determine the vessels' time between stops and required transit speed to maintain the schedule. A vessel resistance curve was developed to determine the propulsion power required to achieve the speed necessary on each route leg. This was estimated by scaling a similarly sized and shaped catamaran, whose principal characteristics are known, and whose sea trial data is available. This analysis is available in Appendix B.

Once the power requirements of the leg are compared with the schedule, one can determine the energy (kWhr) required for the daily operation of each vessel. Using the emissions criteria discussed in Table 16, and scaled based on engine load, the vessel emissions can be determined throughout each leg of its roundtrip sailing. Completing this for each leg of each route provides a fleet-wide depiction of the NYCF annual fuel consumption and emissions profile.

Table 14 Ferry transit and pushing times

Ferry Route	Number of Stops per Round Trip [from schedule]	Total Time Pushing [minutes/round trip]	Total Time Transit [minutes/round trip]
East River - Weekday	12	49	50
East River - Weekend	14	66	49
Rockaway - Weekday	4	23	97
South Brooklyn - Weekday	10	31	59
South Brooklyn Weekend - Governor's Island	12	37	63
Astoria - Weekday	8	31	55
Astoria - Weekend	8	31	55
Soundview - Weekday	6	24	76
Soundview - Weekend	6	24	76
Lower East Side - Weekday	8	26	49
Lower East Side - Weekend	8	31	49

Throughout this analysis, it was assumed that the larger 350-passenger ferries service only the Rockaway route, while the smaller 150-passenger ferries service all other routes. The NYCF operating schedule is somewhat fluid, however, with larger vessels supplementing busy routes as required. This is typically seen on the Soundview and Astoria routes. By 2022, there will be larger vessels on the East River route following terminal upgrades. This is an important operational consideration, and any propulsion upgrades must maintain this redundancy in vessel ability.

Each ferry route is divided by legs, and the number of legs in a roundtrip varies depending on the ferry route. These are listed in the first column of Table 14.

Each vessel goes through a sequence of four distinct steps each time it arrives and departs a stop. The breakdown of this sequence is described in Table 15. Power requirements at each stage of this sequence are assumed to build a round-trip operational profile of each vessel. This breakdown is based on typical requirements seen on ferries in similar service, and through onboard observation during a December 2018 shipcheck (See Reference 81).

Table 15 Leg sequence power and time assumptions

Stage	Assumed % Installed HP	Assumed Time [seconds]
Pushing the Dock	20%	route dependent
Departure Maneuvering and Handling	60%	30
Full Speed Transit	route dependent	route dependent
Deceleration for Docking	40%	30
Layover (Pushing the Dock)	20%	route & vessel dependent
Deadheading	40%	route & vessel dependent

In addition to typical operational profiles, the NYCF vessels have two more operating modes described on their schedule: *layover* and *deadheading*. Layover is a longer than normal time period the vessel spends pushing the dock at either end of a round trip. It is assumed the vessel is operating at 20% of the installed power during this period. It is also assumed that this time can serve as a contingency to allow the vessel to make up time if it is behind schedule. Deadheading describes the vessel's transit to or from its overnight moorage to its first stop. It is assumed the vessel is operated at 40% of its installed power during this transition.

Baudouin EPA Tier 3 engines are installed on all the NYCF vessels. EPA Tier 3 emissions testing results for the Baudouin engines were used to determine the CO, PM and HC + NOx emissions for each route. Emissions factors for NOx, PM, HC, and CO were estimated using a fit curve, as described in Section 4.2.2.2. CO_2 and SO_2 emissions were estimated based on the chemical composition of ULSD and mass of fuel burned. Tier 3 emissions criteria for the Baudouin 6M26.3 and 12M26.3 are reported in Table 16.

The Baudouin engines operate significantly below the EPA Tier criteria for both the Tier 3 and Tier 4 requirements. Tier 4 emissions metrics were provided by the manufacturer. In the case of CO and HC, however, Tier 4 criteria was not available, and it was conservatively assumed these engines perform similar to their Tier 3 counterparts.

Table 16 Installed power and Tier 3 emission limits

Vessel Class	Engine	Installed HP	CO [g/kWhr]	PM [g/kWhr]	NOx + HC [g/kWhr]
River 150	(2) Baudouin 6M26.3	1606	5	0.11	5.6
Rockaway 150	(2) Baudouin 12M26.3	2760	5	0.11	5.6
Rockaway 350	(2) Baudouin 12M26.3	2760	5	0.11	5.6

[1] Tier 3 engines installed after 2018 have a PM standard of 0.10 g/kWhr

Two 65-kW ship service generators are installed on board the vessels. This study assumes one generator is operating at 50% load at all times. The fuel consumption and emissions produced by the generators are included in all totals reported. The generators' contribution to the vessel's fuel and emissions profile is typically below 5%, and for this reason the study focuses on improving the performance of the propulsion engines.

4.3.2.2 Model Validation

The calculation results described above were validated through analysis of the fuel consumption for August 2018, provided by NYCF (Reference 82). This document provides the volume (gallons) of diesel pumped into each vessel, for every day of August 2018. It does not, however, indicate which route each vessel operates.

Several assumptions were made when analyzing this data to validate the calculations, largely because the data provided does not differentiate on which route each vessel operates. It is assumed that each vessel operates on only one route each day. The weekend and weekday daily totals, averages and medians were compared with the calculated values. The vessels were split into two groups based on their engine sizes, the 6M23.6 for the 150 River class, and 12M26.3 for the 150 Rockaway and 350 Rockaway routes. During the week, two larger vessels service the Rockaway route full time, while a third services it for only 2.5 round trips.

Using the assumptions described above, the calculated weekday average consumption of the small and large vessels is within +/- 5% of the values given in the August 2018 fuel consumption. The weekend consumption is within +/- 10% of the actual fuel consumption for August 2018. This margin is higher because it is unclear on which routes the larger vessels are operating. This analysis is included in Appendix B.

4.3.2.3 Current Performance

Table 17 shows NYCF's baseline fuel consumption by route. The average consumption for each vessel is used to make estimates for fuel consumption and emissions for the future of the NYCF fleet.

The NYCF summer schedule was used to develop the round trip and daily consumption for each vessel. Based on weekend and weekday scheduling, this was used to predict weekly consumption and emissions. To determine annual rates, this consumption was multiplied by a seasonal scaling factor. The scaling factor was determined by evaluating the number of round trips on each route during the fall and winter. It was assumed the spring season has the same operation as the fall shoulder season. The annual scaling factor used to translate weekly consumption into annual values is 40.03. Calculations are available in Appendix B.

Table 17 NYCF baseline fuel consumption

Route	One Round Trip [gal]	Average Daily Consumption per Vessel [gal]
East River - Weekday	36	335
East River - Weekend	52	400
Rockaway - Weekday	115	965
South Brooklyn - Weekday	37	350

South Brooklyn - Weekend	47	385
Astoria - Weekday	38	435
Astoria - Weekend	38	395
Soundview - Weekday	63	510
Soundview - Weekend	63	635
Lower East Side	29	335
Lower East Side - Weekend	31	445
NYCF Weekly Fuel Consumption (Summer Season)	**60,000**	
NYCF Annual Fuel Consumption	**2,450,000**	

The baseline emissions performance of the NYC Ferries is captured in the table below.

Table 18 NYCF baseline emissions summary, given for a typical day on each route (all vessels)

Route	**CO [kg]**	**PM [kg]**	**NOx [kg]**	**HC [kg]**	**CO_2 [MT]**	**SO_2 [kg]**
East River - Weekday	22	3.5	141	3.1	16.9	0.16
East River - Weekend	15	2.3	96	2.0	12.0	0.11
Rockaway - Weekday	24	3.4	158	3.4	22.6	0.21
South Brooklyn - Weekday	13	2.1	86	1.9	10.6	0.10
South Brooklyn - Weekend	19	2.9	121	2.6	15.6	0.15
Astoria - Weekday	21	2.8	133	2.5	17.6	0.16
Astoria - Weekend	18	2.5	119	2.2	15.8	0.15
Soundview - Weekday	16	2.0	105	2.1	15.5	0.14
Soundview - Weekend	13	1.6	86	1.7	12.8	0.12
Lower East Side	12	1.9	80	1.7	10.1	0.09
Lower East Side - Weekend	11	1.7	72	1.5	9.0	0.08
NYCF Weekly Emissions (Summer Season)	**695**	**100**	**4,500**	**93**	**596**	**5.6**
NYCF Annual Emissions	**28,000**	**4,000**	**180,000**	**3,700**	**24,000**	**220**

4.3.2.4 Expansion Progress

With the surge in ridership, seven additional 350-passenger vessels have been purchased to serve existing routes, with only two left to be delivered. The new vessels have the larger 12M26.3 diesel engines.

NYCF is in the process of expanding its routes to include Staten Island, West Manhattan, Coney Island, and the East Bronx. These expansions are scheduled to take place by 2021. The expansion routes will require additional vessels that are not yet ordered. The schedule for these new routes has not been published but estimated schedule information for two expansion routes, shown in Table 19, is used to predict fuel consumption, energy requirements, and emissions.

Table 19 Expansion route schedule assumptions

Route	Stops per Round Trip	Total Time Pushing [minutes/round trip]	Total Time Transit [minutes/round trip]	Round Trips/Day	Launch Date
St George	4	20[1]	74	10[1]	2020
Coney Island	4	20[1]	69	10[1]	2021

[1] Assumed values, schedule not published

The weekly and annual consumption and emissions including these two new routes are given in the table below:

Table 20 Weekly and annual consumption for major expansion routes, three vessels per route

Route	Fuel Consumed [Gal]	CO [kg]	PM [kg]	NOx [kg]	HC [kg]	CO_2 [MT]	SO_2 [kg]
St George	4,000	9	1.8	57	1.3	5.7	0.05
Coney Island	4,000	7	1.2	47	1.1	5.7	0.05
Weekly Totals	7,900	110	21	730	17	80	0.75
Annual Totals	320,000	4,500	830	29,000	670	3,200	30

Section 5 Fuel & Propulsion Technology Overview

5.1 Introduction

This section introduces a range of fuels and propulsion technologies that may reduce fuel costs or emissions for the City's existing ferry fleets or for the City's future ferry fleets.

Alternate fuels considered included:

- Biodiesel (B5 – B20)
- Renewable Diesel
- Methanol
- Liquefied Natural Gas
- Compressed Natural Gas
- Hydrogen

Alternative propulsion systems considered included:

- Variable speed diesel-electric
- Plug-in hybrid battery-electric
- Non-plug-in hybrid diesel-electric
- Fuel cell-electric

Efficiency options to either directly reduce emissions or hydrodynamic resistance or empower operators to better manage fuel consumption considered included:

- Emissions upgrades
- Optimizing double-ended ferry propulsion
- Low friction hull coatings
- Fuel flow monitoring

Aspects considered include operational, emissions, and cost impacts, technical feasibility, and current level of adoption in marine applications. Section 6 further investigates which items are best suited for adoption and/or retrofit in the City's existing fleets, and Section 7 considers future fleet options in detail. Not all the technologies and fuels introduced in this section were determined to be appropriate for the City's existing or future fleets; this section does include some solutions initially judged plausible but subsequently determined not feasible due to cost, lack of benefits, technical infeasibility, or some combination of these elements.

5.2 Biodiesel

5.2.1 Summary

Biodiesel is a readily available fuel that is only compatible with marine diesel engines at low blend levels. The manufacturer of the main propulsion engines for the SIF fleet only certifies engine performance for biodiesel blends up to B5 and the NYCF propulsion engine manufacturer limits biodiesel blends to B10. Operating with biodiesel blends above those limits recommended by the engine manufacturers would be done at the City's risk.

Federal subsidies offset high production costs and B20 blends are sold with a minimal price premium over diesel. Using biodiesel would likely result in occasional clogging of filters and could cause fuel system leaks and engine sludge formation, risking loss of propulsion and increasing maintenance costs. Switching to biodiesel would reduce CO_2 equivalent emissions, but the impact on criteria emissions is less clear, with some studies showing small reductions to criteria pollutants and others showing small increases. Biodiesel's lower reliability due to clogging and other engine impacts makes it a less attractive option than renewable diesel

(Section 5.3), which offers similar emissions benefits, higher blending rates, and existing engine compatibility without biodiesel's operational downsides.

5.2.2 Background

The term "biodiesel" most commonly refers to pure or blended fuels produced from plant- or animal-based feedstock. Common feedstock sources include soybean oil, canola oil, inedible animal fat, and recycled cooking oil. Soybean oil dominates biodiesel production in the United States, supplying about half of domestic biodiesel feedstock in 2017 (Reference 15). Biodiesel is produced from feedstock through a process called trans-esterification, which is used to create fatty acid methyl esters (FAME). Coproducts such as glycerin are then removed, and the FAME is purified to meet ASTM D6751 (*Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels*, reference 78). Fuel meeting this standard is referred to as B100. ASTM D975 allows blending ULSD with up to 5% B100 without additional control or marking. B100 is also commonly blended with ULSD in concentrations from 6 to 20% (B6 – B20). Blended fuel is governed by ASTM D7467 (*Standard Specification for Diesel Fuel Oil, Biodiesel Blend (B6 to B20)*, reference 79), which adds specifications for acid number and oxidation stability to the requirements of ASTM D975. In this report, the term "biodiesel" usually refers to a B20 blend to ASTM D7467 standards.

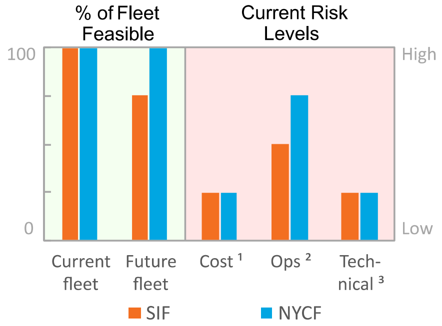
Biodiesel at a Glance

Benefits may not outweigh costs, see Section 6

○
●
○

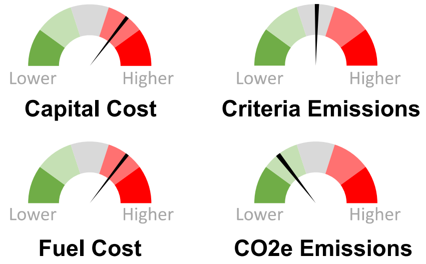
- May not lower criteria emissions
- Limited manufacturer support
- Operational risks

Recommendation



¹ Future tax and subsidy uncertainty
² Clogged filters could trip engines offline
³ Manufacturers not developing this option

Feasibility and Risk Areas



NYC DOT conducted a biodiesel trial in 2007-2008. After eight months, the trial was discontinued due to a significant increase in maintenance of fuel oil purifiers, fuel filters, and fuel injectors. Washington State Ferries (WSF) experienced similar results with its first attempt to use biodiesel in 2004-2005. Glosten assisted WSF with a detailed biodiesel study (Reference 16) in 2008-2009 that used blends of increasing biodiesel content (B5, B10, and B20) over the course of a year. A total of 800,000 gallons of B20 were used successfully in the 2008-2009 study. The principal lessons learned from this study were to thoroughly understand the fuel supply, that the transition to biodiesel should be preceded by a thorough cleaning of on-board fuel tanks, and that biocide should be used as a fuel additive to prevent biological sludge buildup.

Although biodiesel has been widely adopted for road vehicles, marine usage is much more limited. ISO 8217 (*Specifications of Marine Fuels*) is used as a fuel specification for most worldwide ship fuel and restricts FAME content to 0.5% in normal fuel grades. Even this level is only allowed due to the impracticality of avoiding trace amounts – intentional blending is forbidden. New grades were added in the 2017 edition of ISO 8217 that allow up to 7% FAME. This is the limit in European road diesel (similar to the 5% limit in ASTM D975). Discussion on this change notes that the main purpose is to provide flexibility for ships that might otherwise have difficulty sourcing FAME-free low sulfur fuel in some ports. Accompanying this change is an appendix advising caution and discussing many of the concerns documented in the following sections.

The US Navy has conducted a great deal of alternative fuel research; their allowance for renewable diesel will be discussed in Section 5.3. Like ISO 8217, the Navy's diesel fuel standard (MIL-DTL-16884N) acknowledges the impossibility of avoiding trace amounts of FAME and forbids the intentional blending of FAME into fuel supplied to military customers. MIL-DTL-16884N has an even stricter limit (0.1%) for trace FAME than ISO 8217.

5.2.3 Operational Considerations

Biodiesel blends differ from ULSD in several ways that that are relevant to shipboard use. These include material compatibility, higher water absorption, greater susceptibility to biological growth, higher cloudpoint, and solvent-like properties when first introduced into a fuel system. Each of these topics will be individually addressed below.

Some materials, such as natural rubber, are incompatible with biodiesel. O-rings seals, hoses, gaskets and other software in fuel systems and engine systems could require maintenance to replace incompatible materials. All engine manufacturers contacted gave vague assurances that material compatibility was not an issue. However, the manufacturer of the main propulsion engines for the SIF fleet (EMD) only provides explicit support for biodiesel blends to B5 and the NYCF main propulsion engine manufacturer (Baudouin) limits biodiesel blends to B10. Despite repeated attempts, clear documentation of this compatibility in written technical guidance (engine operating manuals, etc.) could not be obtained from manufacturers during this study. EMD provided a clarifying memo stating that use of biodiesel blends above B5 is neither approved nor prohibited. If an engine problem occurred while using a biodiesel blend in excess of these limits, uncertainty as to the cause of the problem might complicate a warranty claim and could give the manufacturer grounds to deny warranty coverage.

Water absorption potentially affects biodiesel use on ships more than in land-based applications because of the combination of high humidity and extreme temperature fluctuations associated with shipboard operations. Water collects below the diesel in storage tanks and low concentrations can also dissolve into the fuel. Normal treatment of fuel oil using centrifugal purifiers should remove any dissolved water as the fuel is transferred from storage tanks to service tanks. For ships without purifiers, filter manufacturers recommend modifying the fuel system to use larger filters to improve water removal capabilities. The NYCF ferries are at greater risk from water and clogging issues. While increasing filter size is a mitigator, it should be noted that the NYCF ferries do not have engineering watchstanders during normal underway operations. Their propulsion plant arrangement is also less capable of absorbing the loss of an engine compared to most SIF ferries.

Biological growth is believed to be the cause of fuel purifier sludge observed during the WSF biodiesel trial. Although the exact mechanism of the sludge formation is not known, water absorption can contribute to biological growth. On the WSF trial, adding a biocide additive to the fuel resolved the sludge issues, so it was recommended to add biocide preventively to each load of fuel. Fuel turnover is also a factor, since slower turnover allows more time for both water absorption and microbial growth. This is especially a concern for the fuel barges at SIF and the fuel storage tanks at the NYCF homeport. Fuel turnover is much slower in these tanks than onboard the ferries, and there is no straightforward means to remove entrained water. This aspect of fuel handling was not examined in the WSF biodiesel study. Rather, B20 was blended into tank trucks and immediately transported to the ferries without long-term storage. Extended storage of B100 blendstock was done at the fuel supplier's facilities, away from the moist marine environment.

Both petroleum and biological diesel fuels have the potential to precipitate a wax-like substance under sufficiently cold temperatures. This is called the cloudpoint and is approximately 4°F for #2 ULSD. No cloudpoint limit is specified in ASTM D975; alternative test procedures such as the cold filter plugging point (CFPP) and low temperature flow test (LTFT) are suggested as methods to determine the acceptability of fuel for a specific cold-weather use. Specifications for these tests can be incorporated into contracts with fuel suppliers. The cloudpoint of biodiesel varies widely. In general, the more common soy-based biodiesels have a cloudpoint below 30°F, whereas biodiesels from animal or recycled feedstocks could have cloudpoints as high as 50°F. When blended as B20, the resulting fuel has a cloudpoint between 5-25°F, depending on the properties of the B100 used in the blend (Reference 17). Both the SIF and NYCF have fuel storage and transfer systems that would expose fuel to extreme winter temperatures. Any use of biodiesel would require studying and potentially modifying this infrastructure to avoid cold flow issues. Preliminary discussions with a potential biofuel supplier indicated that suppliers are familiar with these challenges and solutions could include lowering the percentage of biodiesel in the blend during winter or blending in some #1 ULSD to improve cold flow properties.

Fuel tanks and fuel piping systems have been observed to retain deposits from the use of petroleum fuels. Guidance from biodiesel producers and equipment manufacturers notes that biodiesel can act like a solvent when first introduced into fuel systems. This can result in freeing these deposits into the fuel stream, resulting in shortened purifier cleaning intervals and increased filter changes when first introducing biodiesel. Preventive tank cleaning is intended to minimize these issues, but some increase in filter changes immediately following a transition to biodiesel blends would be expected. WSF cleaned all fuel tanks at the start of the biodiesel trial in 2008, which may have contributed to the success of the trial.

Biodiesel also has a marginally lower energy content than petroleum diesel. For a B20 blend, this should theoretically result in 1-2% greater fuel consumption by volume. This small difference is difficult to observe in practice; 2% is less than half of the historic variability in annual SIF fuel consumption. The increase in fuel consumption would also cause a small increase in the CO_2 produced during combustion. The effect on other pollutants is incorporated into specific emissions factors since these are reported per unit power.

5.2.4 Environmental Impact

5.2.4.1 CO_2e Emissions

The California Low Carbon Fuel Standard (Section 2.3.3) was used to assess biodiesel's environmental impact. Lifecycle GHG emissions analysis to calculate biodiesel carbon intensity scores for LCFS is comprehensive and includes emissions associated with farming, agricultural chemicals, transport of raw soybeans, production of biodiesel, and transportation of finished fuel. Notably, this analysis gives credit for the carbon removed from the atmosphere as biological feedstocks grow, so the net CO_2 production when combusting biofuels is taken to be zero. Accordingly, the carbon intensity scores for biofuels are primarily a measure of the energy (and therefore carbon) used to farm and process the feedstock and get the fuel into the vehicle – the so called "well-to-tank" emissions. CI values for biodiesel available in California range from 8-60 gCO_2e/MJ depending on the feedstock. Midwest soybeans are taken as a reference fuel, with a score of approximately 50 gCO_2e/MJ. Compared to ULSD at 102 gCO_2e/MJ, this indicates a reduction in lifecycle GWP of approximately half (Reference 43). A 50% reduction in lifecycle CO_2 will be used for analysis in this report, as this is also the threshold for a biofuel to be considered under the federal EISA policy (Reference 38) .

Although biofuels offer a promising path to reduce GHG emissions, some critics have claimed that the lifecycle GHG emissions for biofuels may exceed conventional petroleum fuels in analyses that account for carbon released when converting land for agricultural use. Reference 38 documents comprehensive analysis of both direct and indirect land use carbon emissions, concluding that federal policy requiring the use of biofuels could initially result in net increases in equivalent CO_2 emissions. These emissions would be paid back within two years, and significant long-term CO_2 reductions are predicted. Land use effects are also included in LCFS CI scores. Further evaluation of land use effects is beyond the scope of this report but could be considered by the City when evaluating policy on use of biodiesel; more detail can be found in Reference 18.

5.2.4.2 Criteria Emissions

A draft technical report released by the EPA in 2002 (Reference 19) found that biodiesel blends reduce CO, PM, and uncombusted HC relative to petroleum diesel in highway engines. For B20, reductions of 10-20% of these regulated pollutants were observed. The EPA reconfirmed these results with more modern engines in 2010 in support of a regulatory impact analysis for federal policy requiring annual consumption of specified volumes of biofuel (Reference 38). The wide variety of engine types and emissions aftertreatment technologies already in use by the SIF and NYCF fleet make it challenging to quantify specific changes to expected stack emissions when utilizing a biodiesel blend. Furthermore, most testing has been done on smaller engines such as those used in road vehicles. Very little research has been done on the emissions effects of using biodiesel blends in large medium speed engines, and many past studies used higher sulfur fuels as the baseline for comparison, so some of the emissions reductions in these studies should be attributed to the low sulfur content in biodiesel. Comparable reductions would not occur when ULSD is the baseline fuel. Reference 45 documents a biodiesel trial on a locomotive using the same model of EMD diesel engine used on the Molinari class SIF. This trial found no significant changes in any criteria pollutant when utilizing B20, in contrast with the changes in emissions observed in highway diesel engines shown in Reference 38.

Many studies, including References 19 and 38, report increased NOx emissions on the order of 2-5% for engines burning biodiesel. Despite significant study in the intervening years, a review of the literature found that although there is general agreement that biodiesel has increased NOx emissions, there is still no definitive understanding of the magnitude or cause of this effect. Furthermore, many studies have found no significant change, and some have even found a NOx reduction relative to ULSD when burning B20. A review of recent literature showed that this is still an active research area, and a variety of effects contribute to the overall emissions performance, not all of which are fully understood. Tier 4 emissions control systems include NOx sensors, so the impact of this NOx increase on future ferries would likely be an increase in urea consumption rate with no change to NOx at the stack.

It should also be recognized that the emissions upgrades proposed in Section 6.1.1 and the performance of the future Tier 4 ferries leaves little room for fuel-based improvements. For example, upgrading the Molinari class propulsion engines to EPA Tier 3 would give a 30 MT reduction in the fleet's 20-year PM emissions. Converting the *entire fleet* to B20 would only provide an additional 9 MT reduction over 20 years even using the full 15% reduction assumed in this study. For a Tier 4 Ollis class ferry, B20 would eliminate a maximum of 36 kg (0.036 MT) of particulate emissions per year.

In summary, biodiesel offers modest reductions in lifecycle CO_2 emissions relative to petroleum-based diesel. Reductions in other regulated pollutants are possible but should not be assumed without conducting a full-scale emissions study. For the purposes of comparing alternatives in this report, 15% reductions in CO, PM, and HC and a 2% increase in NOx emissions will be used for a B20 blend of biodiesel and ULSD. It should be understood that these numbers, based on Reference 38, represent an educated guess at a possible emissions change resulting from biodiesel, but that the available research performed to date does not support predicting specific criteria emissions changes on board SIF or NYCF vessels.

5.2.5 Cost

Since 2012, average nationwide B20 prices have been 3.5%-4% higher than ULSD. However, starting in the fourth quarter of 2017, B20 prices dropped below ULSD prices, averaging 4% cheaper in the first three quarters of 2018 (Reference 25).

B20 is already available through the Department of Central Administrative Services (DCAS) to NYC government users. Comparing truck-delivered fuels, B20 is approximately $.05/gal more expensive (reference 37) than ULSD. Fuel is currently delivered to SIF by a barge that also services several other government facilities. Barge deliveries are cheaper than truck deliveries, but some of this cost advantage could be lost if SIF were receiving different fuels than the other barge customers. NYCF would be negotiating for separate fuel contracts, but a similar small price premium is expected.

The price of biodiesel is influenced by several government incentive programs. First, the EPA’s renewable fuel standard (RFS) obligates certain fuel producers and importers to meet renewable fuel targets. Obligated parties can do this directly, or through a trade system where they can purchase credits called RINs from others. The market value of RINs, which fluctuates with demand, impacts the effective costs of biodiesel. Separately, from 2005-2017, a credit was available to incentivize blending biodiesel. The producer or retailer who blended the fuel was eligible for $1 for each gallon of B100 used. The future regulatory environment surrounding these incentives is unclear. For example, at the time of writing, the blender’s tax credit is expired but was retroactively extended in several recent years. Similar incentives exist at the state level and in some foreign countries. Analysis of these factors is beyond the scope of this report, but the uncertainty in future biodiesel prices should be noted.

Separately from the higher invoice price, the theoretical lower energy content of biodiesel discussed in Section 5.2.3 should result in increased fuel consumption. At $2.40 per gallon, 2% lower energy content is equivalent to paying an extra 5 cents per gallon. In other words, B20 would be expected to cost approximately $2.50/diesel gallon equivalent (DGE).

Other costs would also be incurred to shift to biodiesel. A controlled trial would be strongly advised and would include associated engineering, planning, and monitoring costs. Tank cleaning would be required at approximately $10,000 per vessel (Reference 44). Fuel system modifications could be required to include additional sampling points or instrumentation, both on the vessels and in the shoreside infrastructure.

5.3 Renewable Diesel

5.3.1 Summary

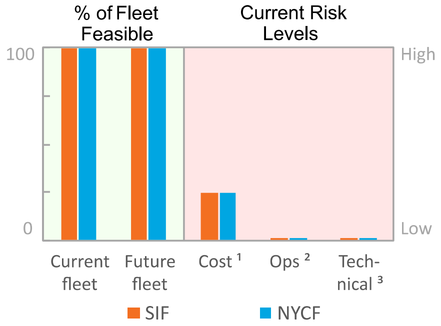
Although chemically more similar to petroleum diesel, renewable diesel has many of the same benefits as biodiesel. It is more expensive than biodiesel, but it may be readily substituted for ULSD with no risk of operational issues. Using renewable diesel results in lower CO_2 equivalent emissions, and preliminary results suggest lower criteria emissions as well, although it is recommended that the City carry out further benchmarking tests to quantify actual benefits. Renewable diesel does rely on a limited supply of feedstocks, and therefore its price may be sensitive to market fluctuations; in addition, it is currently around $1.50/gallon more expensive than the ULSD the City currently uses in its ferries. Still, given renewable diesel's emissions benefits, engine compatibility, and low operational impacts, it is a good emissions reduction option for the City's existing fleet.

Renewable Diesel at a Glance

Recommended for immediate implementation on SIF & NYCF fleets

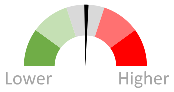
- Best near-term CO2 reduction
- Feasible for all vessels
- No capital expense

Recommendation

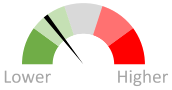


¹ Influenced by petroleum & biodiesel prices
² Operationally equivalent to ULSD
³ Meets ULSD ASTM, tested by US Navy

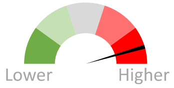
Feasibility and Risk Areas



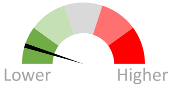
Capital Cost



Criteria Emissions



Fuel Cost



CO2e Emissions

5.3.2 Background

Hydrotreated Renewable Diesel (HRD) refers to fuel that is chemically similar to regular fossil-fuel diesel but is produced from renewable feedstocks. Whereas traditional biodiesel is a mono-alkyl ester produced from lipids, renewable diesel utilizes different chemical processes to add hydrogen to and eliminate oxygen from the feedstock (hydrodeoxygenation), resulting in similar chemical compounds to those produced when diesel fuel is produced from normal petroleum-based feedstock. In some cases, HRD is processed using the same refinery equipment and processes as ULSD. Renewable diesel is required to meet the same ASTM 975 standards as petroleum-based diesel. Both biodiesel and renewable diesel can be produced from lipids such as vegetable oils and animal fats. The hydrodeoxygenation process used for renewable diesel can more economically handle animal fats than biodiesel production processes, which require an additional pre-conditioning step when using animal feedstock rather than vegetable oils. Renewable diesel can additionally utilize cellulose from crop residue and woody biomass, which cannot be used for regular biodiesel production (Reference 10). The governing standard for US Navy F-76 diesel fuel (equivalent to #2 ULSD), allows up to 50% blending with hydrotreated renewable diesel (Reference 46), and it was also successfully demonstrated in multiple trials sponsored by the US Maritime Administration (References 89 and 90).

5.3.3 Operational Considerations

Since renewable diesel is chemically similar to regular diesel, it is advertised as a substitute that requires no special considerations. It is often called “drop-in diesel” for this reason. It can be transported, stored, and consumed using all of the same equipment normally used with ULSD.

The Navy has conducted extensive qualification testing for HRD, resulting in an allowance of up to 50% HRD blended with conventional diesel fuel in their normal diesel fuel specification (Reference 46). The 50% limit was imposed to maintain a minimum aromatic content; an entering argument of the Navy’s research was that no changes to the existing fuel specifications would be permitted to incorporate alternative fuels. The aromatic hydrocarbon content of regular diesel can be as high as 35% (the high specification in Reference D975) and does not normally have a low specification for commercial fuel. The California Air Resources Board is already limiting aromatic hydrocarbon content for non-marine applications to 10% (Reference 12). The FAA initially limited use of renewable jet fuel to a 50% blend due to concerns about fuel system leaks caused by inadequate expansion of elastomers in low-aromatic renewable jet fuel (Reference 13), but there are no reports of similar problems in diesel engines. Reference 46 specifies a minimum aromatic specification that is only applicable when F-76 diesel fuel has been blended with renewable diesel.

5.3.4 Environmental Impact

LCFS carbon intensity values for renewable diesels range from 17-56 gCO_2e/MJ depending on the feedstock. Fuels made from waste streams achieve CI values at the low end, and fuels made directly from vegetable oils achieve CI values at the higher end. Reference 38 found that animal feedstocks are more likely to be utilized in renewable diesel production, so tallow is taken as a reference feedstock, resulting in fuel with a CI score of approximately 35 gCO_2e/MJ. This is slightly better than the 50% reduction in lifecycle CO_2 used for biodiesel. The CI analyses include the contribution of both natural gas and hydrogen used during the refining process. Like biodiesel, these low values are possible because the analysis takes credit for carbon removed from the atmosphere by biological feedstocks. However, since renewable diesel is not limited to a 20% blend, greater substitution for fossil fuel diesel is possible.

Several studies document reductions in all criteria emissions for engines utilizing renewable diesel. Reductions in all criteria pollutants could be as high as 30%, but results currently available in literature vary widely with engine and test cycle selection (References 39, 40, and 41). As with biodiesel, it would be advisable to conduct full scale emissions trials to validate expected changes in local criteria emissions. If a sustained shift to renewable diesel were contemplated, further emissions reductions could be gained by tuning the engine for the small differences in fuel properties between petrodiesel and renewable diesel (Reference 39). For the purposes of comparing alternatives in this report, emissions effects from Reference 39 are adopted as follows: 30% reductions in CO, PM, and HC, and a 5% reduction in NOx emissions will be used for pure renewable diesel. These reductions will be weighted accordingly for blends with ULSD.

5.3.5 Cost

Renewable diesel relies on limited supplies of biological feedstock and may be influenced by the regulatory environment and associated market pressures. Both the federal and state incentives discussed above for biodiesel will also pressure the renewable diesel market. If produced using a process that co-processes feedstock with petroleum products, the administrative status of renewable diesel changes and can be disqualified from some tax incentives. This may be a challenge for the further adoption of HRD. Large refining companies can easily produce significant quantities of HRD using existing capital equipment and with minimal job creation. This puts HRD at odds with biodiesel from a political perspective, since small biodiesel production facilities represent small American-owned businesses that create jobs.

NYC recently announced significant expansion to the use of renewable diesel in road vehicles (Reference 14). During recent trials, renewable diesel was available through NYC DCAS with a price premium of approximately $1.50/gallon compared to regular #2 ULSD. Legislation like California’s LCFS makes renewable diesel cheaper in certain localized markets. This disincentivizes fuel distributors from expanding outside those markets and could result in a cost premium to distribute to other markets.

5.4 Liquefied and Compressed Natural Gas (LNG and CNG)

5.4.1 Summary

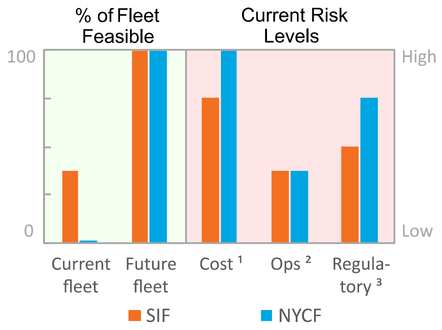
Natural gas is gaining popularity as a marine fuel, primarily because it is less expensive per unit energy than ULSD and can help operators meet more stringent environmental regulations. However, it is complex and very costly to retrofit existing diesel-powered vessels to run on natural gas. Its preferred storage method as a marine fuel, as a cryogenic liquid (LNG), creates numerous operational challenges that arise from handling a cryogenic liquid. While a compressed natural gas (CNG) fuel system is less complex, it is not currently used for marine applications due to its low energy density relative to the liquefied form. Long payback periods driven by high capital costs, limited engine offerings, and negligible CO$_2$e benefits result in a recommendation against natural gas fuel for current or future ferries. At this time, shoreside infrastructure and LNG supply challenges make natural gas an unattractive future fleet option as well.

Natural Gas at a Glance

Benefits may not outweigh costs, see Section 6

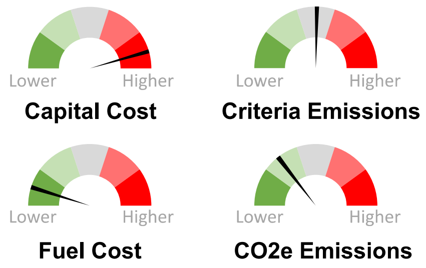
- Conversion cost and technical risk
- Shoreside cost and legal status
- Long payback period

Recommendation



[1] Costly shoreside infrastructure & vessel mods
[2] More complex bunkering processes
[3] Tank location, USCG rules

Feasibility and Risk Areas



5.4.2 Background

Natural gas has developed into a popular marine fuel as an economical way to meet increasingly stringent environmental regulations both in the US and abroad. Natural gas fuel offers several advantages:

- Natural gas is naturally sulfur free.
- Compared to ULSD or low sulfur Marine Diesel Oil (MDO), gas fuel can reduce fuel costs by 50%. Reducing low-sulfur fuel costs is the primary motivation for pursuing natural gas engines.
- Certain engines can also offer alternate means to meet some NOx regulations.

While the ferries in the study have exclusively used ultra-low sulfur fuel for the last decade, low-sulfur fuel prices have historically been a concern for international ship operators only when operating in Emissions Control Areas (ECA’s) close to shore. In 2020, IMO regulations will limit fuel to 500 ppm sulfur worldwide. This will significantly increase the demand for low-sulfur fuels. Natural gas is by far the cheapest such fuel, so continued development of gas engine technology is expected as operators work to meet the new regulations in the most economical way possible.

5.4.2.1 Storage

In the form in which it is delivered to homes, natural gas is unsuitable as a transportation fuel due to inadequate energy density. For comparison, a one-way trip on the Staten Island Ferry would require over 25,000 cubic feet of natural gas at typical residential distribution conditions.

There are two primary ways to overcome this limitation, the first of which is to create liquified natural gas (LNG). In this form, natural gas is cooled below its -259°F boiling point, turning it into a cryogenic liquid and reducing its volume by a factor of 600. Alternatively, significant gains can be achieved by compressing natural gas to high pressure without incurring the complications of handling cryogenic fluids. Typical tanks store compressed natural gas (CNG) at approximately 3000 psig. CNG is already in widespread use in NYC as an alternative fuel for motor vehicles including buses, trucks, and taxis.

Natural gas combustion releases approximately 10% more energy than an equivalent weight of diesel fuel. Conversely, even when liquefied, natural gas has only half the density of diesel fuel. Combining these effects, 1.7 gallons of LNG or 4 gallons of 3000 psi CNG contain the same energy content as 1 gallon of diesel fuel.

5.4.2.2 Engine Technologies

A variety of engine technologies have been developed to utilize natural gas as a fuel. These engine technologies can be broadly subdivided into two categories: spark-ignited Otto-cycle engines and compression-ignited dual-fuel engines. Dual fuel engines retain some diesel usage to initiate combustion, whereas spark-ignited engines eliminate diesel completely. Several varieties of each engine type are in production, varying significantly in terms of economic and environmental aspects such as fuel efficiency, criteria emissions, and methane slip.

Natural gas fueled engines certified for marine use are available from several engine manufacturers, but the product range is limited, and some available models will not have their first production engines put into service until later this year. Of the four different engine sizes investigated for this study, marine certified natural gas fueled engines with appropriate power ratings are available for any application except the NYCF gensets, but multiple gas options are only available in the size range of the SIF propulsion engines. EMD, Wartsila, and Rolls Royce all offer gas engines that could potentially be integrated into an existing or new SIF design. MTU offers a gas engine with comparable power to the Baudouin engine installed on the larger NYCF ferries, but it is nearly twice as heavy and is physically too wide to fit in the existing hull. Mitsubishi offers a gas engine that might be suitable to replace the gensets on the SIF. This engine also has an appropriate power range for propulsion on the NYCF vessels but is currently sold only as a generator package.

Consequently, near-term natural gas options investigated in this report only considered the main propulsion engines of the SIF ferries as potentially viable candidates. Further discussion of future-fleet gas options for NYCF can be found in Section 7.2.

5.4.2.3 Retrofit Options

SIF's existing main propulsion engines are manufactured by EMD. EMD has developed natural gas retrofit kits for their later model engines, which are currently installed on the Molinari class and will be installed on the upcoming Ollis class ferries. Retrofitting existing engines for natural gas, while expensive, will be far less expensive than installing new natural gas propulsion engines. Furthermore, the SIF operating personnel and maintenance staff are familiar with EMD engines, which reduces training and support costs compared to alternate gas engines from other manufacturers. Consequently, for the existing SIF fleet's main propulsion engines, this report has focused on natural gas options developed by EMD.

Two gas-engine concepts developed by EMD have potential applications on the Molinari or Ollis class ferries. Although the first option, dynamic gas blending (DGB), is already in use on EMD locomotive engines, neither it nor the second engine technology option have been put into service on a ship. DGB is not capable of achieving EPA Tier 4 and therefore can't be installed on the Ollis class.

DGB is a dual-fuel technology that substitutes up to 80% of diesel consumption with natural gas, although the gas substitution rate is load dependent. This design injects gas into the combustion air as it enters the engine, retaining a full-size diesel fuel injector. It is therefore capable of 100% normal operation on diesel in case of a problem with the gas system. The second EMD natural gas conversion option is called direct injected gas (DIG). Although also a dual-fuel technology, diesel is meant to only serve as a pilot fuel for this system, and DIG can only provide 30% power capability if the gas fuel supply is interrupted. A DIG engine is normally supplied by 95% gas with 5% diesel pilot fuel consumption.

Natural gas entering the engine is never liquid. Fuel system components for LNG and CNG fuel supplies would include different equipment but would ultimately deliver the same gas to the engine. Many gas engine technologies could be implemented with either CNG or LNG fuel storage. For engines such as DIG that require high pressure gas supply, the necessary fuel compressors might require unacceptable energy consumption, space, or weight. Although numerous compressors with adequate capacity are on the market, most have not been certified for marine use, and those that have are designed for LNG carrier cargo systems. The Ollis class ferries would require two compressors with approximately 600 scfm capacity. Size information from one manufacturer suggests this could require as much space as two 20-foot shipping containers. These compressors would likely exceed the existing auxiliary power generation capability and require further modifications. EMD has used compressors to supply test engines but does not think that CNG fuel is practical for a shipboard DIG engine. The following discussions include some topics that are specific to a fuel storage technology and some topics that are independent of selecting LNG or CNG.

5.4.2.4 Regulatory

Despite the similarities to LNG, the regulatory environment for CNG is less clear. The USCG issued a policy letter (Reference 91) adopting the IMO IGF code (Reference 92) with minor modifications as the regulatory basis for LNG fueled ships. This policy letter specifically states that a CNG fueled ship would require review as an alternative design. This increases the regulatory risk associated with a CNG fueled ship design.

5.4.3 Operational Considerations

5.4.3.1 Shiphandling

Natural gas engines tend to have slower allowable load changes than diesel engines, as shown in Figure 17. This lag is necessary to prevent engine knocking, as gas combustion is more sensitive to air-fuel ratio than diesel combustion. Engine manufacturers have used a range of approaches to address this. Wartsila dual fuel engines can trip to 100% diesel supply if maneuvering rates exceed gas limits. EMD's DGB engines simply change the ratio of diesel fuel burned during the transient load condition. Upon return to steady state steaming, the engines can be manually or automatically returned to normal diesel pilot fuel ratios. Discussions with British Columbia (BC) Ferries about their natural gas experience indicated that frequent shifts to diesel were common when their natural gas engines were first put into service because ferry captains used the same shiphandling practices they were accustomed to for diesel engines. Although management emphasis on the importance of fuel source was necessary, the captains were able to adjust their tactics and can now safely maneuver in and out of dock with fewer shifts to diesel.

EMD has capitalized on this response lag aspect of 4-stroke cycle natural gas engines. One of the main selling points of both the EMD DGB and DIG technologies is that they both have the same load response as their traditional diesel-fueled engines.

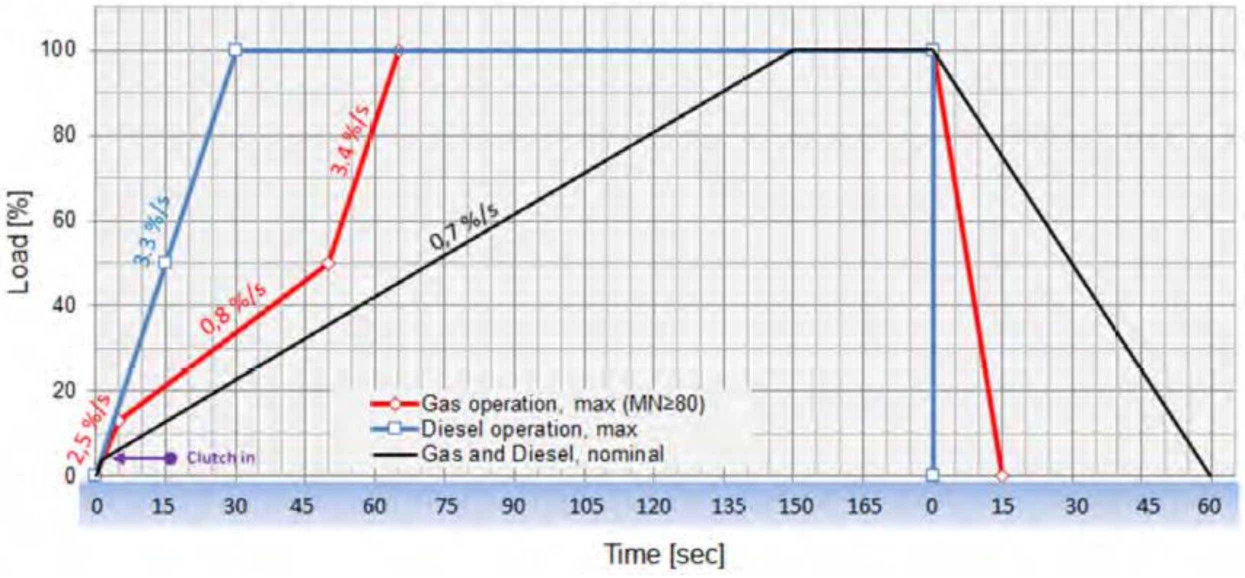


Figure 17 Limitations on rate of load change for gas engines

5.4.3.2 NYC Restrictions on Cryogenic Fuel Facilities and Transportation

Local regulations present a major limitation on the feasibility of LNG fueled ferries. NYC fire code prohibits the transport of LNG by truck (Reference 42, Section 2707.10). Transportation of other liquefied gases, including hydrogen and other petroleum gases (LPG), is also prohibited. On-site liquefaction of natural gas from utility distribution is a technically viable alternative, but construction of new LNG facilities is specifically prohibited by Section 3206 of the Fire Code. Two alternatives within the current legal framework could be delivery by barge or for ferries to transit to New Jersey to bunker LNG there.

5.4.3.3 LNG Bunkering

Even in the best case of changed regulations allowing LNG to be stored or delivered to St. George, current bunkering schedules could be affected by use of natural gas fuel. LNG fuel systems on small ships do not normally include reliquefaction capability. This requires establishing both minimum and maximum tank levels to ensure that the tank structure remains cold and to provide adequate expansion volume for the fuel that vaporizes due to gradual ambient heat input. Combining these limits with the energy density discussed in the previous section means that an LNG tank must have twice the volume of an equivalent diesel fuel tank. Furthermore, LNG tanks require thick insulation to maintain low temperatures and must be cylindrical or spherical to contain pressure that builds up inside the tank. This results in less efficient use of available space compared to prismatic tanks used for diesel fuel. Additionally, USCG regulations may require locating LNG tanks above all passenger spaces where the added weight has a significant negative impact on stability. These factors make it challenging to arrange LNG tanks that provide similar bunkering frequency to diesel, especially when retrofitting an existing ship. On two classes of LNG-fueled ferry in use at BC Ferries, the bunkering schedule is 8 trucks per week – one truck every night and two on one night. This schedule is partly driven by the trucks' limited capacity. A standard-size LNG truck cannot supply a full day's worth of fuel.

An LNG bunkering operation is also significantly more complex than diesel bunkering. The bunkering arrangement used at BC Ferries requires a total of nine mechanical and electrical connections between the truck and the ship. Fuel is only transferred for approximately one hour of a 2.5-hour bunkering evolution. The remainder of the time is dedicated to initial connections, system testing, purging bunkering lines, and disconnecting the truck.

Finally, hazardous zones around the bunkering station restrict personnel access. The impact to passenger and staff access could be problematic for SIF since ferries are operated around the clock.

5.4.3.4 CNG Bunkering

CNG is significantly less energy dense than LNG, so daily bunkering could be necessary. A large SIF ferry operating on 95% CNG would require approximately 25 ft^3 of 3000 psig storage for a one-way trip. The most demanding weekday ferry schedules (for example, route 4A/4B) require 12 round trips. Providing fuel for this schedule with a 15% margin would require 660 ft^3 of 3000 psig storage. Based on preliminary gas consumption estimates, a larger capacity (2260 ft^3) could be used to maintain a twice-weekly bunkering schedule. A sketch showing these tank sizes with the Ollis class hurricane deck for scale is shown in Figure 18.

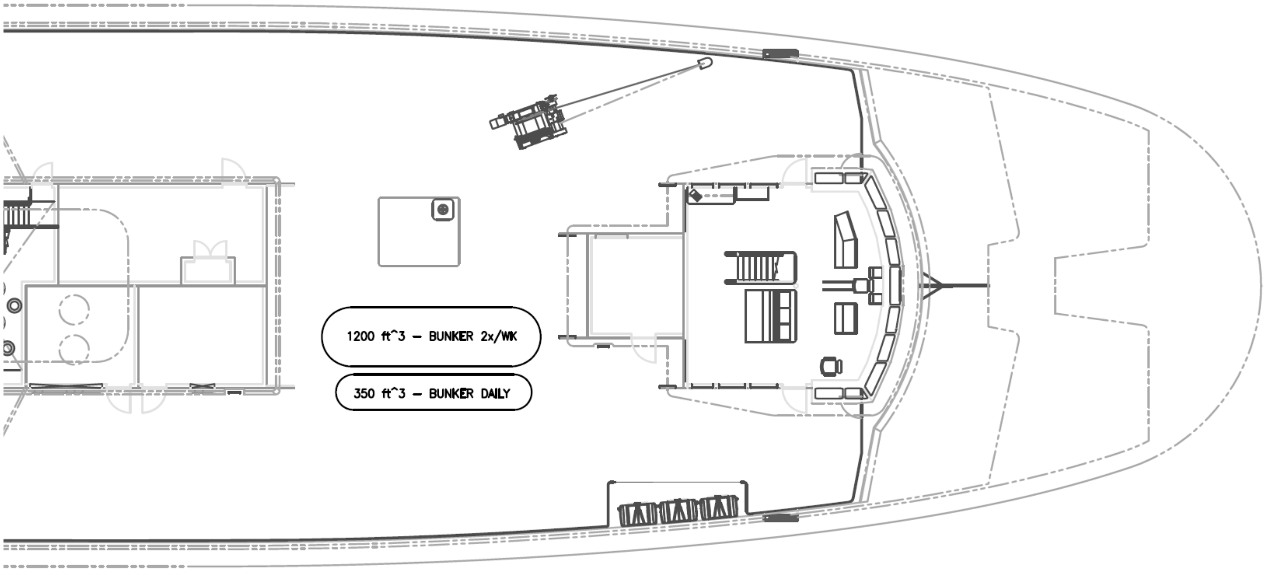


Figure 18 Daily and twice-weekly fill CNG tanks on Ollis-class hurricane deck (one tank required each end)

New shoreside infrastructure would be required to support bunkering operations. The most likely arrangement would be to utilize one or more compressors to raise natural gas from utility lines up to the pressure required for the ferry fuel tanks. Small or large shoreside storage tanks would be used to optimize the combination of infrastructure cost and fueling time. Discussions with representatives of the local gas utility (National Grid) indicate that the existing lines to the terminal are low pressure (4 inches H2O) and are not currently adequate to supply compressors. Upgrades to the gas infrastructure in this area are already in progress, so future expansion could likely be accommodated.

5.4.3.5 Weight and Stability

For either LNG or CNG, both regulatory risk analyses and practical arrangement limitations could dictate placing the fuel tanks above all passenger spaces. A rough estimate of the fuel and tank weight indicates that this could raise the vertical center of gravity (VCG) of a Molinari class ferry by as much as five inches. Additional gas equipment would most likely be collocated with the fuel tank due to the impracticality of meeting hazardous space arrangement limitations otherwise, resulting in further weight additions topside. While fixed ballast could be added to compensate for the stability impacts, the increase in displacement would have a negative effect on speed, requiring greater propulsion power, fuel consumption and potentially result in reduced passenger capacity.

Insufficient data was available on the weight of required components and displacement vs. speed relationship to make a full estimate in this study, but this factor does add both design and economic risk to the feasibility of a SIF gas conversion.

5.4.3.6 Maintenance Benefits

Despite the above challenges, a shift to gas fuel would be expected to provide several operational benefits. Gas fuel is cleaner than diesel, resulting in reduced preventive maintenance requirements on the engines and supporting auxiliary systems. BC Ferries was able to reduce their lube oil purification schedule to 24 hours per week after converting to gas fuel. Engine overhaul intervals may also increase. Due to limited operating experience with gas engines, so far Wartsila has not yet approved any changes. However, BC Ferries is expecting reductions to overhaul requirements in the future.

5.4.4 Environmental Impact

Natural gas has several significant environmental differences from diesel. First, it contains no sulfur, so gas offers a straightforward means to meet sulfur restrictions on fuel without extra refining to remove sulfur. Note that since the point of comparison for NYC DOT is ULSD, gas does not significantly reduce sulfur emissions – the benefit is simply a lower-cost way to meet sulfur requirements.

Natural gas has inherently lower carbon content than diesel. Analysis performed for IMO found that a notional engine operating on LNG would produce approximately 14% less CO_2 than a comparable diesel engine (Reference 2). Conversely, production and use of natural gas does result in the release of uncombusted methane to the atmosphere. This occurs during the "well-to-tank" phase when gas is released from mining, processing, or storage equipment. This could be by design to vent or purge equipment, or by accident due to equipment leaks or failures. On the ferry, some gas may escape without being combusted due to conditions within engine cylinders, leakage past seals and moving mechanical parts, or when venting and purging. The amount of this "methane slip" depends on a variety of factors, including the specific combustion technology, engine loading conditions, and fuel system design.

Regardless of the mechanism or source, methane releases are of environmental concern. Methane is a potent greenhouse gas, with a global warming potential (GWP) 84 times more severe than CO_2 over 20 years (Reference 3). Although the 20-year time horizon is of greater concern for efforts such as the Paris Climate Accord, most literature that reports equivalent CO_2 values uses the 100-year GWP. This value, where methane is 28 times as potent as CO_2, is utilized in this report for consistency with other sources, but it must be understood that this underreports a significant transient effect. Considering the reduction in direct CO_2 together with the GWP of the released methane results in a wide range of equivalent CO_2 (CO_2e) emissions from gas engines. Although a modest reduction in 100-year equivalent CO_2 is possible, higher methane slip rates result in gas engines with significantly greater global warming impacts than comparable diesel engines. Engine manufacturers are aware of concerns regarding methane emissions. Even though methane emissions are not currently regulated, some low-slip engines are available and some information about methane emissions is included in marketing and technical literature.

Even with negligible methane slip from the engine, well-to-tank methane emissions contribute to natural gas lifecycle emissions. Additionally, energy consumed in the liquefaction process also has some level of associated emissions. A detailed evaluation of the full lifecycle emissions profile of natural gas production and delivery to ferries is beyond the scope of this study, but a review of other work performed gives some confidence that upstream GWP for natural gas fuel is no worse than diesel.

First, as with biodiesel, the California Air Resources Board has comprehensively reviewed the lifecycle emissions of natural gas fuels. Distributors must account for releases at their facilities, and estimated methane slip for the California fleet of road vehicles is included. Fossil-fuel LNG sources have Carbon Intensity scores around 90 compared to diesel's score of 102. This indicates that for the specific conditions analyzed for road vehicles in California, LNG has a roughly 12% net reduction in global warming impact, even when full lifecycle emissions and methane slip are included. A similar analysis would theoretically give an advantage to CNG because of the energy required for liquefaction of LNG. Review of CI scores for CNG available in California shows that it is often transported as LNG, revaporized, and then compressed, resulting in slightly higher energy consumption relative to LNG. This is not representative of how CNG would be used for NYCF, since the likely source of gas would be utility gas compressed at ferry terminals.

Reference 93 provides marine-specific analysis of LNG lifecycle emissions. Emissions are separated into three phases: “Well to Terminal”, “Terminal to Tank”, and “Tank to Motion”. Comparisons were made to various traditional fuel oil products and found that the combined Well-to-Terminal and Terminal-to-Tank CO_2e for LNG fueling was slightly less than diesel fuels. It is therefore reasonable to conclude that the full-lifecycle emission improvements for the LNG options presented in this report are no less than the “Tank to Motion” values presented in Section 6.1.7.

A review of scientific and public policy literature for this study found that the understanding, quantification, and regulation of these effects are still changing. Mining technologies such as hydraulic fracturing have expanded significantly in the past 25 years, and oversight and regulation of the associated environmental effects is still developing. There is risk that improved future understanding of the natural gas supply chain could result in significant changes to environmental regulation, prices, or both.

Gas engines also offer theoretical improvements in NOx and PM. Reductions in NOx depend on differences in cylinder conditions during combustion and therefore on the exact gas technology used in the specific engine application. Reductions in PM are attributed to the simpler molecular structure of methane compared to diesel. Reductions in sulfur, NOx, and PM mean that gas fuel has the potential to improve local air quality in addition to reducing lifecycle global warming potential. Limited manufacturer data has been received to demonstrate these theoretical gains. Manufacturer’s data received from EMD indicates no change in NOx emissions for either DGB or DIG relative to the comparable baseline diesel engine.

5.4.5 Cost

5.4.5.1 LNG Costs

Cost has been the main motivator for marine power LNG conversions to date. Natural gas fuel prices are both lower and more stable than diesel prices. The price differential is large enough to pay back the cost of a gas conversion project in as little as 5 years for some applications. Determining an as-delivered price for LNG requires adding several factors to the commodity natural gas price. The most significant of these is liquefaction costs, which could contribute more than half of the delivered price (References 4 and 5). Once a price for LNG is developed, transportation and delivery costs must also be considered, which will depend heavily on the local market, distance to the supplier, and scope of the contract. Even with all these costs included, LNG can be 50% cheaper than ULSD on an energy basis. Furthermore, the EIA projects that this price differential will increase over the next 30 years as shown in Figure 19 (Reference 88).

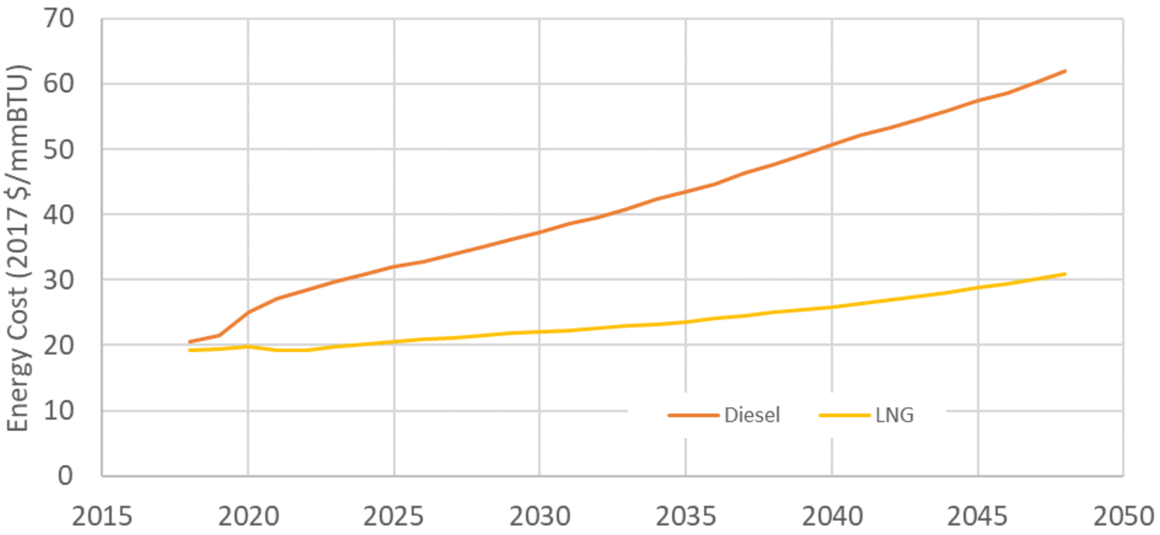


Figure 19 Projected LNG and diesel fuel costs based on the EIA 2019 Annual Energy Outlook

Natural gas prices are typically expressed in energy units ($/mmBTU). This allows accounting for normal variability in gas composition which would prevent volume or mass-based pricing ($/cubic foot or $/ton) from communicating a meaningful price. A nominal LNG price of $12/mmBTU was developed for this study and discussed with a potential LNG supplier. This price is used for analysis in Section 6.1.7.

Capital costs to switch to gas vary significantly depending on the details of the approach. In a SIF conversion project, the existing EMD 710 engines would be modified with new power components (cylinder liners, cylinder heads, etc.). This is similar in scope and cost to a full engine overhaul. Additionally, new components such as gas piping and injection valves would be added. Choosing a gas engine other than EMD's DGB or DIG would require completely repowering the ferries with new engines. Although quotes were not obtained for this project, a rough estimate based on past work is that the cost of each new engine would be on the order of $5 million, compared to $300,000 for a conversion. The fuel systems and other supporting modifications needed to execute a gas conversion project would be in addition to this engine-only cost.

Regardless of the engine selection, conversion to gas would require substantial changes to fuel systems and propulsion monitoring and alarm systems. New components such as the fuel tanks would require significant structural modification. Regulatory safety rules impose specific requirements on the arrangements of gas fuel systems that would need to be considered and could require additions such as airlocks to access certain spaces. Ventilation system design is a key component of gas safety and could require significant changes.

The full scope of an LNG conversion is estimated to cost $15M-25M and would take between four months and a year.

5.4.5.2 CNG Costs

Compared to diesel, CNG fuel shares the same underlying commodity price advantage as LNG. As it does not need to be liquefied and can be distributed using simpler, existing utility lines, other costs should be much lower than LNG. Review of past utility bills for the St. George terminal shows average natural gas costs of $9.50/mmBTU in 2018. This is 20% cheaper than the estimate described for LNG in the previous section. CNG fueling would also include energy and maintenance costs for on-site compression which would be added to the utility cost.

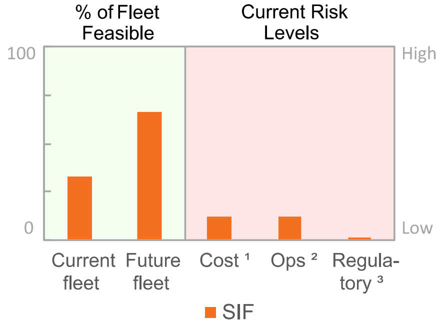
A CNG conversion would include many of the same shipboard elements as an LNG conversion, but with fewer and generally less complicated components in the fuel system. Although equipment costs would be lower, fewer ships have implemented CNG as a fuel, so engineering integration costs and costs associated with regulatory approvals could be higher. For the purposes of this report, the cost to convert the ferries to CNG is assumed to be equal to the cost for conversion to LNG.

Integrated Diesel Electric at a Glance

Recommended for near-term implementation on Molinari class

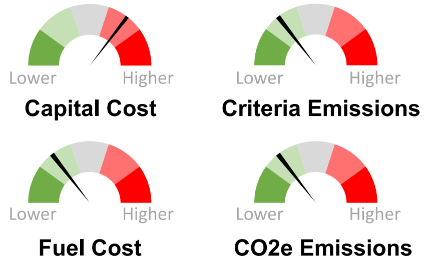
- Only applicable to SIF diesel electrics
- Lifecycle cost may be favorable
- Reduces engine hours/maintenance

Recommendation



[1] Low risk retrofit for SIF diesel electrics
[2] Eliminates ship service generators
[3] Proven marine technology, low regulatory risk

Feasibility and Risk Areas



CNG fueling would also require shore infrastructure that would presumably be purchased and maintained by DOT. Costs of such infrastructure were not determined in detail, but a rough estimate of the required compressor throughput and costs in Reference 69 suggests that approximately $1M of shoreside compressors would be required to power 4 large ferries per day on CNG.

5.5 Diesel Electric Technologies

The diesel electric propulsion technologies discussed in this section are readily compatible for retrofit with existing segregated diesel-electric propulsion plants on certain SIF vessels. The Molinari class vessels have propulsion plants of this type and may be good candidates to be retrofitted with the technologies discussed in this section. Future SIF vessels may also consider the technologies described here if implemented during the design phase. The section is not applicable to NYCF as they have diesel-mechanical power trains.

5.5.1 Integrated Diesel-Electric Propulsion Plant

5.5.1.1 Summary

Integrated diesel electric propulsion plants allow all generators to supply propulsion and ship service loads, as shown in Figure 20 below. This can provide efficiency and redundancy improvements over a segregated power plant. The City's existing diesel electric ferries, the Molinari and Kennedy classes, supply vessel propulsion power with two large generators and supply ship service power with two separate smaller generators. The large and small generators feed into separate, segregated electrical buses. Integrating the two power plants requires capital expenditure but provides greater flexibility in combined generator loading across the vessel load profiles. Operating a generator near its maximum load lowers brake specific emissions and fuel consumption with the net result of lower fuel cost, CO_2e production, and criteria emissions. Improved engine loading efficiency may also allow for generators to be periodically taken offline, reducing wear on the engines. Power quality is a concern for integrated plant installations, and power conditioning equipment is often required on the ship service feed, which adds some operational complexity and cost.

5.5.1.2 Background

Passenger ferries typically have three primary operating modes, as discussed in Section 4.3.1, and typically spend significant time operating below their most efficient operating point (usually about 85% load), particularly when maneuvering and when pushing against the dock during loading and unloading.

With a segregated propulsion and ship service power system, propulsion generators provide power to propel the vessel and separate ship service generators provide power for all other electric loads, including auxiliary systems, lighting, and navigation equipment. With a segregated system, power reserve is maintained on each side to allow for transient changes in load. The amount of power reserve is typically managed by the engineers on watch to meet the specific mission requirements and anticipated electrical loads.

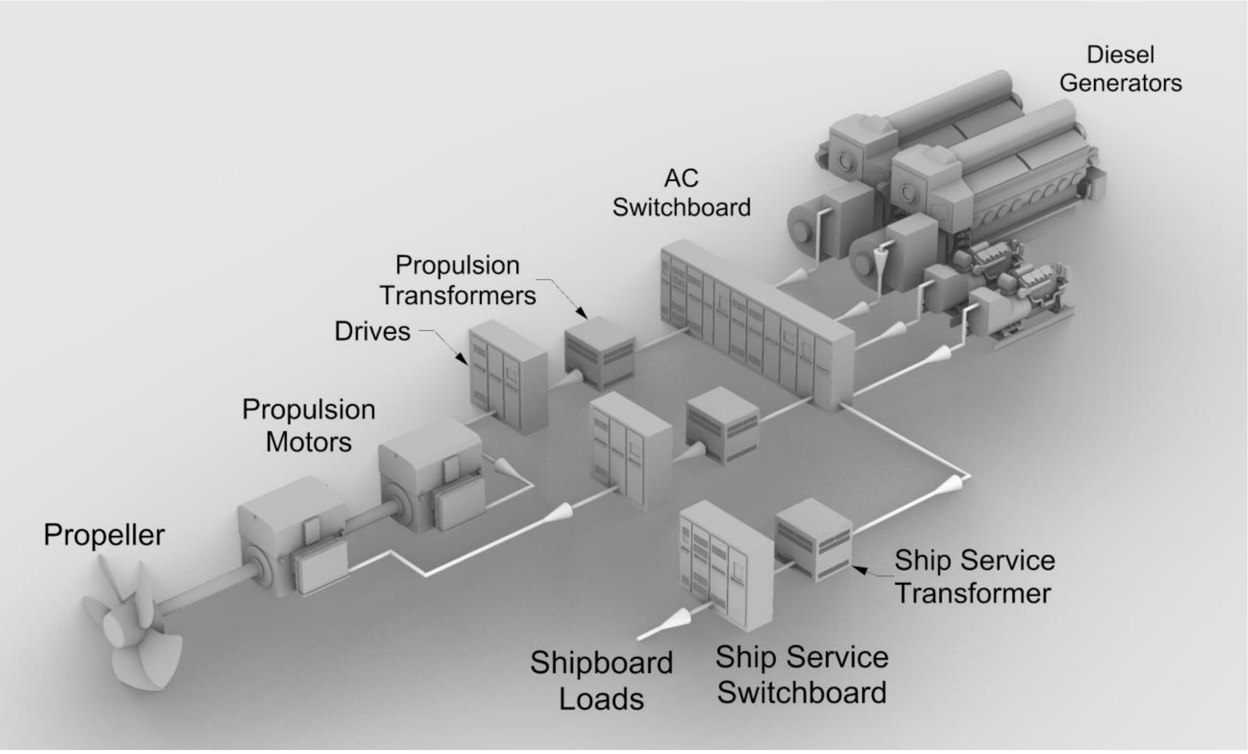


Figure 20 Notional diesel electric powertrain with integrated plants as proposed for Molinari class vessels, propulsion transformers to propeller shown for one end

With an integrated power plant, the propulsion and ship service generators are all connected to a common electric bus from which both propulsion and ship service loads are powered, as shown in Figure 20. In this type of system, a single power reserve can be maintained, which allows for fewer generators to be running, may allow for less installed ship service generator power, and increases average load on the generators in operation. Increasing the average load on the generators reduces the specific fuel consumption of the engines (fuel consumed per kWh of energy produced). This improves overall fuel economy and reduces emissions. Additionally, taking an engine offline decreases total running hours, resulting in potential maintenance cost reduction.

An integrated system also provides power plant redundancy, as all the installed generators can provide power to the combined propulsion and ship service electric loads on the vessel.

The primary concern with integrated power plants is power quality on the ship service side due to connection between the “clean” ship service bus and the “unclean” propulsion bus with its variable frequency drives and large electric motors. Power quality can be managed with a combination of good design and proper equipment selection, but it must be seriously considered. Inclusion of power conditioning equipment such as phase-shifting propulsion transformers, active front end (AFE) propulsion motor drives, and harmonic filtering equipment may be required in such installations.

5.5.1.3 Operational Considerations

The total drivetrain efficiency of an integrated power plant is approximately the same as a segregated power plant, as the primary equipment lineup used will be the same. The slight efficiency loss on the ship service power bus due to the addition of harmonic filtering will be compensated for by the higher efficiency of the large propulsion generators relative to the small ship service generators.

5.5.1.4 Environmental Impact

Sharing load between generators often allows for optimization of engine loading and subsequent decreases in specific fuel consumption and specific exhaust emissions. This leads to reductions in total fuel consumption and emissions compared to a split bus configuration.

5.5.1.5 Cost

The following new equipment would be required to integrate an existing segregated diesel-electric plant:

- Modified propulsion and ship service switchboards to support integration
- Power feeds from the propulsion switchgear to the ship service switchgear
- Electrical power conditioning equipment for the ship service bus
- Step down transformer(s) on electrical feed to ship service switchboard

5.5.2 Variable Speed Diesel-Electric Propulsion Plant

5.5.2.1 Summary

The need to produce a fixed-frequency 60 Hz AC electrical output is a downside of traditional diesel electric propulsion compared to diesel mechanical propulsion. This requires engines to operate at fixed rotational speed across the load profile and causes high specific fuel consumption (fuel consumed per unit power output) at low loading. With variable speed generators, engine speed is optimized and downstream electrical conversion equipment ensures proper frequency. This allows the engines to operate on a standard propeller curve, providing greater engine fuel efficiency at low load and lower generator maintenance. These benefits must be weighed against the higher capital costs of equipment when evaluating this technology.

Variable Speed Diesel Electric at a Glance

Benefits may not outweigh costs, see Section 6

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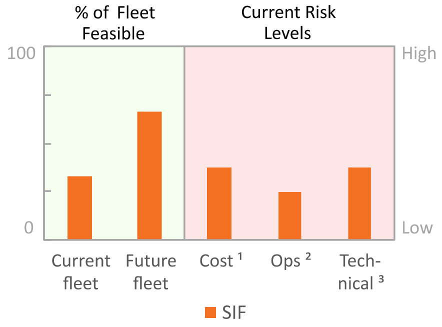
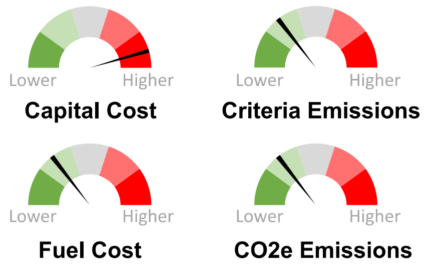
- Only applicable to SIF diesel electrics
- Increased fuel efficiency
- Simpler integration of hybrid/plug-in tech

Recommendation



¹ Relatively low risk retrofit for SIF diesel electrics
² Eliminates ship service generators
³ Relatively new in marine applications

Feasibility and Risk Areas



5.5.2.2 Background

Standard diesel generators, like those currently utilized on the Molinari class vessels, operate at a constant synchronous speed regardless of load. When propulsion load is low (during maneuvering and pushing the dock), the power plant sees relatively high specific fuel consumption. The increased specific fuel consumption is primarily due to engine-driven auxiliary equipment (cooling, fuel and lube oil pumps, etc.) that becomes a higher percentage of the generator output. Operators generally compensate by shutting down unnecessary generators during extended periods of low load; however, most ferries' rapid turnaround times make stopping and starting generators operationally impractical. This low-load inefficiency has traditionally been a disadvantage of diesel electric propulsion systems in ferries.

The evolution of electrical frequency converters over the last several decades has enabled efficient conversion of variable frequency input power using a direct current (DC) link between generator sets and vessel loads. This technology allows the diesel generator to reduce rpm to match reduced load, similar to the way an engine would operate in a diesel mechanical propulsion system.

Use of a DC bus enables and simplifies future integration of energy storage devices such as batteries, capacitors, or fuel cells that produce DC power. It also simplifies the integration of propulsion and ship service switchboards by eliminating the need for transformers, active front end drives, or other power conditioning equipment. It is important to note that variable speed generating technology is relatively new to the marine industry and has a limited operating history. However, the flexibility it offers for energy storage devices and operating scenarios should cause this technology to advance and mature quickly.

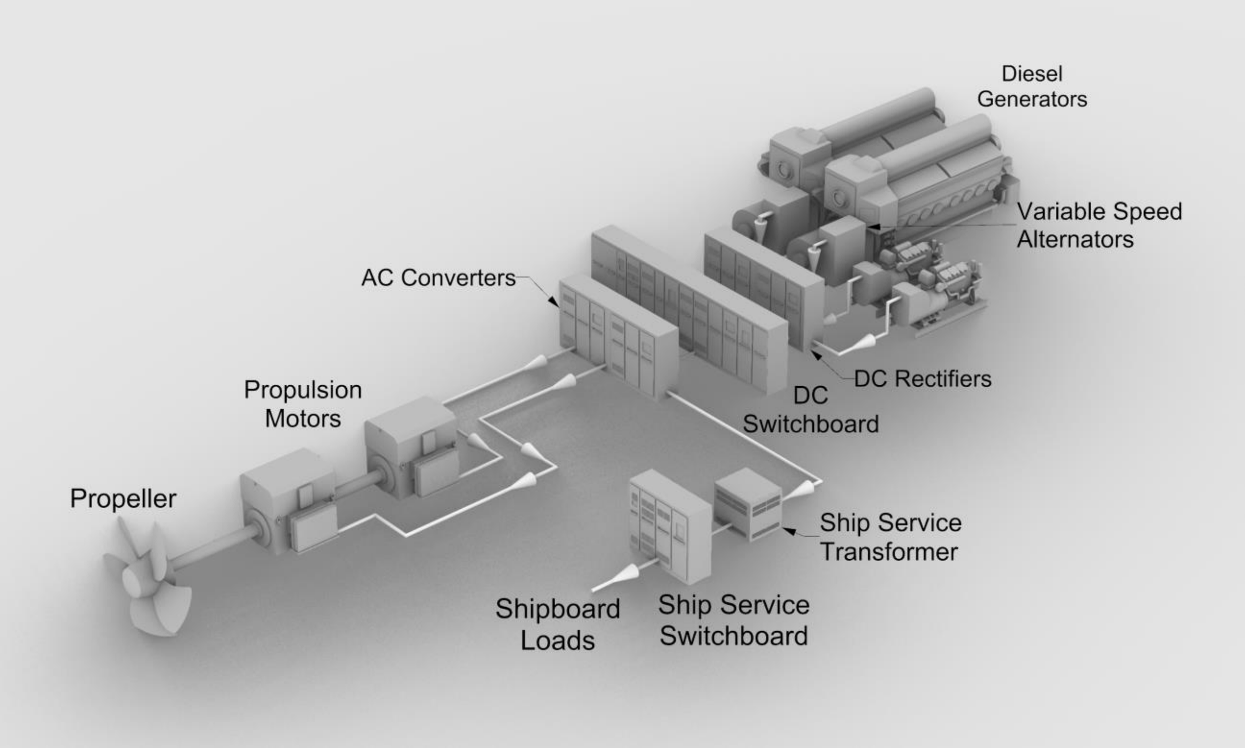


Figure 21 Notional diesel electric powertrain with integrated variable speed generators and propulsion / ship service plants as proposed for Molinari class vessels, propulsion transformers to propeller shown for one end

5.5.2.3 Operational Considerations

Variable speed diesel electric technology has several operational impacts:

- DC switchboard eliminates the need to parallel (i.e. synchronize) generators
- Reduced engine and alternator revolutions can reduce maintenance
- Consolidated equipment leads to smaller overall footprints but often larger local footprints (i.e. no transformers or drives in the motor room but larger switchboards)

5.5.2.4 Environmental Impact

An integrated variable speed power plant optimizes fuel consumption across the load profile, leading to reduced overall fuel consumption and associated emissions. Medium speed engines like those installed on the Molinari class could operate at speeds between approximately 500 rpm and 900 rpm rather than at a constant 900 rpm. Notable reductions in overall fuel consumption have been realized by other ferry operators using variable speed diesel electric technologies.

5.5.2.5 Cost

The following modifications and new equipment are required at a minimum when converting an existing segregated constant frequency AC diesel-electric plant to variable speed generation. It is assumed that the system will also be integrated.

- Modification to each diesel engine control system to allow variable speed operation

- New variable speed propulsion and ship service alternators in place of constant speed machines
- New DC rectifiers – one for each variable speed alternator
- New propulsion switchgear with integrated DC bus
- New AC inverter/drive units – one for each propulsion electric motor
- New AC inverters (2) for ship service switchboard
- Ship service and emergency switchgear modifications

5.6 Electric Energy Storage

5.6.1 Background

Fundamentally, diesel fuel represents stored energy for performing work, whether on a ferry or in a truck. For the purposes of this report, this stored energy is released by combusting the fuel in an engine to perform the work of turning a propeller on the ferry or powering ship service loads. This section discusses electric energy storage options for ferries, and specifically, different ways to utilize rechargeable batteries to power, or help power, propulsion and ship service loads. These batteries must have sufficient energy storage capacity to “fuel” a ferry or some subset of ferry electrical loads or systems for some portion of time, thereby replacing or reducing the energy produced by burning fossil fuels.

Battery storage technologies for marine propulsion are not new; in fact, various forms of battery storage and electric propulsion have been used in submarines since World War I. In the last decade, battery technology has improved significantly while costs have fallen precipitously. The most significant improvements have been in energy storage density, installed cost, and cycle life. These improvements were initially driven by the consumer electronics industry, but more recently have been driven by the automotive and grid storage markets.

Cycle life refers to the number of charge-discharge cycles that a battery can tolerate before its capacity has degraded to a certain level. The standard definition of cycle life is the number of full (0-100% and 100-0%) charge-discharge cycles before the energy storage capacity has reached 80% of its beginning of life capacity. Reduction in battery capacity over time is an experience that most smartphone users are familiar with, and the concept is similar for batteries used in marine and grid storage applications.

The number of charge-discharge cycles that a battery can tolerate is very dependent on the depth of each charge (how much of the capacity is charged or discharged) as well as the starting and ending points of the cycle. Increasing the capacity of the battery bank can greatly increase the cycle life because the depth of the charge-discharge cycle is reduced relative to the overall battery capacity (e.g. a battery with twice the capacity has half the depth of discharge and consequently a longer life). Selecting a battery for a ship is a complex process of trade-offs and optimization for various factors such as capital cost, weight, battery chemistry, space, cycle-life, and safety.

Ship-based battery storage systems are charged by plugging into the shoreside electrical grid, by fuel cells, or by absorbing excess diesel generator loads. This section of the report will look briefly at modern battery technologies and ways in which they can be used in shipboard power systems to reduce fuel consumption and reduce emissions.

Batteries have defined charging and discharging abilities, which are characterized by the C-rate. The C-rate is a multiple of the battery capacity. For example, a battery with a capacity of 50 kWhrs may have a charging C-rate of 3C. This implies the battery can charge at 150kW for 20 minutes. The C-rate limits the power input/output a battery can provide, and along with other characteristics such as weight and volume, plays a significant role in the optimization of a battery propulsion system.

5.6.2 Battery Technology Overview

5.6.2.1 Lithium Ion

For battery installations on most small to medium sized marine vessels, lithium ion batteries are the preferred solution. An increasing number of suppliers are developing systems specifically for the marine market, and there are several passenger ferries currently in service that utilize lithium ion batteries for propulsion power. Lithium ion batteries are increasingly accepted and implemented for onboard energy storage on a variety of vessels including workboats, ferries, fishing vessels, construction vessels, and others. This battery technology is well suited for transportation due to high energy and power density and a relatively high cycle life.

There are many types of lithium ion batteries on the market serving a variety of different purposes. The most common candidate technologies for installation on a passenger ferry are lithium nickel manganese cobalt oxide (NMC) and lithium titanate (LTO) batteries. The main functional difference between the two is that the NMC batteries offer a significantly higher energy density at higher cost, while LTO batteries offer a lower energy density at a lower cost and longer lifespan, (see Figure 22 for a comparison between NMC and LTO batteries). For more detailed information on NMC and LTO batteries as well as the wide range of other lithium ion battery technologies available, see Reference 68. Because weight and space are of significant concern on marine vessels, most marine-approved batteries currently in production and in use are of NMC chemistry. As an electric ferry will require large batteries due to the size of the vessel, the most feasible technology will likely be NMC, although other technologies should be investigated further prior to implementation.

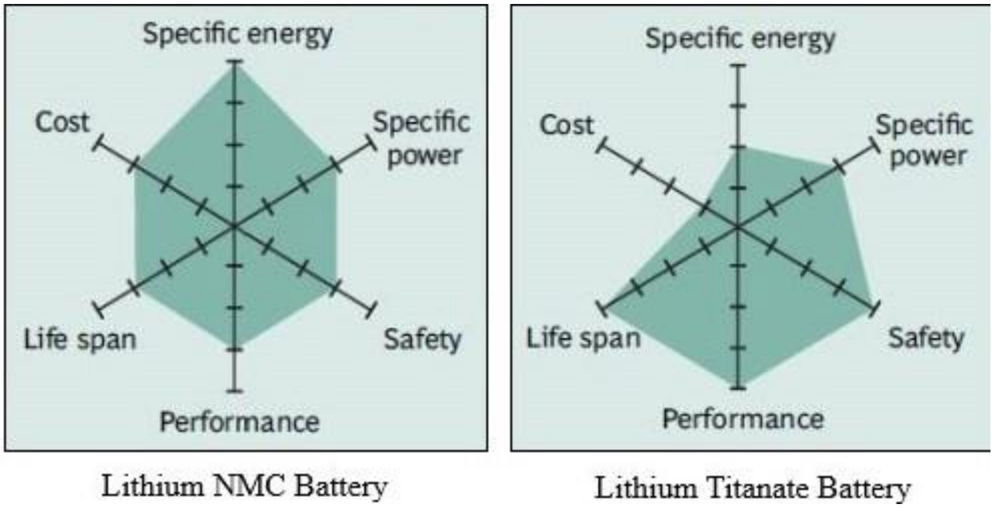


Figure 22 NMC vs LTO battery comparison (Reference 68)

Another consideration for implementation is that not all lithium ion battery types are inherently safe, and for many the safety is managed by sophisticated control and monitoring systems that constantly monitor battery cell conditions and can shut them down if anomalies occur.

Integrating lithium ion batteries on a marine vessel needs to be done with an understanding of the inherent risks and failure modes of the particular battery chemistry that is chosen. Battery storage compartments may require additional fire monitoring and suppression systems as well as special ventilation systems and should be designed in cooperation with regulatory bodies. Classification society rules now exist for designing batteries into marine vessels. USCG does not yet have rules written in the federal regulations, but the increasing number of vessels with batteries provides regulators more experience and over time should streamline the design and approval process.

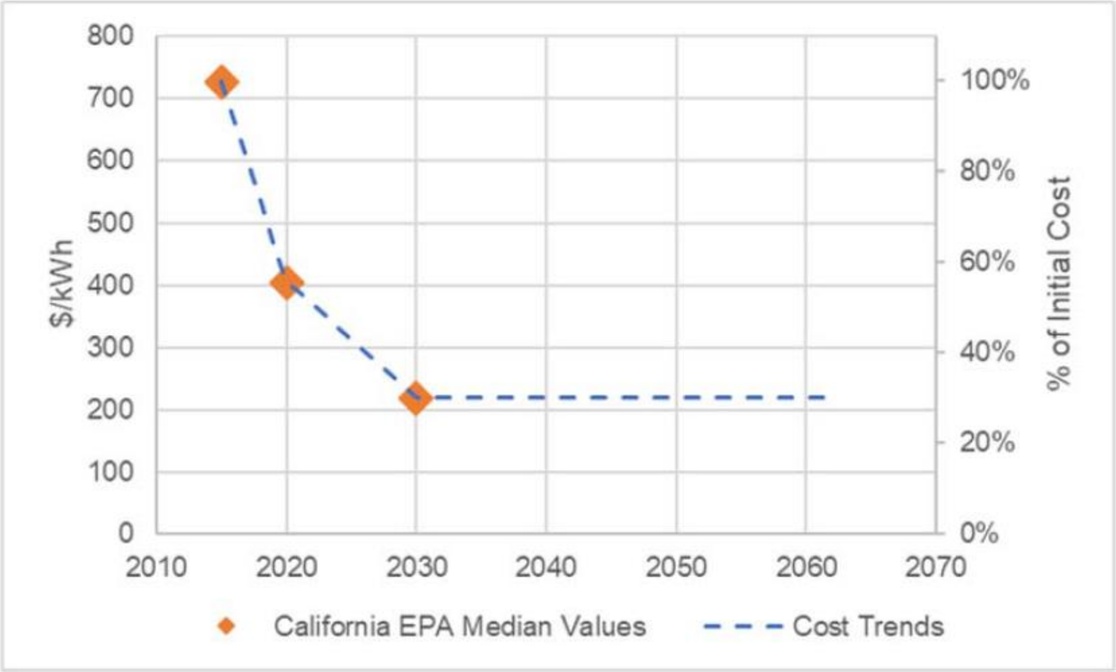


Figure 23 Projected marine NMC lithium ion battery cost trend (Reference 7)

In the past, lithium ion batteries have been quite expensive, but economies of scale primarily driven by the electric vehicle and consumer electronics markets are rapidly driving down costs. Based on discussions with lithium ion battery suppliers and analysis of publicly available information, 2017 marine prices were previously estimated at $650/kWh. The estimated trend for the cost of marine NMC lithium ion batteries is given in Figure 23, with an estimated long-term cost of approximately $210/kWh beginning in 2030.

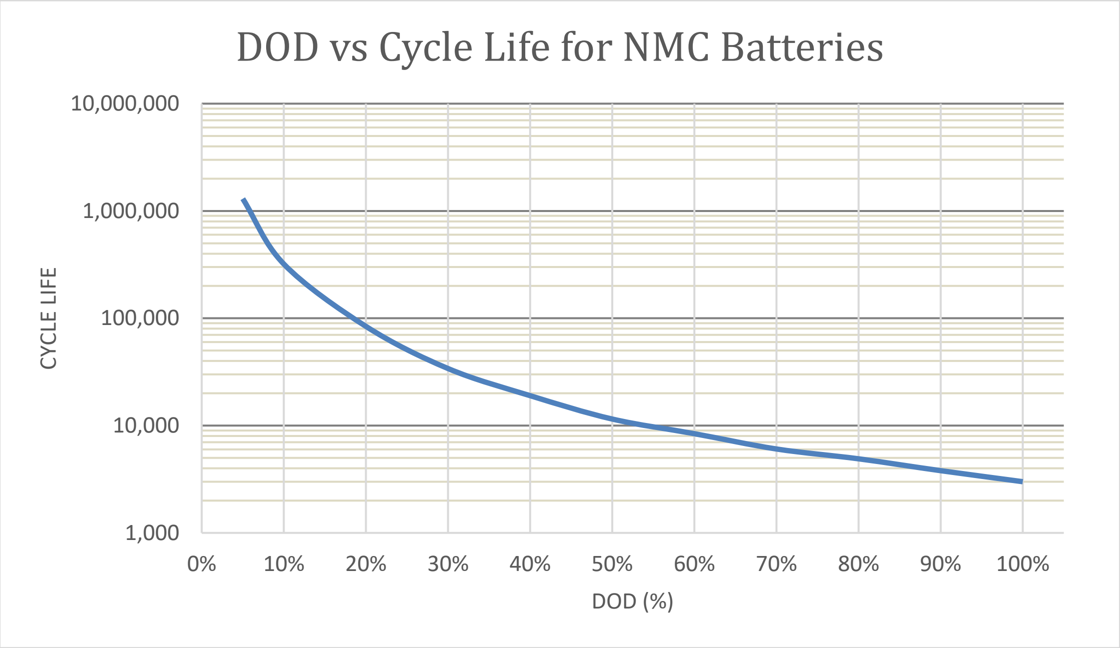


Figure 24 Projected marine NMC lithium ion battery cycle life vs. depth of discharge

The average depth of discharge of a lithium ion battery is directly correlated to the lifespan of the battery. The greater the depth of discharge per cycle, the shorter the number of cycles of battery life. The common design point is a depth of discharge of approximately 30% and a battery lifespan of between 30 and 40 thousand cycles for NMC batteries, as shown in Figure 24. As battery technology continues to advance, it may become possible to increase depth of discharge without affecting lifespan, allowing for installation of a smaller battery or further increasing battery lifespan.

5.6.2.2 Other Advanced Battery Technologies

While the existing lithium ion battery technologies discussed above own most of the present market share and are most feasible for current installations, numerous alternate battery types and startup ventures are attempting to gain a share of the market. While most of these technologies are currently in various stages of pre-commercial design, in the future it is likely that some of them will become viable alternatives to the current lithium ion technology for use in powering marine vessels.

5.6.2.3 Lead Acid

Lead acid batteries are the technology used in a standard 12-volt vehicle battery. This battery technology is typically used on marine vessels for equipment uninterruptible power supply (UPS) applications to power radios and other electronic equipment during an onboard electrical power system failure. There are many different types of lead acid batteries, but they are all generally characterized by low energy and power density, low cycle life, and low cost. They are a good choice for a UPS, but due to low energy and power density, they are a poor choice for auxiliary or propulsion power on a marine vessel.

5.6.3 Hybrid-Diesel Propulsion Systems

5.6.3.1 Summary

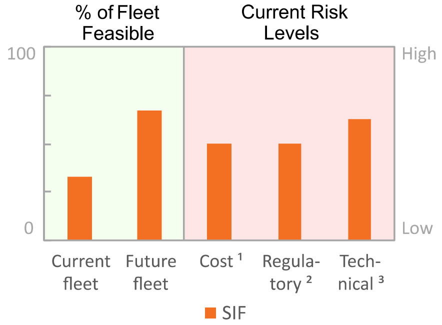
Hybrid-diesel propulsion systems use battery power to assist with propulsion and/or ship service loads. Both hybrid types examined in this section, series hybrid (SIF applicable only) and parallel hybrid (SIF and NYCF applicable), can improve vessel efficiency in both high and low power demand situations. A series hybrid improves generator efficiency by charging a battery with excess generator power during low power demand and using this absorbed energy to help power the vessel during high power demand. A parallel hybrid, on the other hand, allows for the ship service diesel generator to charge a battery which can then supplement a combined electric motor and diesel mechanical drivetrain by exclusively powering the vessel during low power demand and possibly providing extra power during high power demand periods.

Series Hybrid at a Glance

Benefits may not outweigh costs, see Section 6

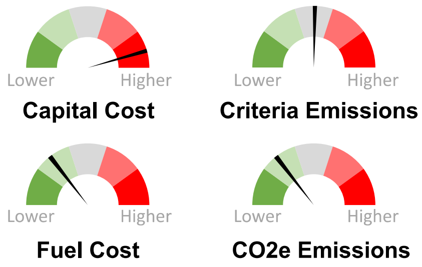
- Only feasible for SIF diesel electrics
- No shoreside modifications needed
- Entry to battery propulsion

Recommendation



¹ Medium risk retrofit for SIF diesel electrics
² Need regulatory approval for battery integration
³ Current engine sizes poorly suited for hybrid ops

Feasibility and Risk Areas



When used in appropriate applications, hybrid-diesel propulsion systems may lower fuel costs, emissions, and engine wear. However, the added batteries and charging equipment carry a substantial weight and interior volume penalty, and careful analysis is necessary to determine whether the efficiency reduction due to added weight offsets the efficiency gain a hybrid's battery assistance provides. The additional equipment and operating modes also moderately increase operational complexity.

While it is technically possible to convert a diesel-mechanical propulsion plant to a hybrid-electric configuration, the conversion would be expensive, and based on projected fuel savings, would not be recoverable from a lifecycle cost perspective. The City's present diesel electric ferries are more viable candidates for hybrid-electric retrofits.

5.6.3.2 Background

Series Hybrid

In a series hybrid system (Figure 25), batteries are added to a diesel-electric propulsion plant both to enhance the propulsion generators' efficiency and to reduce their peak loads. At times of low load, while pushing the dock or maneuvering, reserve generator power that would otherwise go unused charges the battery bank. At times of peak load (transiting), the battery bank discharges this stored energy back to the combined power plant to assist the diesel generators in meeting the demand. In this way, rather than simply following load changes in real-time with diesel generators, the battery bank smooths out the operating profile and enables the propulsion generators to maintain a higher-efficiency operating point.

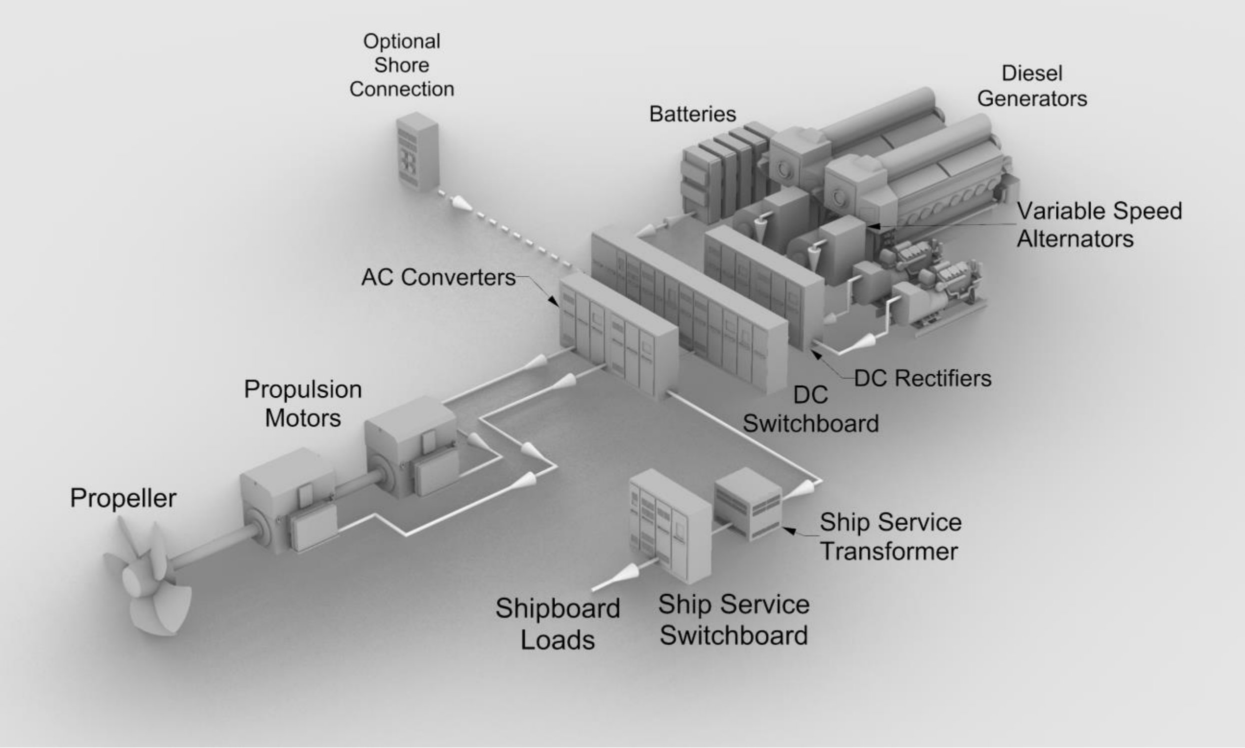


Figure 25 Notional series hybrid electric powertrain with integrated propulsion / ship service plants, and variable speed generators (optional) as proposed for Molinari class vessels, propulsion transformers to propeller shown for one end

This use of battery power reduces the peak load on the generators, reduces specific fuel consumption of the generators during low load periods, and may allow for the reduction in the number of online generators required for normal operations. A reduction in the required number of online generators would also reduce overall runtime and maintenance on the propulsion plant.

There are two options for connection of batteries to a vessel's power plant. One is to install batteries with dedicated a charger/converter connected to the existing AC switchgear on the vessel, as shown in Figure 25. The second option is to switch to a common DC bus where power from the propulsion alternators is rectified and fed to the DC bus in the vessel's switchboard, similar to the arrangement for a variable speed propulsion generator system (Section 5.5.2). A battery bank then ties to the common DC bus to charge batteries when additional generator power is available (demand is less than online generator capacity), and discharge batteries when power is needed (demand is greater than online generator capacity). Power from the DC bus is inverted to AC to supply the propulsion motors and ship service switchboards. At each of these power conversion steps for the second option, some power is lost. Conversion efficiency is therefore an important factor when determining feasibility of a series hybrid system, as the savings from increased generator efficiency must outweigh the power conversion losses.

The general advantages of a series hybrid are:

- Relatively easy conversion from diesel electric
- Potential to reduce size of diesel generators
- Potential to reduce number of online diesel generators
- Reduced maintenance on diesel engines
- Potential for some battery-only operation at low speeds (depending on battery size)
- Easy to integrate alternative power sources (fuel cells, solar, wind, etc.)

The series hybrid will be challenged by a potentially higher up-front cost and added weight. If a diesel electric design is being considered, then series hybrid should be considered, but this option generally will not make sense where lower weight and volume are required.

Parallel Hybrid

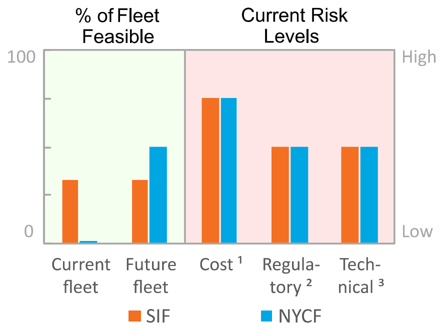
A parallel hybrid system is more similar to a conventional diesel mechanical system, but with a small diesel electric system installed in parallel to the diesel engine through a combining gearbox, as shown in Figure 26 on the page following. In a typical parallel hybrid, there is an electric motor physically geared in parallel with a diesel engine such that either or both can provide power at any given time.

Parallel Hybrid at a Glance

Benefits may not outweigh costs, see Section 6

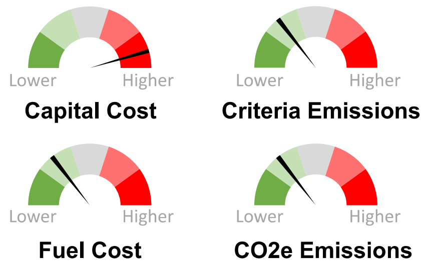
- Only feasible for diesel mechanicals
- Battery only supplements diesel
- High cost for modest benefit

Recommendation



¹ Relatively high risk retrofit for diesel mechanicals
² Need regulatory approval for battery integration
³ Integrating electric motors / mechanical drivetrain

Feasibility and Risk Areas



Parallel hybrid systems are suitable when the vessel load profile has some operational situations requiring high power and some operational situations only requiring low power. For example, a harbor assist tug may need to have very high power available for arresting or moving a large oceangoing vessel. This requires installing very large diesel engines driving very large propellers. However, the high power is only needed perhaps 10% of the time. The remainder of the time, the vessel may be transiting at very low power or loitering. A parallel hybrid design is well suited to this task since it allows the vessel to operate at least partially on battery, reducing fuel consumption, emissions, and noise. When high power is needed, the main engines and the motors can work in parallel, providing an added boost of power. Engines can operate close to their best efficiency, saving fuel. Another example may be a high-speed ferry such as those used by NYCF, where high power is needed for full speed, but not for maneuvering or transiting in higher traffic. Parallel hybrids are typically much lower weight than series hybrids.

Advantages of a parallel hybrid are:

- Enhanced efficiency for the right vessel operating profile
- Potentially smaller main engines
- Reduced maintenance on engines
- Potential for electric only operation at low loads

Parallel hybrids are best suited for applications where diesel mechanical is more typically used, for example in high speed ferries or tugboats. The increased efficiency comes at a higher cost and weight, so this tradeoff needs to be measured against potential fuel and emissions savings.

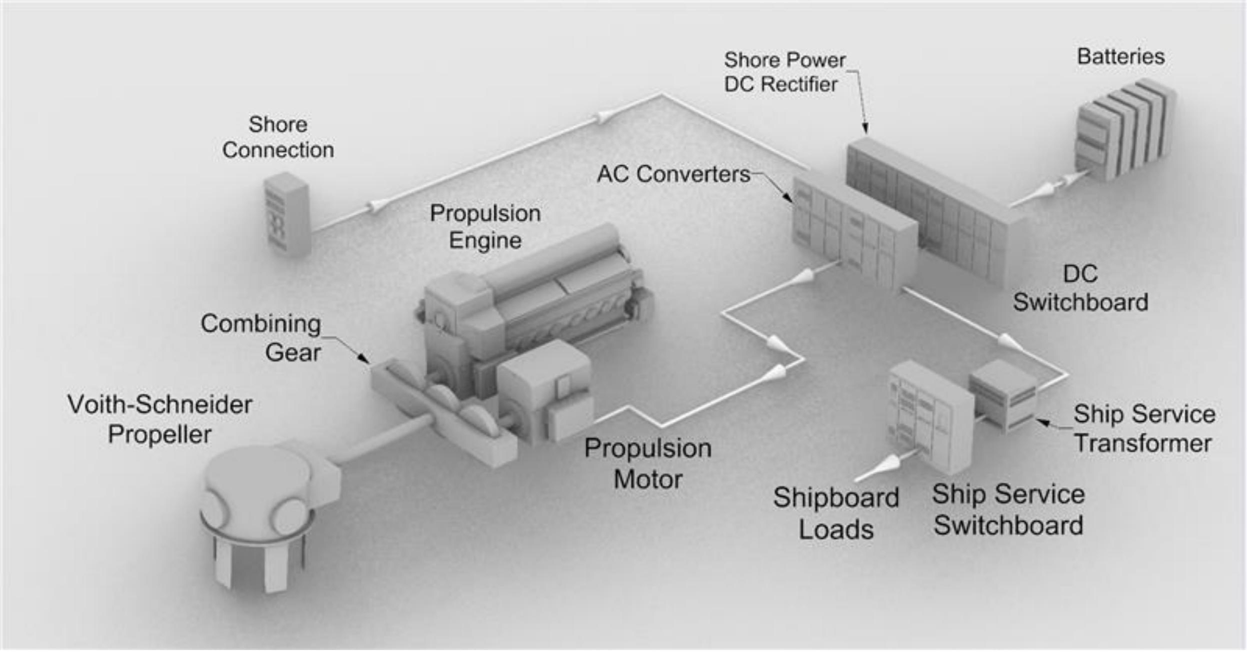


Figure 26 Notional parallel hybrid electric powertrain as proposed for Ollis class vessels – engine, motor and propeller shown for one end; plug-in electric arrangement has two motors and no diesel engine

5.6.3.3 Operational Considerations

Both series and parallel hybrid systems are more complex than diesel electric or diesel mechanical propulsions systems, so the skill sets of the operators and maintenance crew need to be considered before bringing hybrid vessels into the fleet. In terms of required skills, the difference between diesel electric and series hybrid is relatively minor since the vessel is already electric. However, the difference between a diesel mechanical and a parallel hybrid is substantial, requiring significant training for crew and maintenance personnel. For the SIF fleet, which already has diesel-electric vessels in the fleet, the maintenance and operations skills will already exist. For NYCF, which has a fleet of diesel mechanical vessels, additional skilled electricians and engineers will likely be needed.

The addition of stored energy for either type of hybrid provides some potential redundancy advantages. For example, depending on the system, the battery may be able to move the vessel at a slow speed, even if the engines are not operational. This could provide a short distance ‘take-home’ solution.

Installing batteries on a vessel will introduce operational changes for both types of hybrid. Lithium ion batteries require monitoring and additional cooling and ventilation systems. The added cooling and ventilation systems will themselves have components such as fans and pumps that need maintenance. The batteries may also require onboard fire detection and fire suppression systems, which will need to be inspected and maintained.

5.6.3.4 Environmental Impact

A diesel-hybrid system provides environmental benefits in two forms:

- CO_2e and criteria emissions reductions in direct correlation to the reduced fuel consumption.
- Specific criteria emissions reductions (i.e. g/kWh) from the increase in relative engine loading (percent of maximum continuous rating). A sample data set showing this trend is provided in Section 4.2.2.2.

5.6.3.5 Cost

In general, the following new equipment is required when converting an existing propulsion system to a diesel-hybrid system. It is assumed that the onboard electrical systems will also be integrated.

Segregated Diesel Electric to Series Hybrid

- Batteries and battery management system
- Charger/converter for batteries (AC switchgear only)
- DC rectifier – one for each alternator (DC switchgear only)
- Propulsion switchgear with integrated DC bus (DC switchgear only)
- AC inverter/drive units – one for each propulsion electric motor (DC switchgear only)
- AC inverter or transformer for ship service loads
- Harmonic filters for ship service switchgear (AC switchgear only)
- Updated propulsion control system to manage power distribution

Diesel Mechanical to Parallel Hybrid

- Batteries and battery management system
- Charger/converter for batteries (connecting to either generators or shore power)
- Propulsion motors, clutch, and combining gears to parallel with diesel engines
- Updated propulsion control system to manage power distribution

5.6.4 Plug-in Propulsion Systems

5.6.4.1 Summary

A plug-in electric propulsion system uses batteries powered by the onshore utility grid to power all vessel loads. While plug-in electric vessels generally have a backup diesel generator available as a power source in case of battery equipment failures, during normal operation they operate entirely without onboard internal combustion, resulting in zero point-source (localized) air emissions. Plug-in vessels' global emissions impacts are as beneficial as the utility source that powers them, as they receive power from whatever mix of fuel sources the utility uses to produce electricity for the grid. However, due to the incentives in cleaning up the massive electricity market, it is likely that over time the specific emissions from grid-scale electrical production will be significantly less than those for a diesel engine. It should be noted that emissions calculations must consider the power transmission losses that occur as power is routed through the grid from the generating source to its endpoint on the vessel.

Batteries capable of acting as a ferry's sole power source are large, heavy, and must be frequently charged. The exact size and charging frequency requirements must be determined in concert with the vessel's internal arrangement and stability requirements; a larger battery bank can store more power and may therefore require less frequent recharging but may also exceed space and/or weight requirements. A feasible design for SIF vessels would likely need to charge at each one-way crossing, resulting in significant operational impacts. Battery technology has not yet matured to the stage of being a viable option for the NYCF vessels.

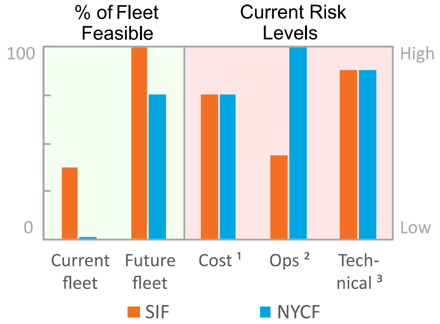
In addition to significant vessel retrofit or new vessel design costs, implementing plug-in propulsion requires costly shoreside infrastructure upgrades, making this a very capital-intensive option. Fuel costs may be reduced or may increase, depending on the electricity rates the utility provider charges.

Plug-in Electric at a Glance

Recommended for long-term implementation on SIF & NYCF vessels

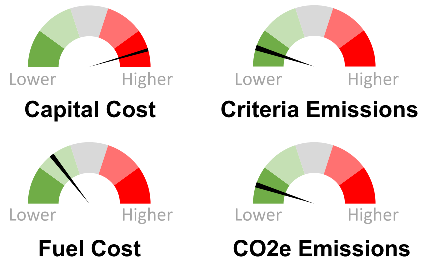
- Capitalizes on grid innovations
- Highest CO2e reduction potential
- High ship and shore capital cost

Recommendation



¹ Requires costly ship & shoreside infrastructure
² Pier use and backup power
³ Marine applications in US still rare

Feasibility and Risk Areas



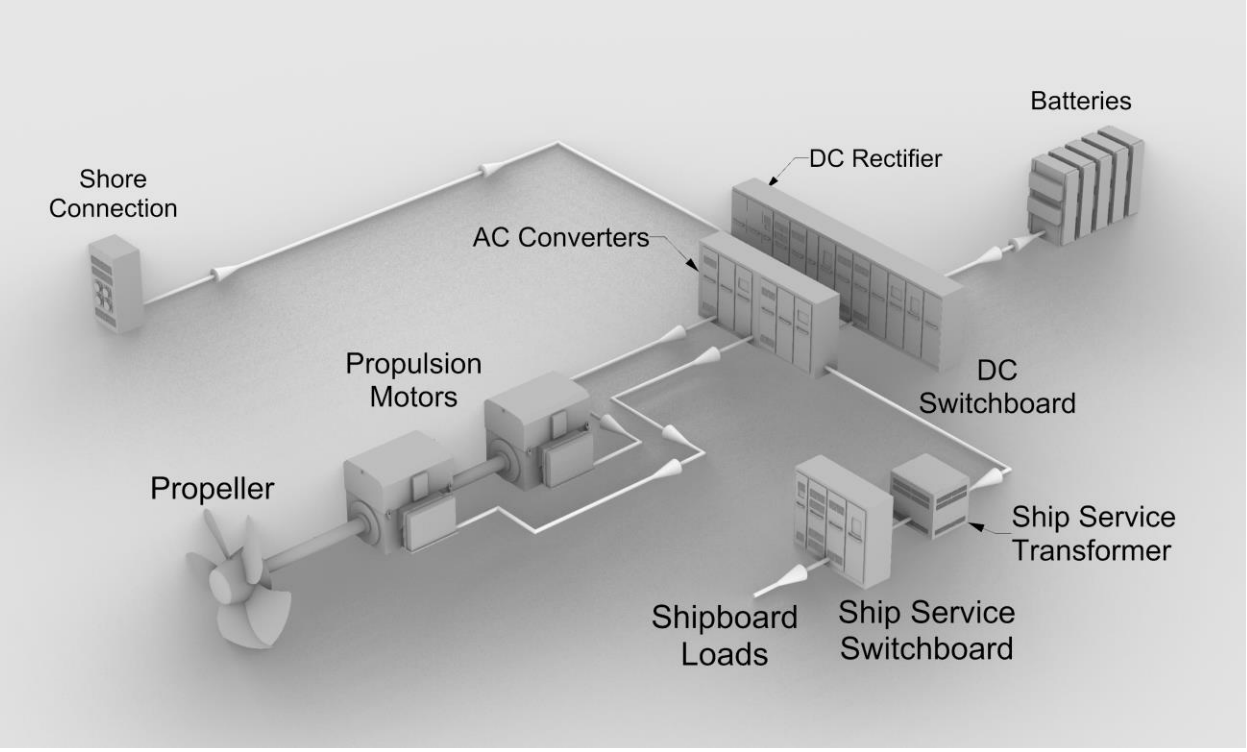


Figure 27 Notional plug-in electric powertrain as proposed for Molinari class or future vessels, motors and propeller shown for one end

5.6.4.2 Background

Propulsion technologies that include a connection to the utility grid have the potential to shift some or all of a ship's energy consumption to a shore based electrical grid. These technologies have the potential to greatly reduce or eliminate diesel fuel consumption on the ferries and the associated local emissions. However, these systems typically require extensive modifications to the ferries themselves, the ferry terminals, and the surrounding shoreside infrastructure. Consequently, the capital costs associated with these extensive modifications are high, and these costs are driven by the size and power levels of the equipment needed to operate the ferries.

Understanding the full lifecycle costs and potential benefits of plugging into grid-based power requires a detailed understanding of the capabilities, emissions profile, and cost structures of the utility company to allow meaningful comparisons to traditional combustion fuels. Washington State Ferries (WSF) conducted a detailed study of plug-in hybridization for its 460' long Jumbo Mk II class ferries (see References 6 and 7). Although there are some differences between the WSF vessels, routes, and applications compared to ferries in NYC, the major takeaways from these studies are relevant to SIF and are summarized in this study.

5.6.4.3 Operational Considerations

Operational considerations for plug-in systems revolve around the relationship between onboard battery bank capacity and dock time available to charge the batteries. A battery bank large enough to power a SIF vessel for a one-way crossing with 30% depth of discharge to achieve a six-year design life would be approximately 4.5 MWh, with an approximate weight of 43 MT. A battery this size would require roughly 33 battery racks, which are each 4.13 ft wide x 7.37 ft tall x 2.68 ft deep and can be banked up to 8 racks deep for a total length of roughly 21.5 feet. The battery racks would be split into two separate banks on the vessel, fwd and aft, for redundancy.

Given these space considerations, investigations into plug-in electric solutions must include provisions for fully recharging the batteries every time the ship docks. In a new vessel design, some battery power might allow adjusting the size or number of generators to reduce construction cost or improve operating efficiency similar to the hybrid designs discussed in Section 5.6.3.

Plug-in hybrid solutions that require major modifications to the existing propulsion plant and installation of shoreside infrastructure which operate on both battery and diesel power at the same time were not considered for retrofit on SIF vessels in this study. Due to the cost of installing any shoreside infrastructure for plug-in systems, it is assumed that any installation of a plug-in system would be done with the target of fully plug-in electric operation even if capability of diesel operation is maintained for emergency situations. Major modifications are considered replacement of the main engines or modifications of similarly high capital cost.

The major difficulty in achieving a feasible operational schedule for a plug-in ferry is the high ratio of underway time to dock time. This necessitates both shoreside and shipboard equipment that can handle very high charging rates, in the range of 12-15 megawatts, and automated shore power equipment that can connect to the ship within seconds of reaching the dock. Although automated shore power technology exists, it is relatively immature, and implementing it for a double ended ferry dock requires solving some challenges not yet addressed in existing installations (Reference 7). However, the field is evolving rapidly, and as higher-powered ferries enter service, more charging solutions will continue to become available.

5.6.4.4 Environmental Impact

With respect to emissions, plug-in systems have the advantage of shifting the point of energy generation and emissions away from the city, with a corresponding benefit to local air quality. The U.S. Energy Information Administration (EIA) and the U.S. Environmental Protection Agency (EPA) both tabulate information about electricity generation and emissions. In New York state, over 50% of power generation comes from zero-emissions sources (mostly nuclear and renewable), and most of the remainder comes from natural gas. Based on the worst-case emissions scenarios from the EIA (see Reference 9) and the EPA (see Reference 77), the specific emissions rates for New York state electricity generation are as follows:

Table 21 New York state electricity generation emissions rates

Emission	Emission Rates (g/kWh)		
	NY Electric Grid	SIF Average	NYCF Average
CO_2	200	740	740
NOx	0.2	6.6	4.5
CO	0.1	0.8	0.7
HC	0.007	0.4	0.1
PM	0.01	0.1	0.1
SOx	0.1	0.007	0.007

The small contribution of coal fired power plants to the state's power generation results in average SOx emissions significantly higher than a ferry burning ULSD. However, as natural gas-powered electric plants emit very little SOx, this difference may be reduced over time as coal plants are taken offline or better sulfur exhaust cleaning systems are installed. Average CO_2 and regulated emissions other than SOx from the New York State electrical grid are significantly less than the EPA Tier 4 diesel engine limits, the highest current marine emissions standard. Only the new SIF Ollis class will meet EPA Tier 4, all current vessels are Tier 3 or lower.

5.6.4.5 Cost

Due to the extensive nature of the upgrades required for conversion to plug-in operation, the capital cost of this option is much greater than the baseline. In general, the new equipment listed below would be required when converting an existing propulsion system to a plug-in hybrid system. It is assumed that the onboard electrical systems will also be integrated. This list only includes high-level changes and equipment and should not be considered comprehensive.

- Electrical supply infrastructure upgrades at each terminal
- Shoreside automated charging stations at each terminal
- Onboard batteries and battery management system
- Onboard charger/transformer for battery charging
- Propulsion motors and clutches to parallel with diesel engines (parallel hybrid only)
- Common DC bus to integrate batteries with existing generators (series hybrid only)

- Updated propulsion control system to manage power distribution

Up-front capital costs associated with a plug-in fully electric conversion would be significant. Reference 6 estimated vessel conversion costs for WSF to be approximately $30 million per vessel. While the WSF ferries are somewhat larger than the SIF vessels, they are diesel-electric, offering some advantage in converting to a hybrid system compared to NYC's fleet of both diesel-electric and diesel-mechanical ferries. Shoreside infrastructure upgrades added another $7-17 million per terminal, depending on the existing shorepower capability and extra equipment required.

5.7 Methanol

5.7.1 Summary

Methanol produces lower criteria and CO_2e emissions, but it is energy intensive to manufacture. While it is corrosive, methanol is much simpler to handle than hydrogen and natural gas since, like the various forms of diesel, it is a liquid at room temperature. It adds bunkering complexity and requires retrofits to be compatible with standard diesel engines, but it can be stored in a normal double bottom fuel tank once on board. Methanol's availability is a concern. No marine-certified methanol-compatible engines in SIF's and NYCF's size ranges currently exist, so methanol is not considered a viable retrofit option in this report.

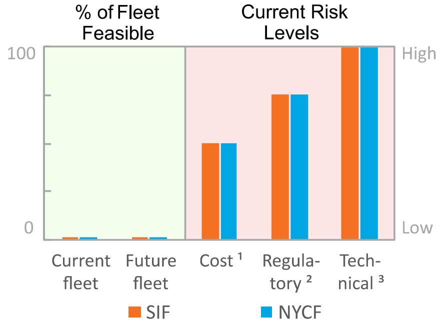
Methanol at a Glance

Not recommended for implementation on SIF or NYCF vessels

●
○
○

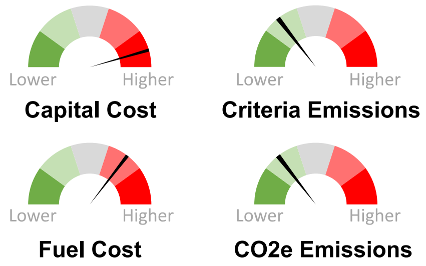
- Energy intensive to manufacture
- Engines not developed
- Overcome by natural gas

Recommendation



[1] Increased bunkering complexity
[2] Stringent hazardous zone requirements
[3] No engine retrofits, rarely used as marine fuel

Feasibility and Risk Areas



5.7.2 Background

Methanol is a clear liquid chemical that is water soluble and readily biodegradable. It is the simplest organic alcohol, with a chemical formula of CH_3OH. Methanol is commonly used as feedstock to produce other chemical derivatives, particularly formaldehyde and acetic acid.

Methanol is an attractive alternative fuel for marine propulsion for several reasons:

1. Methanol combustion is much cleaner than diesel combustion. Engine manufacturers report a significant decrease in SOx and PM emissions, and report lower NOx emissions than with comparable diesel engines.
2. As a liquid at standard conditions, methanol is easier to store and transport than natural gas and hydrogen. This minimizes the modifications required for existing vessels and infrastructure.
3. Methanol is biodegradable, miscible in water, and has low toxicity (Reference 32).

Methanol also has the advantage of 'polygeneration,' meaning that it can be made from multiple feedstocks that are first converted to synthesis gas, a combination of CO, CO_2, and H_2. Synthesis gas can be produced through the gasification of any plant-based material. This includes biomass, such as agricultural and forestry resources, algae, and solid municipal waste. Currently, however, methanol is typically produced using natural gas or coal.

Methanol has half the energy density of diesel, containing approximately 22 MJ/kg compared to diesel's 43 MJ/kg. This means that a vessel would have to carry approximately twice as much fuel to maintain the same refueling cycle. Additionally, the supply chain for methanol in the quantity either ferry system would require for full adoption is underdeveloped, making it impractical to use in large quantities in NYC.

A dual fuel methanol-diesel engine does not have a clear path forward on either the SIF or NYCF. There are no conversion kits for EMD or Baudouin engines, so this type of retrofit would involve a complete engine repower with a different manufacturer. Although some dual-fuel vessels are in operation today, these engines are not readily available commercially and this would result in a custom/special order project.

Given these energy density, supply chain, and engine compatibility obstacles, methanol was not analyzed in detail in Section 6.

5.7.3 Operational Considerations

Methanol can be used to fuel vessels in two capacities – as a combustion fuel and as an anode in a proton-exchange fuel cell.

With a methanol-fueled dual-fuel engine, vessel operations would remain largely similar to diesel-fueled operations. Similar to LNG, the engine would regulate the amount of ignition fuel (diesel) and methanol injected. Performance curves for these engines are not available since there are so few in operation, and the responsiveness of the engine compared to a traditional diesel is not known at this time. Methanol bunkering is similar to diesel bunkering, and aside from having a different tank arrangement and additional piping, there would not be significant changes. However, because of methanol's low flashpoint, additional safety precautions would likely be needed during bunkering.

In addition to these operational considerations, dual fuel methanol use would require some overall vessel design changes. These are largely led by regulatory requirements. DNV-GL and Lloyd's Register have established regulations for low flashpoint liquid (LFL) fuels. DNV-GL focuses on five specific areas for use of LFL fuels. The table below summarizes these areas, along with shipboard design features to accommodate the novel fuel.

Table 22 Regulatory requirements specific to methanol

Regulatory	Vessel Design Modification Summary
Bunkering	• Bunkering modifications are similar to those for LNG fueled ships and therefore proven • Requires sophisticated control systems including overfill alarms, automatic shutdown, ventilation monitoring, and gas detection
Storage	• Can be stored in double bottom tanks since it is not considered harmful to the environment • Can be installed in existing ballast or fuel tanks with additional coating
Handling and Processing Towards Main Engine	• Double walled piping and remotely operated valves required throughout the system • Gas detectors and ventilation at low elevations required • Seal selection must accommodate low viscosity fluids

Regulatory	Vessel Design Modification Summary
Combustion in Main Engine	• Additional methanol booster injectors and liquid gas injection block is fitted on the cylinder and supporting valves for return piping network • Methanol has lower lubricity than diesel and can impose greater wear on engine components
Processing after the Main Engine	• Installation of a nitrogen purging system is required (similar to LNG)

Methanol is a corrosive material and is particularly damaging to aluminum which makes storage on challenging on aluminum vessels like those used by NYCF. Minimal modifications to the engine and infrastructure that delivers the liquid fuel (Reference 22) must be completed. MAN reports that even though methanol is particularly corrosive, they have not seen any additional evidence of corrosion in the combustion chamber, which is already designed to withstand a highly corrosive environment (Reference 28).

Formaldehyde generation can occur when methanol is not fully combusted. Methanol will burn in the combustion chamber at temperatures up to 1300°C. Formaldehyde is generated at temperatures of approximately 400°C - 600°C and can cause irritation of the skin, eyes, nose and throat. Exposure to high levels of formaldehyde may cause some types of cancer (Reference 30). MAN claims that their engines do not have any fuel slip, and therefore would not generate formaldehyde.

5.7.3.1 Existing Methanol Vessels

Two engine manufacturers, Wartsila and MAN, currently supply dual-fuel engine conversion kits, which have been installed and are operating on a total of eight vessels.

There is currently one roll-on/passenger ferry (ro-pax) that runs on methanol as the combustion fuel – the Swedish *Stena Germanica*, a 790 ' overnight passenger ferry between Germany and Sweden that carries up to 1300 passengers. The vessel has been in operation since March 2015.

The *Stena Germanica* methanol conversion modifications were accomplished over a 7-month shipyard period in 2015, with a budget of approximately $25M (Reference 27). Major modifications included:

- Converting four Wartsila 8ZAL 40S MD (4x 8000 hp) engines for methanol combustion
- Installation of double-walled fuel pipes
- Ballast tank conversion to methanol fuel tank
- Modifications to pump room, including installation of a high-pressure methanol transfer pump

In addition to this passenger vessel, there are currently seven methanol-carrying product tankers that use methanol as a combustion fuel. These vessels are classed by DNV-GL as LFL fueled. MAN B&W 6G50ME-9.3 ME-LGI dual fuel, two-stroke engines are installed onboard. These engines were installed new, not as a retrofit conversion. Similar to the passenger vessel, these engines operate on methanol and diesel. Four additional methanol-diesel vessels are scheduled for delivery in 2019 (Reference 31)

5.7.4 Environmental Impact

Methanol's environmental impact as a propulsion fuel occurs in three phases: production, transportation, and combustion.

5.7.4.1 Production

Methanol production is inherently energy intensive. Typical feedstocks for methanol include natural gas, coal, and biomass. The figure below illustrates common feedstocks for methanol production and their associated production processes.

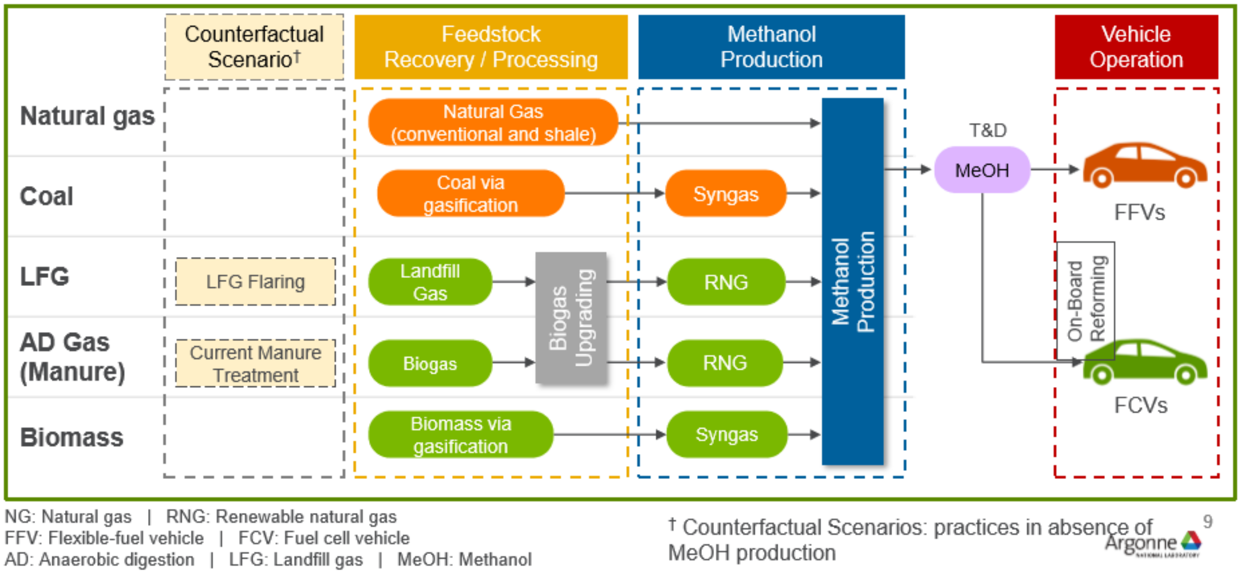


Figure 28 Methanol feedstock (Reference 33)

Methanol production is broken into two phases: feedstock to syngas/renewable natural gas, and syngas/renewable natural gas to methanol, as illustrated above. Table 23 lists overall methanol processing plant efficiencies. These values reflect both phases of methanol production. For comparison, natural gas recovery and processing has an overall efficiency of approximately 95% (Reference 33).

Table 23 Methanol production efficiencies (Reference 36)

Fuel	Plant efficiency
Woody Biomass to Methanol	56%
Overall Biomass to Methanol	52%
Natural Gas to Methanol	64%-72%
Coal to Methanol	55%

Producing methanol from natural gas is more efficient, on average, than producing it from biomass. However, there are efficiency gains anticipated over the next 5-10 years that should improve the gasification process, (Reference 36) which will increase the overall efficiency of a biomass processing plant.

Table 24 Methanol Production Emissions (Reference 33)

Emission type	Amount (g/kWhr)
VOC	0.00233
CO	0.0041
NO_x	0.0266
SO_x	3.5E-4
CO_2	47.52

The use of biomass in methanol production significantly reduces the carbon emission in synthesis. The USDA/DOE Billion-Ton Study (Reference 34) concluded that there will be 814 million dry tons of potential biomass resources, available at $60/dry ton, by 2022.

5.7.4.2 Transportation

Transportation of methanol is similar to diesel fuel. It is simpler and safer to transport than both hydrogen and LNG, one of its main advantages.

5.7.4.3 Combustion

Methanol combustion produces NO_x and CO_2. SO_x emissions correlate to the sulfur content of methanol, which is negligible (Reference 24). NO_x emissions from methanol combustion are very specific to the engine manufacturer and combustion conditions. Wartsila and MAN have both completed methanol combustion testing on their methanol-converted engines and report NO_x reductions of 30%-60% compared to heavy fuel oil (Reference 24).

IMO’s study of methanol as a marine fuel (Reference 24) gives 69g CO_2/MJ as its basis for methanol combustion carbon emissions. However, analysis involving the combustion of biofuels generally gives credit for the carbon removed from the atmosphere as the biological feedstocks grew, so the net CO_2 production when combusting methanol generated by plant-based biomass is taken to be zero.

5.7.4.4 Unintended Release

Methanol, unlike hydrocarbon fuels, is water soluble due to the OH group’s role in its chemical composition (CH_3OH). The carbon chain is non-polar, while the OH group is polar. Since water is polar, it is attracted to the OH group and the carbon chain is repelled. So long as the OH group is more strongly attracted to water than to the carbon chain (as in methanol, ethanol and propanol), these alcohols will dissolve in water. The solubility of a four-carbon chain, butanol, starts to decrease. Methanol’s half-life in surface water, ground water, and soil is 1-7 days. In air, its half-life is 3-30 days (Reference 36). This half-life is significantly shorter than other hydrocarbons, and therefore the environmental impact of catastrophic spills is notably lower.

5.7.5 Cost

Methanex, a global supplier of methanol, lists their methanol non-discounted reference price at $1.30/gal, which becomes $2.65/DGE (Reference 26, valid April 2019). Further investigation would be required to determine the price and availability of methanol delivered to the City’s ferry terminals.

5.8 Hydrogen Fuel Cells

5.8.1 Summary

Hydrogen fuel cells are a relatively new fuel source in marine applications. Their primary application is as a zero-emission solution when plug-in battery electric operation is infeasible, for example when operating on long routes or with very short turnarounds. There are numerous challenges and barriers to adopting hydrogen fuel cells for shipboard use.

While hydrogen produces only water as a byproduct when combusted or used in fuel cells, energy-intensive processes are needed to produce it. If carbon-intensive power sources are used to fuel its production, hydrogen's CO_2e benefits will be partially or fully offset. Hydrogen fuel cells are not compatible with standard diesel propulsion systems, so implementing this fuel source for propulsion would require either fully repowering the City's vessels (engine replacement) or procuring new, purpose-built vessels.

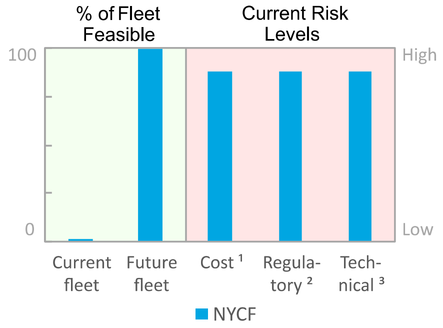
Due to its low volumetric energy density, hydrogen must be stored as a highly compressed gas or as a cryogenic liquid, both of which create regulatory, operational, and technical challenges on board vessels. A regulatory framework exists for LNG, which is also a cryogenic liquid. Many of these regulations may apply to an LH2 installation, but hydrogen's unique properties warrant specific regulations that do not yet exist. Installing tanks to store hydrogen and retrofitting engines to combust it carries significant capital costs, and hydrogen's fuel costs are significantly higher on a per unit energy basis. Given all these challenges, hydrogen fuel cells are not considered an appropriate option for the City's existing or future fleets.

Hydrogen Fuel Cells at a Glance

Benefits may not outweigh costs, see Section 6

- Energy intensive to manufacture H2
- Local LH2 transport ban
- Only considered for NYCF

Recommendation

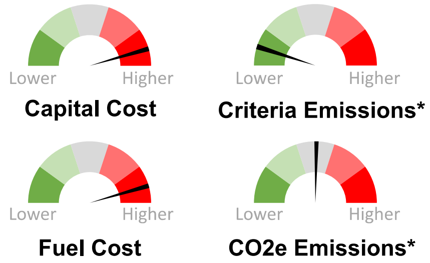


[1] Increased bunkering complexity

[2] Stringent hazardous zone requirements

[3] Very few existing marine applications

Feasibility and Risk Areas



5.8.2 Background

5.8.2.1 Introduction

Hydrogen and fuel cells each may be utilized in multiple fueling applications; hydrogen may also serve as a combustion fuel, and fuel cells may make use of methanol, natural gas, or diesel. However, their use in combination (i.e. hydrogen fuel cells) is the only permutation currently in use as a marine fuel. This study therefore confines its focus to hydrogen-based fuel cells and does not examine hydrogen combustion or alternative fuel cell fuel options in detail.

5.8.2.2 Fuel Cells

Fuel cells are devices that directly convert chemically stored energy to electricity. Internal combustion engines, by comparison, must first produce mechanical energy which can then be converted to electricity by spinning generators. The electricity fuel cells generate can be used on a marine vessel to power propulsion motors and ship service loads. Fuel cells' most attractive quality is that they produce no local emissions when a non-carbon-based fuel such as hydrogen is used. They are typically used in applications where a vessel owner values reduced emissions but cannot use batteries due to the vessel's operational profile or configuration. The New York City Ferries, for example, may be a potential candidate for fuel cell propulsion due to their long routes and short turnaround times. The Staten Island Ferries, as discussed in Section 5.6, have an operational profile better suited for a battery installation.

***** Zero local emissions, but well-to-waves emissions depend on hydrogen production power sources

All fuel cells are based on the same chemical theory. Every fuel cell is composed of an anode, a cathode, and an electrolyte membrane. Hydrogen is passed through the anode, where it is split into electrons and protons. The protons pass through the electrolyte membrane, but the electrons are forced to go through a circuit, creating an electric current. The electrons, protons and oxygen combine at the cathode to produce water molecules. If a carbon-based fuel such as diesel, natural gas, or methanol is used, the carbon in the fuel leads to production of carbon emissions. The schematic below shows the basic operation of a proton exchange membrane type fuel cell with hydrogen as the fuel source, along with a rendering of the Hydrogenics 30kW unit.

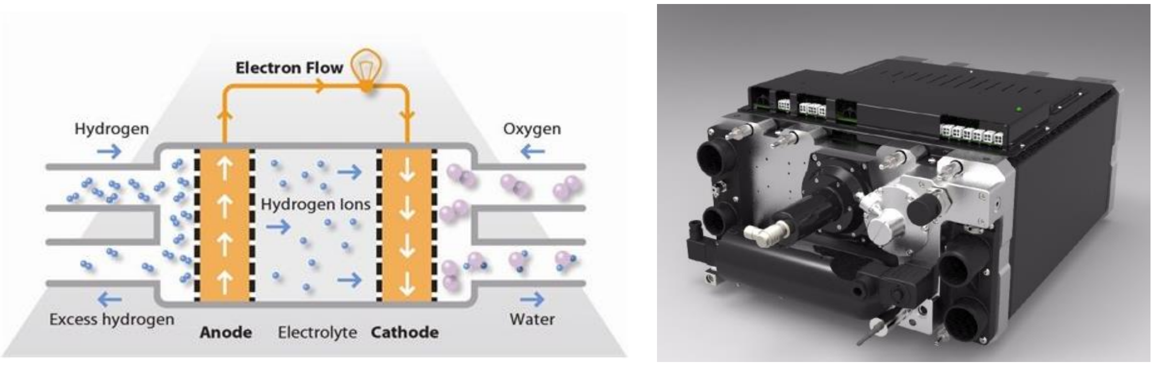


Figure 29 Typical PEM fuel cell (left, see Reference 72) and the rendering of a Hydrogenics PEM fuel cell (right, Reference 74)

Several types of fuel cells are available on the market, typically categorized by the materials used in the membrane. Reference 72 describes seven market-ready types of fuel cells as they pertain to the marine industry and discusses their relative merits and potential for commercial application. This study selected three fuel cell types as the most promising candidates from among the seven options. As shown in Table 25, this selection process rated the fuel cells on several characteristics, including relative cost, power levels, lifetime, tolerance for cycling, flexibility towards fuel type, technological maturity, physical size and weight, sensitivity for fuel impurities, emissions, safety, and efficiency. This study finds proton exchange membrane fuel cells (PEMFC), high temperature PEMFC (HT-PEMFC) and solid oxide fuel cells (SOFC) to be the most promising technologies for the maritime transportation industry.

Table 25 Fuel cell characteristics compared

	PEMFC	HT-PEMFC	SOFC
Module power levels	Up to 120kW	Up to 30kW	20-60kW
Tolerance for cycling	Good	Good	Low
Fuel	Hydrogen	Natural gas, Methanol, Diesel, Hydrogen	Natural gas, Methanol, Diesel, Hydrogen
Maturity	High, extensive experience from several applications including ships	Low, experience from some applications including ships	Moderate, experience from several applications including ships
Sensitivity to fuel impurities	Medium	Low	Low
Emissions	None	CO_2, and low levels of NOx if carbon fuel is used	CO_2, and low levels of NOx if carbon fuel is used
Safety Aspects	Hydrogen	High temperature (up to 200C). Hydrogen and CO in reforming unit	High temperature (600-700C), hydrogen and CO in cell from internal reforming
Efficiency	50-60% electrical	50-60% (electrical)	60% electrical

5.8.2.3 Hydrogen

Hydrogen (H_2) is one of the most plentiful elements on Earth. It is used as a clean-burning combustion fuel, or in fuel cells to power cars, heat houses and offices, and generate energy. In the United States, hydrogen is used mainly as a feedstock in the chemical and petrochemical industry to produce ammonia and refined petroleum products. It is also used in the metallurgic, electronic, and pharmaceutical industries. Hydrogen has been used as a propulsion fuel in spacecraft and is gaining ground in the automotive industry.

Hydrogen is an attractive alternative fuel because its oxidative conversion to produce energy is clean, producing only water and generating no pollutants at the point of use. Unlike fossil fuels, hydrogen is an energy carrier. In this sense, it is analogous to batteries in that it must be manufactured before it can be used as a fuel. Today, 95% of the hydrogen is produced through steam reforming of fossil fuels, typically natural gas or methane (Reference 54). Hydrogen is also produced through the electrolysis of water. Separating H_2 from the H_2O molecule is energy intensive, so hydrogen can only be considered an environmentally beneficial fuel if renewable energy is used to produce it. The critical questions concerning mainstream use of hydrogen revolve around how to produce the fuel economically and in an environmentally sound manner, and how to use it safely.

Hydrogen is a very light and highly flammable gas at standard conditions. Its energy density per pound is approximately three times higher than traditional diesel. However, since its volumetric energy density is very low, a vessel would require 5-10 times the storage tank size to equal the energy content of an equivalent diesel tank, depending on the state in which the hydrogen is stored (Reference 61).

Table 26 summarizes some of hydrogen's relevant properties:

Table 26 Properties of hydrogen

Property	Properties of Hydrogen	Properties of ULSD Diesel
Chemical Formula	H_2	$C_{10}H_{20}$ to $C_{15}H_{28}$
Appearance	Colorless and odorless gas	Translucent liquid
Flammability limits in air	4%-74%	0.6%-7.5%
Energy Content (LHV)	119.96 MJ/kg	43 MJ/kg
Density at standard conditions	0.09 kg/m^3	830 kg/m^3
Density of LH2 (-423°F)	70.8 kg/m^3	N/A

5.8.2.4 Hydrogen Infrastructure

Hydrogen supply infrastructure is developing primarily through the automotive industry, with the marine industry benefitting from these advances in the small number of hydrogen installations that have begun to emerge. Several hydrogen fueling stations are currently being installed in New York to support zero-emissions fuel cell vehicle development. Fuel cell cars typically use compressed hydrogen, but for a ferry's energy demands, it is more advantageous to use a more energy dense liquified hydrogen (LH_2).

Nine northeastern states, including New York, have signed an MOU to have 3.3M Zero Emission Vehicles (ZEV) on roads by 2025 (Reference 49). ZEVs are not limited to hydrogen fuel cell vehicles, but also include pure battery-electric vehicles and plug-in hybrid electric vehicles. Hydrogen fueling stations for vehicles are typically planned for areas with high population density, early market adopters, areas with hydrogen production and use, and areas that already have alternative fueling stations. The New York Hydrogen and Fuel Cell Development Plan (Reference 51) claims that a state investment of $15.58M to $41.58M for infrastructure development and FCEV deployment could provide a solid framework to support 2,038 passenger FCEVs and development of up to 23 hydrogen fueling stations. They anticipate funding will come from private, federal, and state resources, potentially including the VW Partial Consent Decree. The VW Partial Consent Decree has allocated approximately $117.4M (Reference 63) to New York for transportation, which includes engine repowering and alternative fueling.

Hydrogen is available from three main domestic suppliers: Praxair, Air Products, and Air Liquide. Air Liquide is working with Toyota to install 12 hydrogen fueling stations stretching from New York to Boston, along with two filling and distribution centers (Reference 56). Air Liquide is also currently constructing compressed gas fueling stations in Hartford, Hempstead and Brooklyn (Reference 51). Refueling infrastructure costs range from $1M to $3.2M per station (Reference 51). A thorough investigation of the supply chain for either compressed or liquid hydrogen should be conducted to evaluate the availability of the fuel to support the demands of either ferry system.

5.8.2.5 Hydrogen Fuel Cells in the Marine Industry

Hydrogen fuel cell usage in the marine transportation industry is at an early stage of development. Like other alternative fuels, the production, transportation and use of hydrogen is developed, and no part of the supply chain or operation is entirely novel. Marine installations that use hydrogen are novel, however, and a regulatory framework has not been developed for such installations. Infrastructure to produce and supply a larger quantity of the fuel must be developed for the fuel to become more mainstream, and regulatory agencies such as USCG continue to approach shipboard use of hydrogen with caution due to safety and reliability concerns.

Because hydrogen fuel cells are not compatible with standard diesel propulsion systems, it is not feasible from a cost standpoint to retrofit an existing, conventionally powered vessel for hydrogen fuel cell propulsion. Hydrogen fuel cell development in the marine industry therefore takes place in the context of new, purpose-built vessels, with various pilot projects underway globally.

Norway is at the forefront of this technology, using fuel cells to power zero-emission ferries with route distances that exceed current battery technology capabilities. The Norwegian government runs a Pilot-E project that provides funding for innovative zero-emissions marine transportation projects (Reference 75). The funding is available to companies implementing research or full-scale demonstration projects. Two hydrogen fuel cell vessel projects were approved in late 2018 - a hydrofoil zero emissions high speed ferry and a short sea freightliner equipped with autonomous cargo handling. Designs for these projects will be underway in 2019. In both cases, the Pilot-E funding was awarded to Hyon, a joint venture of various hydrogen supply equipment companies, including Nel (Hydrogen onshore production and fueling), Hexagon (storage tank manufacturer), and PowerCells (fuel cell manufacturer).

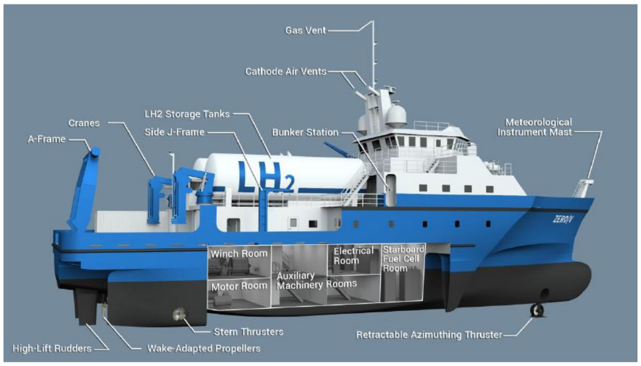
Domestically, a partnership between the State of California, the commercial sector, and the maritime community is in the process of building *Water-Go-Round*, a proof-of-concept hydrogen fuel cell ferry funded through the California Air Resources Board (CARB). This 84-passenger, 360kW aluminum catamaran is designed to transit at 22 knots on a route from Oakland to San Francisco, approximately 5-6 miles, with daily refueling. The vessel may also be used as a slower speed tour boat, cruising around the San Francisco area at approximately 8-10 knots. This operating profile would require filling the 250 kg compressed hydrogen tanks every 2-3 days. This vessel is designed with Hydrogenics PEM fuel cells, BAE propulsion motors, and 100 kWhrs of instantaneous top-up battery energy. The vessel is currently being built at Bay Ship and Yacht in San Diego and is scheduled for delivery in fall 2019.

Sandia National Laboratories, in collaboration with the US Department of Transportation Maritime Administration (MARAD), has been working to advance hydrogen fuel cell applications. This partnership has funded several hydrogen fuel cell vessel feasibility studies, including the *SF-Breeze* high speed catamaran passenger ferry feasibility study (Reference 61) and *Zero-V* research vessel feasibility study (Reference 73). Both studies confirmed the feasibility of using hydrogen fuel cells for these purpose-built vessels. Metrics from these public reports are used to verify the feasibility of fuel cells on the SIF and NYCF ferries.

SF-Breeze

Purpose:	Passenger ferry
Type:	Aluminum catamaran
Length:	109 feet
Passengers:	150
Cruising Speed:	33-35 knots
Installed Power:	4.92 MW
LH2 Storage:	1200 kg Type C tank
Regulations:	USCG Subchapter T, ABS Approved in Principal

Zero-V



Purpose:	Research vessel
Type:	Aluminum trimaran
Length:	170 feet
Range:	2400 nautical miles
Cruising Speed:	10 knots
Installed Power:	1800 kW
LH2 Storage:	2x 5840 kg
Regulations:	USCG Subchapter U, DNV Conditional Approval in Principal

Water-Go-Round

Purpose:	Passenger ferry
Type:	Aluminum catamaran
Length:	70 feet
Passengers:	84
Cruising Speed:	22 knots
Installed Power:	600 kW
H2 Storage:	264 kg 250 bar compressed gas
Regulations:	USCG

Figure 30 ***SF Breeze*, *Water-Go-Round* and *Zero-V* characteristics compared**

5.8.3 Operational Considerations

5.8.3.1 Hydrogen

Hydrogen fuel cell vessel design must account for numerous regulatory, systems, and operational challenges not seen in conventional installations. These are summarized below, and must be considered whether retrofitting an existing vessel or designing a purpose-built one:

1. Hazardous Areas - Because it is a low-flashpoint gas like natural gas and methanol, hydrogen requires large hazardous area space restrictions in case it must be vented to the atmosphere. This can be particularly challenging to accomplish in existing vessel layouts.

2. Ventilation mast - Locating the vent mast and ventilation inlet and outlets is also challenging, particularly when retrofitting an existing vessel. This mast serves as emergency ventilation for the H_2 storage and tank piping.
3. Fire Protection - Additional fire protection, including increased structural fire protection insulation and added fire suppression systems, must be installed.
4. Increased ventilation - Large ventilation supply and exhaust air quantities are required for the tank room(s) and fuel cell space(s).
5. Fuel Bunkering Station - Because hydrogen is highly flammable, its transfer and storage are highly regulated. Bunkering piping must be double-walled and additional safety systems must be implemented during the bunkering routine.
6. Support Systems - Auxiliary systems to support fuel cells have greater requirements, particularly the seawater cooling system's capacity. In the case of LH_2, vaporizing equipment must be provided to bring the cooled gas to a useable operational temperature.
7. Storage tanks - Hydrogen is energy dense by weight but has a very low volumetric density. As a result, when used on marine vessels it requires installation of large storage tanks, where it is stored as either a very high pressure gas (2,000-7,000 psi, see Reference 61) or a cryogenic liquid (-423 deg F).

Due to these considerations, while modifying an existing vessel may be technically feasible, it would very likely be challenging and costly. From an engineering standpoint, it would be preferable to design a purpose-built hydrogen fuel cell vessel rather than attempting to retrofit an existing one, as this enables the vessel designer to customize the layout of the hydrogen systems.

Several hydrogen system characteristics must be evaluated before modifying existing vessels or developing purpose-built designs, including storage state (solid state, liquid, or gas), storage tank characteristics, and fuel cell type. Hydrogen is typically stored in one of three states, each summarized in Table 27. The storage method selected will influence the type of storage tank used.

Table 27 Types of hydrogen storage

Type of Storage	Relevant Characteristics
High Pressure Gas	• Storage pressure typically around 2000 psi. • Typically stored in carbon steel or aluminum cylinders, where weight is not critical. • Tanks are heavy, and relatively low storage pressure limits the amount of fuel that can be stored in the tank. • Using a composite tank (aluminum liner with composite wrap) can increase the storage pressure to approximately 7000 psi.
Solid State	• Uses a compound or chemical host that can store and release the hydrogen. • Research in the past 20 years has focused on finding a material that can 'soak up' hydrogen like a sponge, concentrating it beyond high-pressure storage densities without adding too much weight. • Can be achieved with chemical hydrides, sorption materials, and metal hydrides. Sorption materials are high surface area materials that can bind hydrogen as a molecule, as opposed to hydrogen atoms in chemical compounds.

Type of Storage	Relevant Characteristics
	• No commercial tanks available to date.
Cryogenic liquid (LH2)	• Boiling point of -423˚F • Typically stored in cylindrical tanks. • Not currently allowed within New York City limits. • Inner liner of the tank is separated from an outer metal liner, with a vacuum and perlite insulation in between. • Imperfect insulation leads to heat leak of liquid hydrogen and gaseous build up inside the tank as the liquid is vaporized. Tanks must be vented, with the amount vented is proportional to the surface area of the tank.

Hydrogen tanks are mounted on the vessel and are spherical, cylindrical, or composite construction. Several factors influence the type of storage tank, including cost, weight, heat leak (in the case of storage of a cryogenic liquid), and size.

In evaluating the appropriate storage properties and tank type, two metrics are used.

1. Gravimetric Specification: A ratio of the empty tank weight to the weight of the stored hydrogen. An ideal system would have a very low gravimetric specification, indicating the weight of the empty tank is negligible compared to the weight of the hydrogen stored.
2. Volumetric Specification: A ratio of the outer tank volume to the mass of stored hydrogen. An ideal storage system volumetric specification would be hydrogen's gas density at the temperature and pressure of storage.

Reference 61 researched these characteristics of hydrogen storage and recommended using LH_2 stored in cryogenic cylinders. Since *Water-Go-Round* is similar to the NYCF ferries, the same conclusions may be valid. Should NYCF decide to move forward with a hydrogen fuel cell-powered vessel in the future, a customized evaluation of storage methods and tanks should be conducted for their specific operating conditions, vessel requirements, and hydrogen availability.

The bunkering and storage systems on board a ferry must be modified to adapt to hydrogen's requirements. The procedure for bunkering hydrogen is very similar to that of LNG. It involves checking equipment, precooling shoreside infrastructure, connecting bunkering hoses, and inerting, purging, and precooling the system. The LH2 is transferred and the fill system is inerted prior to disconnecting the bunkering hose.

Several shoreside bunkering configurations can be considered to supply hydrogen to the vessel. These include:

- An onsite facility, wherein a truck fills onsite storage tanks periodically and hydrogen is bunkered from those tanks to the vessel. The fueling truck can also directly fuel the vessel with LH_2.
- Swappable tanks, wherein empty hydrogen tanks are lifted off the vessel and new tanks are installed in their place.

Each system has costs and benefits. The volume of hydrogen required and the availability of shoreside delivery will influence the most suitable fueling method. These fueling strategies are discussed in detail in Reference 61.

5.8.3.2 Fuel Cells

A fuel cell-powered vessel would not have any combustion engines. Propulsion and auxiliary power would be provided by the fuel cell plant. This significantly impacts vessel design and maintenance. Without any engines, the fuel cell vessel would be very quiet, with only the parasitic loads such as fans and blowers creating noise.

Fuel cell service life is typically driven by the lifetime of the proton exchange membrane and is based on the operating hours of the fuel cell stack. Hydrogenics fuel cells, for example, can achieve 10,000 to 15,000 hours of operation before the fuel cell membrane must be replaced. It should be noted, however, that fuel cell voltage degrades over time. This implies that towards the end of a fuel cell’s useful life, it will continue to produce power, but at a lower efficiency. Aside from changing the membranes every 10,000 to 15,000 hours, very little maintenance is required for fuel cell upkeep. Supporting equipment such as blowers, heat exchangers, and cooling water pumps will require regular maintenance.

Fuel cell useful life depends on the membrane usage hours and not necessarily the plan usage hours. For example, NYCF operates their 150-passenger River class vessels approximately 5,000 hours annually, but their fuel cell membranes would not need to be replaced every two to three years, because each cell is not necessarily being utilized for those 5,000 hours. Power generation from the cells is optimized to distribute the load and increase membrane replacement intervals.

Fuel cells respond to load quickly. A PEM fuel cell takes approximately five seconds to go from offline to standby, and less than 30 seconds to reach rated power from standby (Reference 73). As discussed in Section 5.6, electric propulsion motor responsiveness is also greater than that of a diesel-mechanical configuration. It is common to include a battery bank to support the fuel cells, providing instantaneous power for operations where this is required (such as dynamic positioning). The appropriate configuration for SIF and NYCF would need to be further refined to determine the necessity and/or size of battery bank required to supplement the fuel cells.

Fuel cell efficiency varies with power output. Hydrogenics fuel cell modules have a peak efficiency of approximately 51%. When operated at rated power, the efficiency is closer to 43%. Figure 31 shows the typical performance of a Hydrogenics PEM fuel cell (Reference 74); for this 30 kW fuel cell, the peak efficiency occurs at low current and high voltage. As the current and voltage vary to produce the rated load, the efficiency decreases.

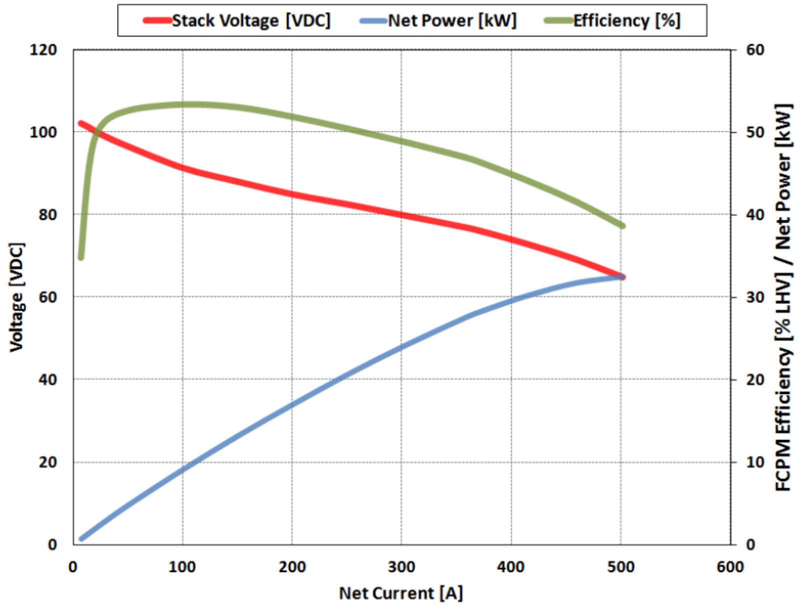


Figure 31 Efficiency of a 30kW fuel cell

5.8.3.3 Regulatory Considerations

There are no regulations that currently cover the use of hydrogen on board marine vessels. Existing hydrogen-powered vessels generally use a compilation of several regulations to cover gaps. Natural gas and hydrogen share some similar physical properties, and using this as a basis of justification, some natural gas regulations have been used applied to hydrogen-fueled vessels, with modifications for the different fuel properties. Historically, the regulations applied for hydrogen fueled vessels are:

- 2015 International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) - This title is inclusive to hydrogen as a low flashpoint fuel but is generally written to govern natural gas. The code is also written for vessels that fall into the Safety of Life as Sea (SOLAS) category, typically large, oceangoing vessels. SIF and NYCF ferries will not be SOLAS.
- 2016 ABS Guide for Propulsion and Auxiliary Systems for Gas Fueled Ships.

Specific areas where the current regulations do not cover the use of hydrogen gas include fire protection and hazardous zone designations. Fire protection refers to onboard systems that protect the passengers, crew, and vessel in the case of a fire on board. In the case of *SF-Breeze* and *Zero-V*, both vessels required fuel isolation systems, fire suppression systems, emergency ventilation, and alarm and monitoring specific to hydrogen fuel’s properties and possible failures. These designs were developed in conversation with regulatory bodies using an alternative design approach wherein the vessels’ equivalent safety, reliability, and dependability to a conventional oil-fueled vessel were demonstrated.

5.8.4 Environmental Impact

Hydrogen fuel cells produce only water as a byproduct, meaning that they produce zero local criteria emissions. However, an evaluation of hydrogen fuel cells’ environmental impact must also consider the hydrogen production process. Hydrogen is typically produced in the United States using an energy intensive process of steam reforming methane or natural gas. Steam methane reforming accounts for 95% of the hydrogen used today in the United States. (Reference 52). Hydrogen is also produced by electrolyzing water, using an electrical current to split water into its basic elements of hydrogen and oxygen. Technological advancements are improving the efficiency of electrolysis, but it is also laborious to produce hydrogen with this method.

From an overall emissions perspective, hydrogen is a more attractive fuel carrier when it is produced with renewable energy. Renewable hydrogen uses a renewable energy source to provide electricity for electrolysis. A major challenge to hydrogen production, especially using renewable sources, is to make the hydrogen cost competitive, and 100% renewable energy-based hydrogen production is not likely to occur in the near- or mid-term future. One strategy for producing renewable hydrogen more cost effectively is to produce it during off-peak grid times, when renewable energy installations are producing energy in excess of grid requirements.

There are several hydrogen production facilities in the United States. These are located primarily in the Gulf region. Hydrogen is typically transported in pipelines, in high-pressure tube trailers or in liquified hydrogen tankers. Air Liquide is currently supplying gaseous hydrogen to two fueling stations in New York, where hydrogen is being trucked in from Canada or Calvert City. The transportation emissions produced throughout this supply chain should be evaluated, although doing so is beyond the scope of this study. Transporting LH_2 into New York City is not currently allowed for reasons discussed in Section 5.4.3.2.

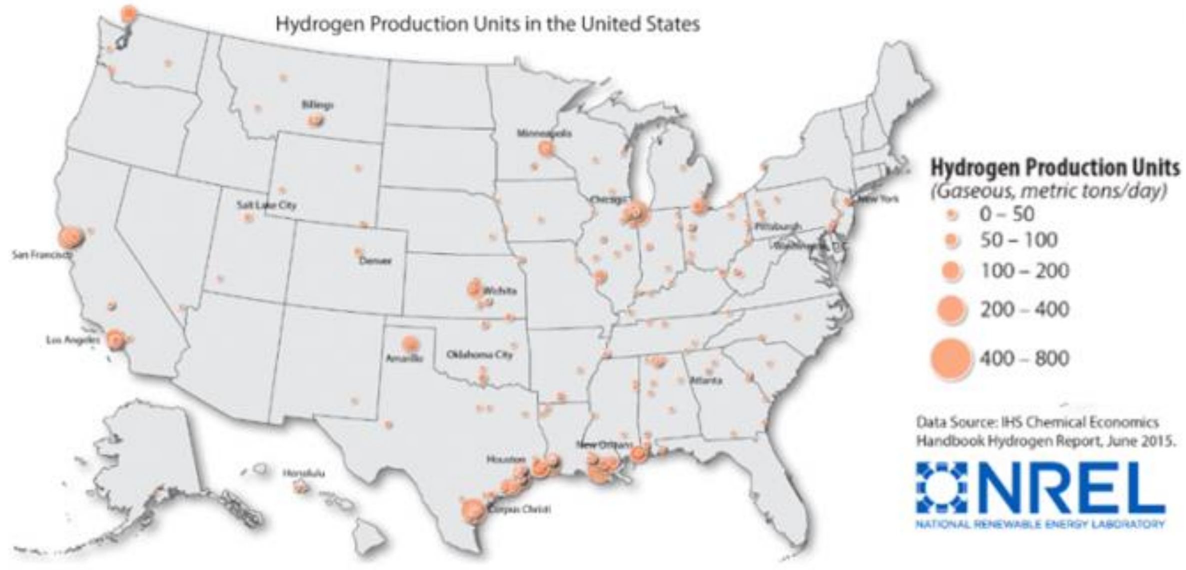


Figure 32 Hydrogen Production Units in the United States (Reference 54)

Hydrogen fuel cell systems achieve very poor well-to-waves efficiency. Figure 33 shows approximate efficiencies for each step of the fuel cell well-to-wave process. The figure assumes the most environmentally sound method to create hydrogen, in which renewable energy is used to electrolyze water. Although the efficiency numbers shown are approximate and were developed for electric road vehicles, they indicate how much energy is consumed in hydrogen production, processing, and delivery.

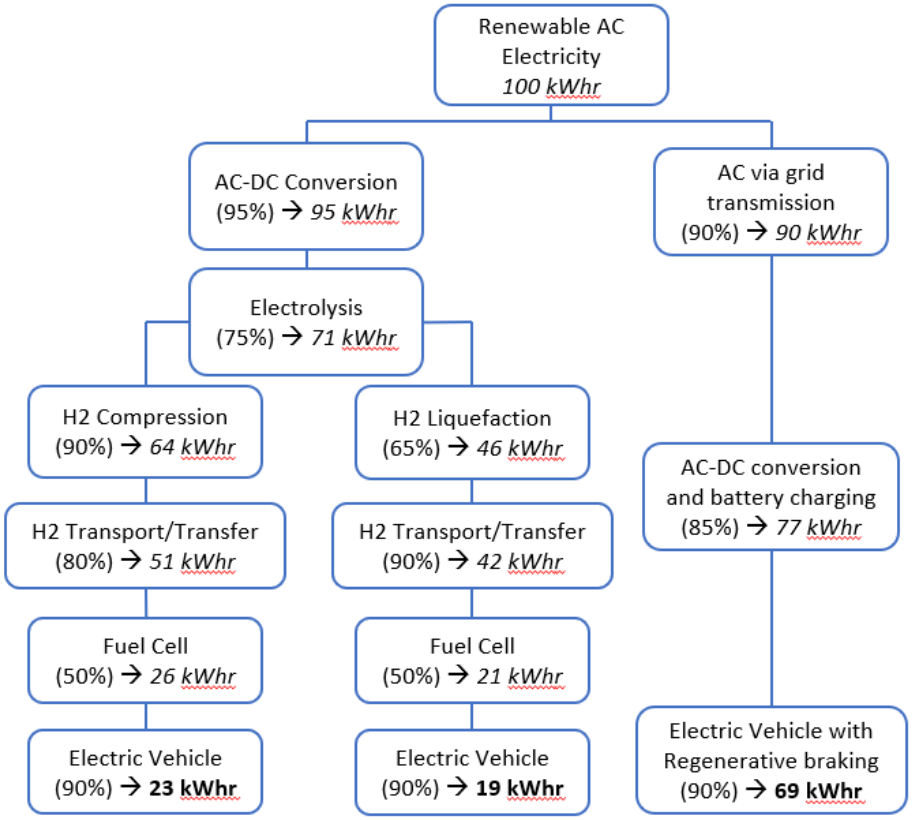


Figure 33 Electrical conversion efficiencies when comparing fuel cells and batteries

As the figure shows, it is significantly more efficient to use grid-based energy for marine transportation than it is to generate electricity with fuel cells. Since using grid-based electricity for propulsion power is feasible for SIF, fuel cells are not considered further as an option for the SIF fleet. NYCF's operational profiles are challenging for an all-electric configuration given current technology, so fuel cells could be an attractive propulsion option for this fleet in the future. Adoption of fuel cells would eliminate *local* emissions if that is the City's main priority. Section 6.2.8 discusses this option further.

Studies have been conducted to document the hydrogen's behavior in the event of a spill. Because of exceptionally low heat of vaporization (amount of energy required to vaporize the gas), spills are very short duration events. This characteristic has a second important consequence in use as a maritime fuel; because it takes less energy to vaporize the fuel, LH_2 will have a reduced cooling effect (Reference 54) on the surrounding ferrous steel, which can undergo brittle fracture when exposed to cryogenic temperatures. Typically, stainless steel is used to prevent fracturing.

5.8.5 Cost

The cost for using hydrogen fuel will vary depending on the frequency of fueling, and the pressure at which the hydrogen is delivered. The SF-Breeze study (Reference 61) reports vendor quotes for liquid hydrogen supply in the San Francisco region. These values, reported in 2016 dollars, range from $6.35/kg to $7.40/kg. One manufacture estimated a 10% increase in cost for supply of 33% renewable LH_2. These reference values need to be further refined to New York City's supply network.

Hydrogen prices are defined for the hydrogen fueling station network in California, listed in Reference 64. This resource lists hydrogen fuel prices ranging from $12.85 per kilogram to more than $16 per kilogram, but the most common price is $13.99 per kg. This results in $15.64/DGE. This hydrogen is delivered in a pressurized state, not as LH_2. LH_2 requires more processing and more elaborate transportation and storage equipment, so would be expected to be even more expensive.

Fuel cell installation costs include the capital cost of the fuel cells and the shipboard electrical infrastructure required to convert the current generated from the cell to useable power for the propulsion motors. Using a geared diesel for baseline comparison, a fuel cell vessel will have higher construction costs to accommodate the fueling system, additional fire protection, and unique electrical equipment. Reference 61 and Reference 73 include full cost estimates for the fuel cell propulsion vessels. The estimated costs for the fuel cells and propulsion equipment are summarized in the table below.

Table 28 Estimated costs for fuel cell installation

	SF-Breeze 4,920 kW installed power	*Zero-V* 1800 kW installed power
Fuel Cells	$1800-2500/kW	$2,200/kW
Switchgear	$3.87M	$2.5M[1]
Fuel Cell Maintenance	$290,000/MW annually (based on 3.6 years/10,000 hours on *SF-Breeze* operational profile)	Included in fuel cell cost.
Hydrogen Storage	$850,000 for 1200 kg LH_2	$1.87M, two tanks of 5840 kg LH_2 (each)

5.9 Additional Measures

5.9.1 Low Friction Hull Coatings

Low-Friction Coatings at a Glance

Recommended for immediate implementation on SIF fleet

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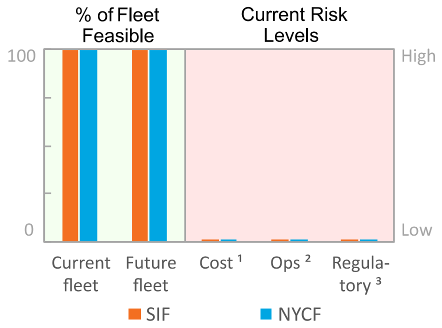
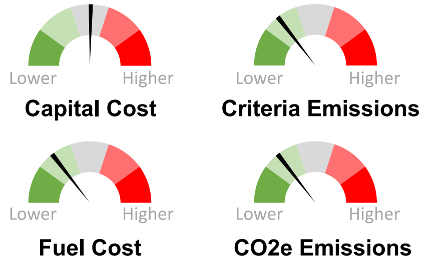
- Fuel savings exceed coating cost
- Longer life than traditional coatings
- NYCF already using advanced coatings

Recommendation



¹ No cost risk, already used on NYCF
² No operational risk
³ No regulatory risk

Feasibility and Risk Areas



Low friction hull coatings, which in the context of this report refers to biocide-free fouling release hull coatings, can be used to reduce the friction force between a vessel's hull and the surrounding water, leading to reductions in required power and fuel usage. The two main factors affecting hull friction are the surface roughness of the hull coating and biofouling on the hull. Biofouling is the gradual accumulation on the hull of microorganisms, which include various types of bacteria commonly referred to as "slime," and macroorganisms, such as algae and barnacles. There are several coating solutions on the market that can reduce biofouling and friction force on the hull:

- Controlled depletion polymer biocidal antifouling hull coating
  - Currently used on SIF & NYCF vessels
    - SIF: International Interclene 245NA
    - NYCF: International Interspeed 5640
- Self-polishing copolymer biocidal antifouling hull coating
- Biocide-free fouling release hull coating; including silicone, fluoropolymer, and hydrogel-based coatings
  - Example: International Intersleek 1100SR

Controlled depletion polymer biocidal antifouling hull coatings contain a biocide that leaches into the surrounding water over time as the coating depletes, killing organisms in the area and thereby reducing growth on the hull. Self-polishing copolymer biocidal antifouling hull coatings work similarly, but as they deplete, they are also polished by the movement of water over the hull, reducing surface roughness.

In general, biocidal coatings in the marine industry reduce biofouling by releasing some form of toxic ingredient into the surrounding water. This ingredient was originally a form of tin that has since been banned from use due to its negative environmental impact. More recently, biocidal coatings have commonly contained a form of copper, and the most modern types use copper-free organic biocides. While the use of approved biocides is acceptable, they are not the most effective method to reduce biofouling, and they are not the most environmentally friendly solution.

For vessels that move frequently at or above a designated speed, biocide-free fouling release hull coatings are more effective at reducing hull fouling, with the added benefit of a lower environmental impact. By design, low-friction coatings reduce surface roughness and increase fuel efficiency. They are designed to be smooth enough that organisms find it difficult to attach to the hull even when the vessel is stationary. Any persistent biofouling is washed from the hull when the vessel moves above a certain operating speed – usually above 10-15 knots but varying depending on the coating used.

Numerous competing options for this type of coating exist, but this study’s focus was confined to Intersleek 1100SR, as it is the most advanced option offered by SIF& NYCF’s current hull coating vendor. Intersleek 1100SR reportedly provides a worldwide average of 3% fuel savings over standard self-polishing biocidal antifouling hull coatings and controlled depletion biocidal antifouling hull coatings while the vessel is underway. This savings is due to the friction reduction the coating’s decreased surface roughness provides as well as its superior long-term antifouling performance, both of which maintain low overall surface roughness over the life of the coating. Additionally, Intersleek 1100SR advertises a lifespan of up to 10 years, whereas SIF’s current coating, Interclene 245NA, only advertises a lifespan of 3 years.

5.9.2 Fuel Flow Meters and Operational Improvements

One area for further consideration by both SIF and NYCF is whether behavioral changes might result in greater fuel savings. During Glosten’s shipcheck, it was noted that captains tended to drive the ferries based on propeller RPM rather than ship speed or schedule. Once clear of the dock, they set their transit RPM, and maintained that RPM until commencing arrival maneuvering at the other side. It should first be noted that this is more prudent than some alternatives. For example, if captains attempt to make up time in the schedule, very high fuel consumption could result with minimal benefit.

However, defaulting to setting propeller RPM potentially misses out on some savings that could be achieved on runs where the ferry is ahead of schedule. If a ferry arrives at the dock one minute early, the transit speed could have been reduced by almost a full knot to arrive "just in time". This modest speed reduction would save approximately 5 gallons of fuel. If only 10% of trips identified such savings, it would reduce annual fuel consumption by approximately 20,000 gallons. Table 29 illustrates the effect of a minor change in trip timing.

Table 29 The cost of one minute at the dock

	Slower	Baseline	Faster
Transit Time (min)	20	19	18
Speed (kts)	14.7	15.5	16.4
Power (kw)	3100	3600	4300
Fuel (gal)	73	77	83
Change (gal)	-5	-	+6

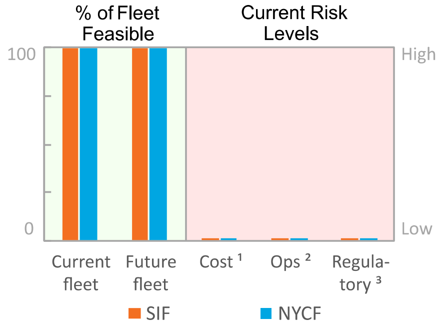
A key element in promoting such fuel-conscious behavior would be increasing the visibility of fuel consumption using fuel flowmeters. Fuel usage is normally monitored through fuel tank sightglasses or sounding tubes. This is adequate to track the general level of fuel on board and determine when refueling is required but is insufficient to identify minor differences in fuel consumed for an individual trip. Flowmeters would measure the flow of fuel in the line to each engine and present this information in real time. While no well-documented studies of the benefits of flowmeters were found, numerous anecdotes exist in the marine sector describing how simply presenting this information to captains resulted in more fuel-conscious ship handling.

Fuel Flow Metering at a Glance

Recommended for immediate implementation on SIF fleet

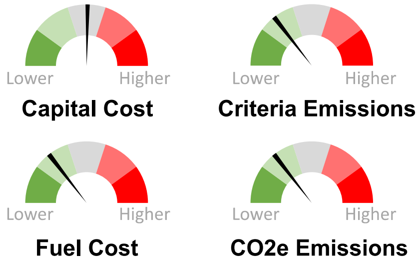
- Already implemented on NYCF fleet
- Low cost
- Improves vessel operators' efficiency

Recommendation



¹ No cost risk
² No operational risk
³ No regulatory risk

Feasibility and Risk Areas



Taking this idea one step further, fuel usage could be incorporated into the existing "on-time performance sheet". Requiring captains to report fuel consumption and explain unusually high usage, and making this information visible, could help contribute to an organizational culture of fuel conservation.

Several of the options in this report offer power reductions or fuel savings of 5% or less. Without a culture focused on precise route timing – arriving on-time, but never early – these changes will make minor differences in trip timing rather than producing fuel or emissions savings. For example, applying low-friction hull coatings to SIF vessels but operating at the previously used engine RPM will simply result in more early arrivals, with no reduction in fuel burned or emissions produced.

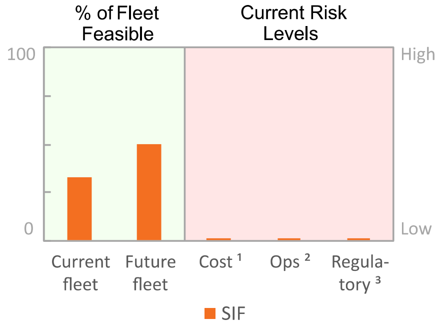
5.9.3 Operational Improvements to Propulsion Split

Propulsion Split Operational Improvements at a Glance

Recommended for immediate & long-term implementation on SIF fleet

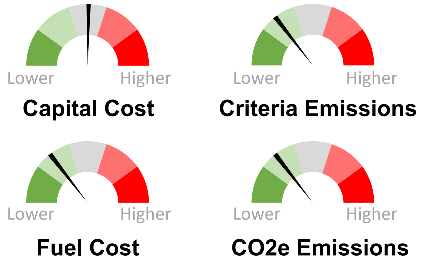
- Study already completed for Molinaris
- Very low cost, significant benefits
- Not applicable to NYCF vessels

Recommendation



¹ Minimal cost risk
² Minimal operational risk
³ Minimal regulatory risk

Feasibility and Risk Areas



The SIF Molinari class ferries are double ended with a single fixed-pitch propeller on each end. All other current SIF ferry classes are double ended with a single Voith cycloidal propeller (VSP) on each end. The Molinari class vessels are currently operated with an 83%/17% power split between the aft and fwd propellers during the transit phase of operation. This means that 83% of the propulsion power is supplied to the pushing aft propeller, while 17% of the propulsion power is supplied to the fwd propeller, which is operated in reverse to reduce drag. The ferry classes with Voith cycloidal propellers are operated with a 50%/50% power split with both propellers operated in a pushing manner.

In 2012, a study was completed on the Molinari class ferries that investigated the potential to save fuel by changing the power split during the transit phase of operation, thereby reducing the power required to maintain a given operational speed. The testing and results will not be discussed in detail here, but the final report from the study, Reference 65, can be referenced for more detailed information. The result of significance for this study is that there is a potential for a 15% fuel savings during operations between 14 and 16 knots if the propulsion split is changed from 83%/17% to 90%/10% on the Molinari class vessels.

The power split in question is a setting in the software that controls how power is shared between the fwd and aft drive motors. Changing this split requires no physical modification to the ship. For the purposes of this analysis, it is assumed that all three Molinari class ferries currently have the same propulsion power settings and that similar savings could be achieved on all three vessels.

Design work for modifications to the Molinari class rudder and propeller is ongoing. The new configuration may result in an optimum split different from 90/10. Full scale optimization trials are planned as part of the modifications. Nevertheless, it is recommended to change the propulsive split immediately to save fuel under the existing configuration.

The optimum propulsive split depends heavily on the specific flow characteristics around a ship. This dependency precludes extending results from one class of ship to another, but rules of thumb can be developed by examining multiple ships with similar characteristics. In general, double-ended ferries with fixed pitch propellers like the Molinari class perform best with most of the propulsive power delivered aft. Voith-Schneider ferries, on the other hand, are typically designed with equal power distributed forward and aft (during straight line transit). There is potential fuel savings on the Barberi, Austen, and Ollis class ferries by optimizing this power distribution as well. Model basin testing of the Ollis class design included a very brief investigation into power distribution (Reference 66). One test delivered slightly more power to the forward VSP and one test delivered slightly more power to the aft VSP. Increasing power to the aft VSP by 4% (54/46 split aft/forward) reduced overall power required by 2% compared to a 50/50 baseline. The opposite split (46/54 fwd/aft) increased overall required power by 3%.

Two options would allow for refining these results and investigating the Barberi and Austen class. First, a new run of model tank testing could be conducted. This would allow carefully controlled experimentation with precisely measured results. Such model tank testing would be costly and could be subject to errors from scaling effects. Alternatively, full scale testing could be conducted with the SIF fleet. This would require careful selection of test location and weather to minimize the effect of wind and waves but has the advantage of eliminating scale factors if a precise test setup can be developed.

Regardless of the test method chosen, implementing the split would require greater engineering effort than modifying the Molinari class, since the concept of splitting total required power forward and aft is not consistent with the current design of the propulsion control system. Depending on the engineering and modification costs, a minor power savings identified for VSP ferries might take several years to pay back. Our recommendation is to explore this concept further with staff at Voith and MARIN, who have greater familiarity with optimizing VSP ships generally and with the Reference 66 power split testing specifically. Based on uncertain benefits and implementation costs, results in Section 6 for improving the efficiency of propulsive splitting include only the Molinari class.

5.9.4 Automated Mooring Systems

Ferry operators around the world use automated mooring systems to secure the main propulsion machinery, or at least to reduce the pushing load, during ferry loading and unloading operations. These systems are usually associated with side mooring or corner mooring configurations, not the end mooring arrangements currently used for the SIF and NYCF terminals.

Automated mooring systems typically have a positive restraining mechanism on the dock and a receiving mechanism on the ferry, maintaining the ferry's position at the dock for the duration of loading and unloading. For end loading operations, these systems need to be robust enough to withstand wind and current side loads on the ferries. For the City's ferries, this would require extensive modifications to both the ferry docks and the ferries themselves. Consequently, automated mooring systems are expensive from both an initial capital cost perspective and a maintenance perspective.

For present SIF operations, the primary benefit would be to allow the propulsion plant to reduce the dock pushing load down to engine idle for the estimated eight minutes each trip that the ferries are loading/unloading. Eight minutes is not adequate time to justify stopping and then restarting the ferry's main engines at each docking. Since automated mooring will not allow the securing of any propulsion engines, it will provide only marginal reductions in fuel consumption and emissions generation. Should future SIF ferries move to battery electric or hybrid electric propulsion systems, automated mooring systems should be investigated, because they will allow a reduction in the size of the required battery bank, the charging rate, and the overall electrical power needed by each ferry.

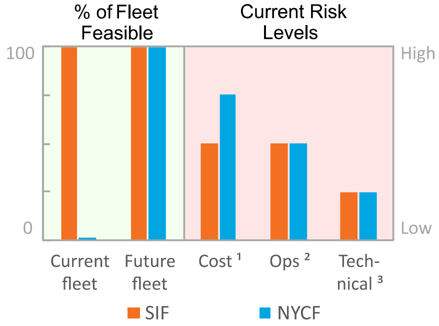
NYCF operations would require an automated mooring system at every vessel mooring position at every terminal, along with a receiving system on every ferry, resulting in an impractically large number of automated systems. Given these ferries' shorter loading and unloading times compared to the SIF ferries, automated mooring has a greater economic disadvantage than their present method of pushing the dock.

Automated Mooring Systems at a Glance

Benefits do not currently outweigh costs, but may complement plug-in ops

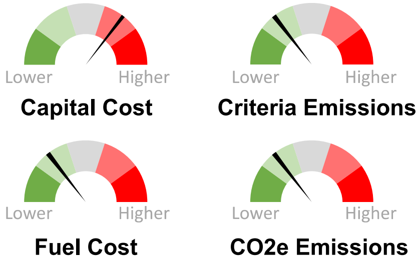
- Reduces dock pushing fuel burn
- Significant cost
- Poor fit for quick turnarounds

Recommendation



¹ Front mooring requires custom build
² Extra equipment adds failure modes
³ SIF & NYCF differ from common applications

Feasibility and Risk Areas



5.9.5 Other Renewables

5.9.5.1 Solar

Solar power, while a zero-emission option, is limited by the amount surface area on the ferry available for solar cell placement. The average yearly insolation – a measure of the available solar radiation energy per surface area unit – for New York City is roughly 3.5-4.5 kWh per square meter per day annually. Standard photovoltaic cells can convert approximately 15-21% of available solar radiation into energy due to efficiency limitations.

Solar cell efficiency is improving steadily due to advancements in the field, but even a very high-efficiency solar cell can ultimately only capture a portion of the available energy. Using a generous 50% efficiency factor, which is more than double the efficiency of any solar panel currently on the market, the amount of solar power that could be generated on board an Ollis class vessel can be calculated as follows:

- Vessel dimensions of 220' x 70' multiplied by a clear factor of 0.67 = 10,300 ft^2 = 960 m^2 surface area available for solar cell placement
- 4.5 kWh/m^2 per day / 24h = 0.19 kW/m^2 continuously available solar energy
- 0.19 kW/ m^2 available energy * 50% efficiency factor = 0.09 kW/ m^2 solar energy continuous output for a high efficiency solar cell
- 0.09 kW/ m^2 * 960 m^2 = 90 kW energy available for shipboard use

This calculation assumes a constant available power level over the course of the day, whereas the available solar power in fact depends highly on the angle at which the sun's rays strike the cell. While it is possible to use the solar panels to charge a battery which can provide a flatter continuous output, additional transmission losses would occur in charging and discharging the battery.

This 90 kW of energy, produced by 50% efficient solar cells covering the majority of exposed deck area, could power roughly half of an Ollis class ferry's ship service loads, assuming a continuous level of available power. Daily and seasonal variability in the amount of solar energy reaching solar cells installed on the ferry would result in an uneven power profile, so backup generators would need to be available to handle any dip in solar cell power output.

Using the same assumptions, a NYCF 350 Rockaway class ferry with dimensions of 97' x 28' could generate approximately 53 kW for shipboard use, enough to cover ship service loads. However, this would require converting the entire upper deck passenger area to solar panels.

Given solar cells' low power production levels per unit area, their uneven power profile, and their large deck area requirements, they are not a recommended application for the City's fleets.

5.9.5.2 Wind

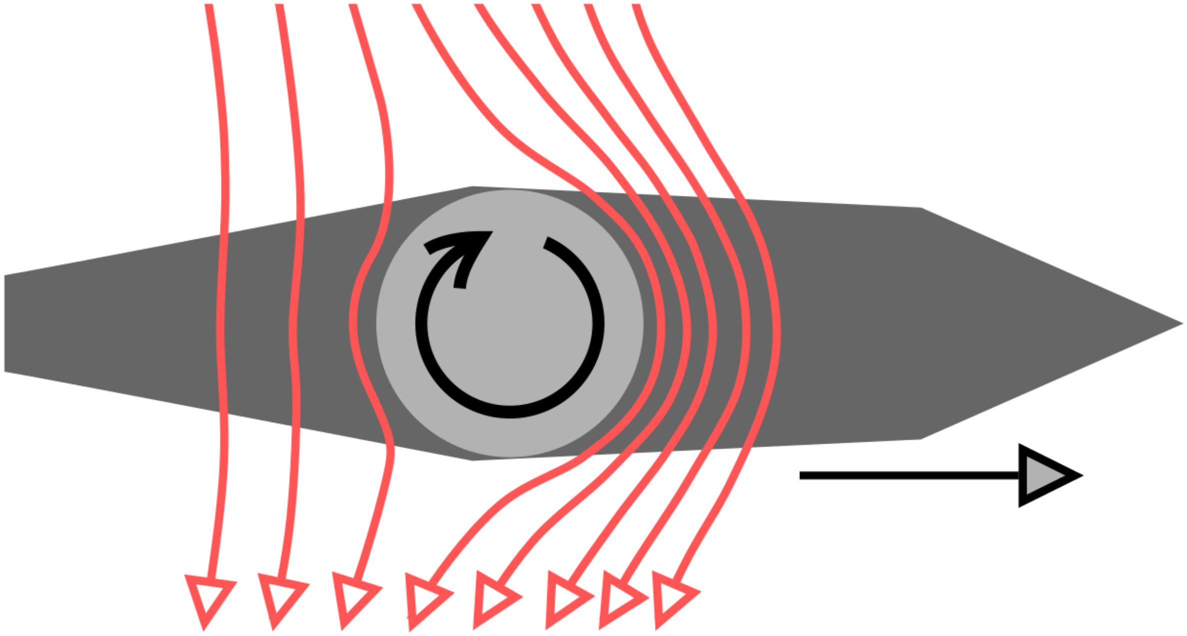


Figure 34 Vessel with one clockwise-spinning Flettner rotor (image courtesy of Reference 84)

Flettner rotors, a wind-assisted propulsion option, have provided fuel cost savings in some large, oceangoing vessel applications. A Flettner rotor consists of a large spinning cylinder (18-30m high and 3-5m in diameter) vertically situated on the deck of a vessel that provides thrust as air passes over it. The cylinder’s spin imparts a positive acceleration to air passing over it in the direction of the spin and a negative acceleration to air passing over it against the spin direction, causing a low-pressure region to form on the side of the rotor 90º clockwise from the point on the rotor facing the wind direction. This low-pressure region creates thrust in the direction of the low-pressure region, “pulling” the vessel forward.

Flettner rotors are most efficient in a perpendicular crosswind and provide no positive thrust when the vessel is proceeding directly upwind or downwind, since the direction of thrust is 90º relative to the wind direction. When transiting upwind or downwind, the thrust will be either to port or to starboard depending on the wind direction and direction of rotor rotation.

Rotors consume power to spin and produce some wind drag given their exposure above the deck, but in the correct applications they can more than offset these penalties with fuel savings from the thrust they impart. Fuel reductions from 5%-20% have been reported, depending on the number of rotors installed, the characteristics of those rotors, and the vessel and route particulars. The thrust imparted by a rotor increases proportional to the square of the rotor diameter, and taller rotors capture additional wind area. In practice, however, the number of rotors installed and their height and diameter characteristics are subject to deck area, stability, and operational constraints.

Flettner rotors are most applicable for vessels that undergo long transits, especially through regions with strong prevailing winds transverse to the vessel’s route. Given SIF and NYCF transit lengths and operating areas, Flettner rotors would provide little to no benefit while also consuming a large amount of deck space and are not recommended for the City’s fleets.

Section 6 Existing Vessel Blueprint

This section discusses potential SIF and NYCF applications for fuels and technologies introduced in Section 5. The fuels and technologies discussed in this section provide modest to significant emissions and/or fuel consumption improvements, with a range of capital investment levels required.

For each technology or alternative fuel, a variety of real-world applications could be practical. Based on the wide variety of technologies and fuels considered in this study, our analysis did not attempt to identify an optimum application for each technology. Rather, the analysis generally assumes fleetwide implementation starting in 2020. In reality, many of the following applications would have to consider planning, engineering, logistical, and operational factors that would spread their implementation over multiple years. The results below should generally be considered the “maximum benefit” for the given technology. Should the City desire to pursue a given option further, a study specifically focused on the selected option would be appropriate to develop the most effective implementation of the technology.

Section 6 provides the following for each option investigated:

- Key assumptions for fuel consumption, emissions factors, and costs, along with additional details on the background and basis for these assumptions.
- A comparison of fuel consumption and emissions between each option and the baseline.
- A cost-benefit analysis and overall lifecycle cost (LCC) analysis for each option.
    - Costs considered are rough order of magnitude (ROM), and a detailed cost estimate should be carried out prior to implementation.

The fuel, emissions, and cost data are typically rounded to two significant figures. Costs greater than 100 million are rounded to the nearest million. Minor differences between the summary tables in this section and the detailed spreadsheets included in appendices may occur. Additionally, the summary tables include some rounding error; for the precise values used in lifecycle analysis calculations, consult the corresponding appendix section.

6.1 Staten Island Ferries

Each option considered for the SIF fleet was analyzed using the same methodology described in Section 4.3.1.1 for the baseline fleet.

6.1.1 Biodiesel

Assumptions

Capital costs to prepare SIF ferries and facilities for biodiesel use were estimated using the following assumptions.

- Costs are primarily due to tank cleaning for both the ferries and fuel barges
- Additional capital costs consist of engineering and modification work required to add instrumentation and monitoring equipment to ferry and barge fuel systems
- Cleaning costs were estimated as $.30/gal (based on Reference 44)

Other key cost and environmental impact assumptions are summarized below:

- B20 cost is $0.05 per gallon greater than projected ULSD cost
- B20 volumetric fuel consumption is 1% higher than ULSD
- The B100 blended into the fuel has lifecycle CO_2 emissions 50% lower than ULSD, so a B20 blend has 11% lower CO_2 emissions than an equivalent volume of ULSD
- NOx increases by 2%. HC, PM, and CO decrease by 15%.

Full details for this option are shown in Appendix A.3.

Results

Under this option, the SIF fleet would use approximately 17 million gallons of B100 over the next 20 years. This compares to a monthly diesel consumption in the East Coast Petroleum District (PADD) of 40M barrels. Using the 5% biodiesel limit allowed in ASTM D975, the east coast PADD could exceed 17 million gallons of biodiesel each week. The 20-year lifecycle performance of the SIF fleet under these assumptions is given in Table 30.

Table 30 20-year performance of SIF fleet utilizing B20 fuel

Metric	Units	Baseline	B20 Biodiesel	Change		Cost Benefit ($/Unit)
Capital Cost	$		$390,000			
Operating Cost	NPV $	$231,000,000	$237,000,000	+$6,000,000	+3%	-
Total Cost	NPV $	$231,000,000	$238,000,000	+$7,000,000	+3%	-
Fuel	gal	82,000,000	83,000,000	+1,000,000	+1%	-
CO_2	MT	850,000	760,000	-90,000	-11%	$78
NO_x	kg	5,300,000	5,400,000	+100,000	+2%	-
HC	kg	470,000	400,000	-70,000	-15%	$100
PM	kg	110,000	98,000	-12,000	-11%	$583
CO	kg	920,000	780,000	-140,000	-15%	$50
SO_2	kg	7,900	6,300	-1,600	-20%	$4,375

Recommendation

→ **Blending biodiesel above the 5% limit allowed by ASTM D975 is not recommended.**

B20 offers a slight improvement in the SIF fleet global warming potential. Although costs would be slightly higher than baseline, B20 is the most affordable alternative fuel in terms of cost/benefit for CO_2 reduction. Despite this apparent affordability, the risk of operational problems could not be quantified, and the criteria emissions reductions are a best-case scenario – it is entirely possible that no benefit to local emissions would result. Given the operational risks and uncertainty in emissions performance, these benefits are considered marginal.

6.1.2 Renewable Diesel

Assumptions

The key assumptions of a renewable diesel program at SIF are:

- RD is blended with ULSD and utilized at the R50 level. This conservatively accounts for RD's "drop-in" capabilities while also considering limited availability from fuel suppliers

- Renewable diesel cost per gallon is $1.50 greater than the forecasted ULSD cost
- The R100 blended into the fuel has lifecycle CO_2 emissions 65% lower than ULSD, so an R50 blend has 33% lower CO_2 emissions than an equivalent volume of ULSD
- NOx decreases by 2%. HC, PM, and CO decrease by roughly 15%

Full details for this option are shown in Appendix A.4.

Results

In this option, the SIF fleet would use approximately 41 million gallons of R100 over the next 20 years. Table 31 shows the SIF fleet's 20-year lifecycle performance under these assumptions.

Table 31 20-year performance of SIF fleet utilizing R50 fuel

Metric	Units	Baseline	R50 Renewable Diesel	Change		Cost Benefit ($/Unit)
Capital Cost	$		$0			
Operating Cost	NPV $	$231,000,000	$287,000,000	+$56,000,000	+24%	-
Total Cost	NPV $	$231,000,000	$287,000,000	+$56,000,000	+24%	-
Fuel	gal	82,000,000	82,000,000	-	-	-
CO_2	MT	850,000	570,000	-280,000	-33%	$200
NO_x	kg	5,300,000	5,200,000	-100,000	-2%	$560
HC	kg	470,000	400,000	-70,000	-15%	$800
PM	kg	110,000	98,000	-12,000	-11%	$4,667
CO	kg	920,000	780,000	-140,000	-15%	$400
SO_2	kg	7,900	4,000	-3,900	-49%	$14,359

Recommendation

Although expensive, renewable diesel is a low risk means to achieve substantial CO_2 reduction. It can be utilized at higher blends than biodiesel and usage is limited only by available quantity and budget. Consideration should be given to full scale testing to confirm the changes in criteria emissions. Even if testing did not show significant local emission improvements, renewable diesel offers the largest readily achievable reduction in the SIF fleet global warming potential.

→ Use of renewable diesel is strongly recommended.

Varying quantities can be purchased as budgets dictate with negligible overhead costs required to periodically increase or decrease RD usage. The City should compare the cost of using renewable diesel on the ferries with other green initiatives and utilize as much renewable diesel as is financially feasible.

6.1.3 Natural Gas Conversion

The variety of natural gas options available prompts several considerations for gas conversion. The options are summarized below.

Table 32 Natural gas conversion options

Option	Description
A	3 Molinari class ferries converted to DGB
B	3 Ollis class ferries converted to DIG, midsize built as gas ferries
C	Hypothetical scenario where SIF fleet is powered entirely by DIG. Shows upper limit of fuel cost savings and CO_2 changes.

Options A and C are presented for comparison only, with significant results given in Table 34. A complete comparison of Option B with the baseline is given in Table 33

Costs

- LNG price as delivered in 2020 is $12/mmBTU.
- This price is composed of an assumed $3.50 Henry Hub commodity price, $5 liquefaction cost, and $3.50 to cover delivery, supplier’s markup, etc.
- The commodity price is predicted to change as forecast by the 2019 AEO
- Liquefaction costs are predicted to follow the 2019 AEO forecast for industrial electricity
- Delivery and markup are predicted to match inflation (constant in real 2018 dollars)
- Capital costs for a Molinari class DGB conversion are $10M, an Ollis class DIG conversion costs $12M, and a future midsize ship, designed for DIG, would cost $4M more than a comparable diesel-powered ship.
- No capital costs were included for bunkering infrastructure (barge, shore facility, etc.)

Assumptions – General

- Criteria emissions are the same as the applicable tier diesel engine (Tier 3 for Molinari class DGB, Tier 4 for Ollis and Midsize class DIG)

Assumptions – DGB (Option A)

- Gas substitution and fuel use are as shown in Figure 35
- Diesel SFC is based on the baseline Molinari SFC curve plus 7% loss of efficiency for lowering compression ratio from 18:1 to 14:1
- 5 g/kwh methane slip, with a 28x GWP, for 140 g CO_2e/kwh

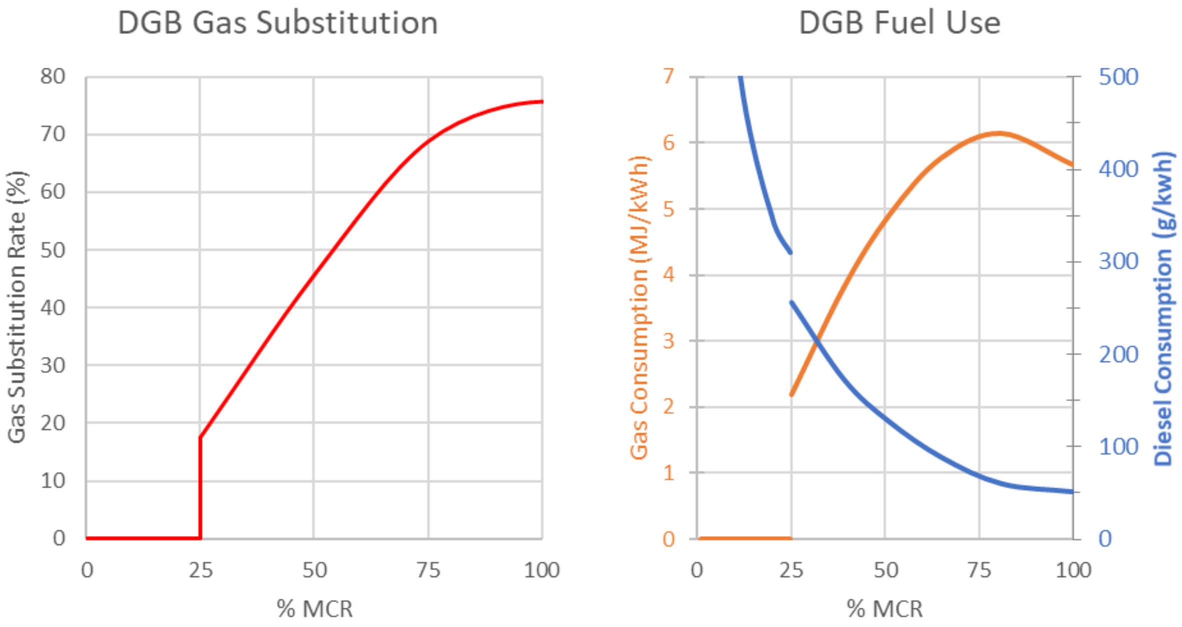


Figure 35 Assumed DGB gas substitution and fuel use

Assumptions – DIG (Option B)

- Gas substitution is constant at 95%
- 5% of required kw are assumed to come from diesel pilot fuel
- 0.1 g/kwh methane slip, with a 28x GWP, for 2.8 g CO_2e/kwh

Assumptions – All Gas (Option C)

Option C is not a true “option” with specific engines, fuel curves, and operating profile calculations like the other options. Instead, the performance of the two DIG ferries estimated in Option B is extrapolated to examine how an “all gas” ferry system might perform.

- Assumed 5% of baseline diesel consumption remains as pilot fuel
- Estimated 100MJ gas required to replace each gallon of the other 95% of fuel
- Estimated 600 g/kwh total CO_2e emissions for the combined gas and diesel fuel

Fuel costs were estimated from the resulting gas and diesel usage using the same approach as the other options. No capital costs were estimated for Option C – the change in cost reported is the NPV of 2020 to 2040 fuel costs only. This shows the upper limit of fuel cost and CO_2e savings that could be expected from a complete conversion to gas.

Full details for options A and B are given in Appendices A.5 and A.6 respectively.

Results

Table 33 20-year performance of SIF fleet utilizing DIG on Ollis and Midsize (Option B)

Metric	Units	Baseline	DIG LNG Ollis/Midsize	Change		Cost Benefit ($/Unit)
Capital Cost	$		$48,000,000			
Operating Cost	NPV $	$231,000,000	$188,000,000	-$43,000,000	-19%	-
Total Cost	NPV $	$231,000,000	$235,000,000	+$4,000,000	+2%	-
Fuel (Diesel)	gal	82,000,000	49,000,000	-33,000,000	-40%	$0
Fuel (LNG)	GJ	-	3,900,000	+3,900,000	-	-
Total Fuel Energy	GJ	12,000,000	11,000,000	-1,000,000	-8%	$4
CO_2	MT	850,000	780,000	-70,000	-8%	$57
NO_x	kg	5,300,000	5,300,000	-	-	-
HC	kg	470,000	470,000	-	-	-
PM	kg	110,000	110,000	-	-	-
CO	kg	920,000	920,000	-	-	-
SO_2	kg	7,900	4,700	-3,200	-41%	$1,250

[1] This indicates that the payback period for the estimated capital costs would be 20 years. Continued operation would show a cost savings vs. the baseline.

Table 34 Comparison of Natural Gas Options

Option	Diesel Reduction	Gas Usage	Change in Cost	Change in CO_2e
A – Molinari DGB	-15M gal	1.8M GJ	+$11M	-208 MT (<-0.1%)
B – Ollis/Mid DIG	-33M gal	3.9M GJ	+$4M	-70,000 MT (-8%)
C – 100% DIG	-78M gal	8.2M GJ	-$114M[1] (-50%)	-142,000 MT (-17%)

[1] Change in Fuel Cost Only. Capital cost not included

Sensitivity

The capital cost and LNG fuel cost used in the above estimates are high level approximations. The economic feasibility of a gas conversion depends heavily on both assumptions. For example, at a price of $10/mmBTU (delivered) for LNG, Option B saves $13M over 20 years instead of breaking even. The “maximum savings” calculated by option C increases by $7 million dollars for each $1 decrease in the 2020 price of LNG.

The EIA develops several alternative cost forecasts with each Annual Energy Outlook. These include high and low estimates to bound future oil prices, and scenarios with varying development in future technology used for oil and gas extraction. High oil prices give a more significant advantage to gas fuel. Conversely, if advances in gas production technology slow significantly, gas costs could increase, making gas conversion less beneficial. A sensitivity analysis was performed to determine if alternative fuel price forecasts warrant greater consideration of gas fuel to mitigate future cost risks. Results are given in Figure 36. The key takeaway is that even with a worst case “high oil price” projection, gas conversions only save $16 million over 20 years (approximately 6%). The payback period is greater than 20 years under all other fuel price forecasts.

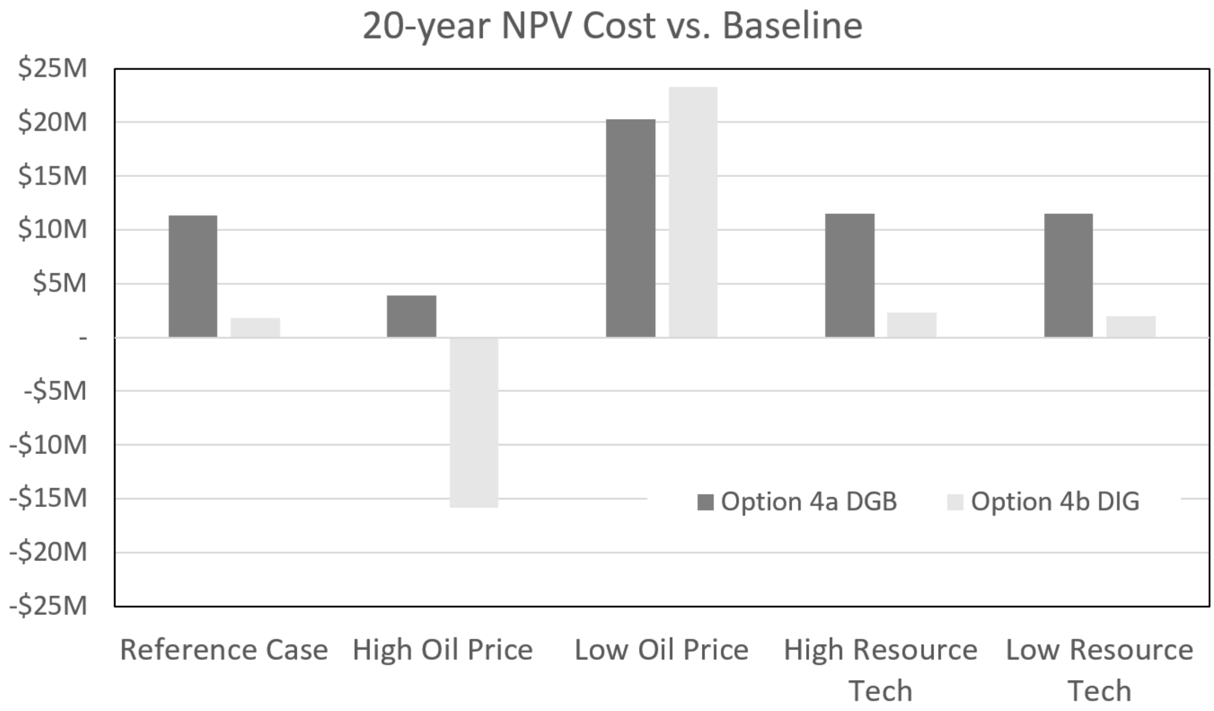


Figure 36 Gas conversion costs under different fuel price forecasts

Recommendation

Natural gas offers marginal environmental benefits but promises 50% lower fuel costs. Despite the promise of gas fuel for many ships, our conclusion is that Staten Island Ferries do not consume enough fuel to repay capital costs in a timely manner. This is particularly true of DGB because of the load dependence of the gas substitution. One way to interpret the $121 Million fuel savings calculated for Option C is as a gas conversion budget – for six ferries already in service, three Ollis class ferries that are nearly complete with construction, and three midsize ferries to be designed in the future.

> Even if twelve ferries could be converted to gas for $10M each, SIF would merely break even in the next 20 years.

CNG offers a clearer path to a fuel supply acceptable under the City's local regulations. It also theoretically provides further cost savings compared to having LNG delivered. However, CNG is not compatible with DIG because of impracticality of using onboard compressors to meet the high fuel supply pressure requirements.

→ Neither LNG nor CNG is recommended for SIF at this time.

6.1.4 Integrated Diesel Electric Plant

This option is only applicable to the diesel-electric Molinari class vessels. While also technically feasible for the *Kennedy*, the *Kennedy* is slated for retirement upon the *Ollis* entering service and was not considered for any upgrades or modifications.

This option assumes integration of the propulsion and the ship service electrical plants on all three Molinari class vessels. Integrating the plant would be an alternative to the third ship service genset modification discussed in Section 4.2.6 and that work would not be required if this option were pursued. The cost of those modifications was not included in this study's baseline – a direct comparison of the two options must consider the capital cost of the third ship service genset.

Assumptions

Other key assumptions are summarized below:

- Vessels operate with only two propulsion diesel generators online; no ship service diesel generators used during normal operation
- Transformer and harmonic filters with an overall efficiency of 97% added to the ship service load

Full details for this option are shown in Appendix A.7.

Results

The 20-year lifecycle performance of the SIF fleet under these assumptions is given in Table 35. Results shown in Table 35 are fleetwide benefits seen as a result of implementing an integrated diesel electric plant on only the three Molinari class vessels with no change to the other classes.

Table 35 20-year performance of SIF fleet with change to integrated diesel electric plant on Molinari class

Metric	Units	Baseline	Integrated Bus Molinari	Change		Cost Benefit ($/Unit)
Capital Cost	$		$6,800,000			
Operating Cost	NPV $	$231,000,000	$227,000,000	-$4,000,000	-2%	-
Total Cost	NPV $	$231,000,000	$234,000,000	+$3,000,000	+1%	-
Fuel	gal	82,000,000	81,000,000	-1,000,000	-1%	$3
CO_2	MT	850,000	830,000	-20,000	-2%	$150
NO_x	kg	5,300,000	4,900,000	-400,000	-8%	$8
HC	kg	470,000	450,000	-20,000	-4%	$150
PM	kg	110,000	110,000	-	-	-
CO	kg	920,000	910,000	-10,000	-1%	$300
SO_2	kg	7,900	7,800	-100	-1%	$30,000

Recommendation

Upgrading the Molinari class vessels to an integrated plant architecture would provide a moderate savings in both fuel and emissions. The capital cost of the conversion is repaid by fuel and maintenance cost savings over a 20-year lifecycle.

→ **This option is cost neutral, provides minor emissions benefits, and would have a lower lifecycle cost than the Molinari class third genset modification being considered at SIF. Integrating the plant is recommended as an alternative to installing a third genset.**

6.1.5 Variable Speed Diesel Electric Plant

This option is only applicable to the diesel-electric Molinari class vessels. While also technically feasible for the *Kennedy*, the *Kennedy* is slated for retirement upon the *Ollis* entering service and was not considered for any upgrades or modifications.

This option assumes integration of the propulsion and the ship service electrical plants on all three Molinari class vessels. Integrating the plant would be an alternative to the third ship service genset modification discussed in Section 4.2.6 and that work would not be required if this option were pursued. Converting to variable speed requires a DC propulsion switchboard similar to the Siemens BlueDrive PlusC solution which comes at higher cost than the upgraded or replacement AC propulsion switchboard discussed in Section 6.1.4. The cost of the ship service generator modifications was not included in this study's baseline – a direct comparison between the two options must consider the capital cost of the third ship service genset, similar to the integration option discussed in Section 6.1.4.

Assumptions

Other key assumptions are summarized below:

- Vessels operate with only two propulsion diesel generators online; no ship service diesel generators used during normal operation
- Inverter and transformer with a total efficiency of 97% added to the ship service load
- Common DC bus propulsion switchgear installed
- Existing alternators replaced with variable speed alternators w/ rectifiers.
- Existing propulsion engines reused
- Existing AC propulsion motors can be reused, but the motor drives would be replaced as part of the new common DC bus
- No change in overall diesel electric system efficiency (per vendor recommendation)
- Based the SFC for variable speed operation on the EMD 16-710 engine propulsion engine curve

Full details for this option are shown in Appendix A.8.

Results

The 20-year lifecycle performance of the SIF fleet under these assumptions is given in Table 36. Results shown in Table 36 are fleetwide benefits from implementing an integrated variable speed diesel electric plant on only the three Molinari class vessels, with no change to the other classes.

Table 36 20-year performance of SIF fleet with change to integrated variable speed diesel electric plant on Molinari class

Metric	Units	Baseline	Int Bus & Var Spd Molinari	Change		Cost Benefit ($/Unit)
Capital Cost	$		$33,000,000			
Operating Cost	NPV $	$231,000,000	$220,000,000	-$11,000,000	-5%	-
Total Cost	NPV $	$231,000,000	$252,000,000	+$21,000,000	+9%	-
Fuel	gal	82,000,000	78,000,000	-4,000,000	-5%	$5
CO_2	MT	850,000	800,000	-50,000	-6%	$420
NO_x	kg	5,300,000	5,000,000	-300,000	-6%	$70
HC	kg	470,000	470,000	-	-	-
PM	kg	110,000	100,000	-10,000	-9%	$2,100
CO	kg	920,000	910,000	-10,000	-1%	$2,100
SO_2	kg	7,900	7,500	-400	-5%	$52,500

Recommendation

Upgrading the Molinari class vessels' propulsion plants to an integrated variable speed plant architecture would provide increased savings in both fuel and emissions compared to only an integrated plant, but at a significantly increased overall cost.

→ **Due to the significant lifecycle cost increase for marginal fuel and emissions savings over an integrated plant, this option is only recommended as a stepping stone to plug-in electric.**

The Molinari class diesel electric plants should be upgraded. However, due to the high cost of and marginal emissions improvements of this option, it is only recommended as a step toward plug-in electric. The DC propulsion switchboard associated with variable speed operation allows for simpler addition of battery storage and shore charging.

6.1.6 Non-Plug-in Hybrid Diesel Electric Plant

This option is only applicable to the diesel-electric Molinari class vessels. While also technically feasible for the *Kennedy*, the *Kennedy* is slated for retirement upon the *Ollis* entering service and not considered for any upgrades or modifications. A hybrid diesel electric system with no plug-in option was investigated for the future midsize vessels, but there were no cost, fuel, or emissions benefits seen, so this propulsion system is not recommended.

This option assumes integration of the propulsion and the ship service electrical plants on all three Molinari class vessels. Integrating the plant would be an alternative to the third ship service genset modification discussed in Section 4.2.6, and the third genset modification would not be required if this option were pursued. Converting to battery hybrid requires a DC propulsion switchboard similar to the Siemens BlueDrive PlusC solution, which comes at higher cost than the upgraded or replacement AC propulsion switchboard discussed in Section 6.1.4. The cost of the ship service generator modifications was not included in this study's baseline – a direct comparison between the two options must consider the capital cost of the third ship service genset, similar to the integration option discussed in Section 6.1.4.

Assumptions

Other key assumptions are summarized below:

- Vessels operate with one propulsion diesel generator and one ship service diesel generator online during normal operation.
- Hybrid system efficiency of 97% when both charging and discharging the batteries
- Existing propulsion engines, alternators and propulsion motors are reused
- Capital cost for this option assumes full implementation of an integrated variable speed propulsion system with the addition of energy storage modules

Full details for this option are shown in Appendix A9.

Results

The 20-year lifecycle performance of the SIF fleet under these assumptions is given in Table 37. Results shown in Table 37 are fleetwide benefits from implementing a non-plug-in integrated hybrid diesel electric plant on only the three Molinari class vessels, with no change to the other classes.

A diesel hybrid system for the Molinari class is feasible but with very little margin, and in practice, a second ship service generator would be required during some transits. Due to increased load on the existing untiered ship service diesel generators, the overall criteria emissions reductions are limited, and actually increase in some categories. Calculations for this option were completed assuming that the existing Molinari class engines (propulsion and ship service) would be retained.

As the Molinari class vessels are currently in service, they would be retrofitted to non-plug-in hybrid configuration. In order to maintain operation as discussed above, the battery energy required for each one-way trip is roughly 290 kWh. Based on the lithium ion NMC battery DOD vs. cycle life chart (see Figure 24), with a vessel cycle rate of 5130 cycles per year, a lifespan of approximately six years can be achieved at 30% DOD. This design point yields a battery size of approximately 1 MWh with an approximate weight of 9.5 MT. A battery this size would require roughly eight battery racks, each 4.13 ft wide x 7.37 ft tall x 2.68 ft deep. These can be banked up to eight racks deep for a total length of roughly 21.5 feet. The battery racks would be split into two separate banks, fore and aft, for redundancy. This likely would not pose any serious arrangement challenges on the Molinari class due to the currently unused car deck.

Table 37 20-year performance of SIF fleet with change to integrated hybrid diesel electric plant on Molinari class

Metric	Units	Baseline	Diesel Hybrid Molinari	Change		Cost Benefit ($/Unit)
Capital Cost	$		$37,000,000			
Operating Cost	NPV $	$231,000,000	$223,000,000	-$8,000,000	-3%	-
Total Cost	NPV $	$231,000,000	$259,000,000	+$28,000,000	+12%	-
Fuel	gal	82,000,000	78,000,000	-4,000,000	-5%	$7
CO_2	MT	850,000	810,000	-40,000	-5%	$700
NO_X	kg	5,300,000	5,600,000	+300,000	+6%	-
HC	kg	470,000	490,000	+20,000	+4%	-
PM	kg	110,000	99,000	-11,000	-10%	$2,545
CO	kg	920,000	910,000	-10,000	-1%	$2,800
SO_2	kg	7,900	7,600	-300	-4%	$93,333

Recommendation

Upgrading the Molinari class vessel's propulsion plants to an integrated non-plug-in hybrid plant architecture would have mixed impacts on fuel and greenhouse gas emissions at slightly increased overall cost compared to integrated variable speed architecture. This option shows a potential reduction in fuel consumption and thus greenhouse gas emissions, but has varying effects on the different criteria emissions, from increases to slight decreases.

This study's findings for a diesel hybrid system on the Molinari class assume concurrent conversion to variable speed generation with a common DC bus, which provides greater flexibility with respect to future upgrades, similar to the non-hybrid variable speed option discussed above. There is also potential for a low overall cost version of this option via the simple integration of batteries through a charger/converter unit while maintaining an AC switchgear and existing generators, motors, and drives. Calculations showed that that this option was just within the realm of technical feasibility, but with little margin. Additionally, it provides no stepping stone for future upgrades to plug-in electric operation, and this option was not investigated further.

→ Non-plug-in diesel hybrid technology is not recommended for Molinari class vessels.

The Molinari class diesel electric plants should be upgraded. However, due to the non-plug-in diesel hybrid option's high cost and emissions uncertainty compared to variable speed, it should not be pursued. While a diesel hybrid system would provide experience utilizing battery power prior to a conversion to plug-in electric, the increased cost outweighs the benefit.

6.1.7 Plug-in Electric

Analysis for this option assumes that both diesel electric and diesel mechanical vessels (Molinari class and Ollis class, respectively) will be retrofitted for plug-in operation, and that future midsize class vessels will be purpose-built plug-ins. The following configurations were assumed:

- Molinari class and future midsize class: plug-in series hybrid configuration with fully electric operation and back up diesel engines
- Ollis class: fully plug-in electric configuration with four existing diesel propulsion engines replaced with electric motors

Implementing plug-in electric operation on the Molinari, Ollis, and future midsize classes achieves the maximum benefit for the upfront logistics costs. This composition of vessels encapsulates the maximum feasible level of plug-in electric implementation for SIF, thereby depicting the maximum possible fuel usage and global emissions reductions while best leveraging the required electrical infrastructure upgrades with the current fleet. As this option's upfront implementation cost is very high, it must be implemented on as many vessels as possible to achieve the maximum benefit for money spent.

Due to the Ollis class's diesel mechanical drivetrain and engine sizes, it would be necessary to fully convert these vessels to plug-in electric operation by replacing each propulsion engine with an electric motor. A parallel hybrid configuration was considered, but two diesel engines in operation (one per end) do not provide enough power to make transit speed and maintain schedule. It was therefore determined that full electric conversion is the best option to consider in this study. This proposal does not provide diesel backup power, and shoreside infrastructure must be fully operational prior to conversion of the Ollis class.

Assumptions

Other key assumptions are summarized below:

- Molinari class and future midsize class vessels operate with no diesel engines online during normal operation, but diesel generators are kept onboard for backup and emergency situations
- Ollis class conversion accomplished by removing both propulsion engines from each end and replacing each one (four total) with an equivalently sized propulsion electric motor with a battery bank on each end of the vessel
  - Ollis class vessels operate with fully plug-in electric power; total installed power would be similar to current design
- Automated charging stations installed at both ferry terminals, with an allowance of two minutes for connect/disconnect and power ramp up/down time and six minutes of charging time
  - Charging power would need to be approximately 17-18 MW on an Ollis class vessel
    - Automated charging stations in the 12 MW range are currently in operation (Forsea Ferry, Sweden) and 15+ MW range are currently in the pre-operation/design phase (Color Line, Norway); it is assumed that charging infrastructure will not be a future barrier
  - Small schedule adjustments could allow for longer charging times and reduce required charging power and associated costs
- Battery system efficiency is 97%, both when charging and when discharging the batteries
- Emissions rates for the New York state electric grid were taken from US Energy Information Administration, Reference 8, and US Environmental Protection Agency, Reference 77. Worst case scenario emissions were used when the data was in conflict:

Emission	CO_2	NOx	CO	HC	PM	SO_2
Emission Rate (g/kWh)	200	0.2	0.1	0.007	0.01	0.1

Full details for this option are shown in Appendix A.10.

Results

Table 38 shows the SIF fleet’s 20-year lifecycle performance under these assumptions. These results are fleetwide benefits seen as a result of implementing plug-in hybrid electric operation on the three Molinari class vessels, three Ollis class vessels, and the three future midsize class vessels with no change to the other classes.

Table 38 20-year performance of SIF fleet with change to plug-in electric operation on Molinari, Ollis, & midsize class

Metric	Units	Baseline	Plugin Electric Operation	Change		Cost Benefit ($/Unit)
Capital Cost	$		$160,000,000			
Operating Cost	NPV $	$231,000,000	$213,000,000	-$18,000,000	-8%	-
Total Cost	NPV $	$231,000,000	$374,000,000	+$143,000,000	+62%	-
Fuel	gal	82,000,000	9,200,000	-72,800,000	-89%	$2
Electricity	kWh	-	1,100,000,000	+1,100,000,000	-	-
CO_2	MT	850,000	310,000	-540,000	-64%	$265
NO_X	kg	5,300,000	1,300,000	-4,000,000	-75%	$36
HC	kg	470,000	76,000	-394,000	-84%	$363
PM	kg	110,000	33,000	-77,000	-70%	$1,857
CO	kg	920,000	260,000	-660,000	-72%	$217
SO_2	kg	7,900	130,000	+122,100	**	-

***The theoretical SO_2 emissions rate is dramatically influenced by the few remaining coal plants in New York. The remaining coal plants are likely to be decommissioned by 2021, reducing SO_2 emissions to approximately zero.*

As the Molinari and Ollis class vessels are either currently in service or under construction, they would need to be retrofitted to support plug-in electric service. In order to maintain operation as discussed above, the battery energy required for each one-way trip is roughly 1690 kWh on the Ollis class, which constitutes the most demanding scenario. Based on the lithium ion NMC battery DOD vs. cycle life chart (see Figure 24), with a vessel cycle rate of 5130 cycles per year, a lifespan of approximately six years can be achieved at 30% DOD. This design point yields a battery size of approximately 5.5 MWh, with an approximate weight of 52.5 MT. A battery this size would require roughly 40 battery racks, each 4.13 ft wide x 7.37 ft tall x 2.68 ft deep. These can be banked up to eight racks deep for a total length of roughly 21.5 feet. The battery racks would be split into two separate banks, fore and aft, for redundancy. A notional battery arrangement for an Ollis class vessel is provided in Figure 37 for proof of concept; it is assumed that the Molinari class arrangement will be less challenging due to the currently unused car deck.

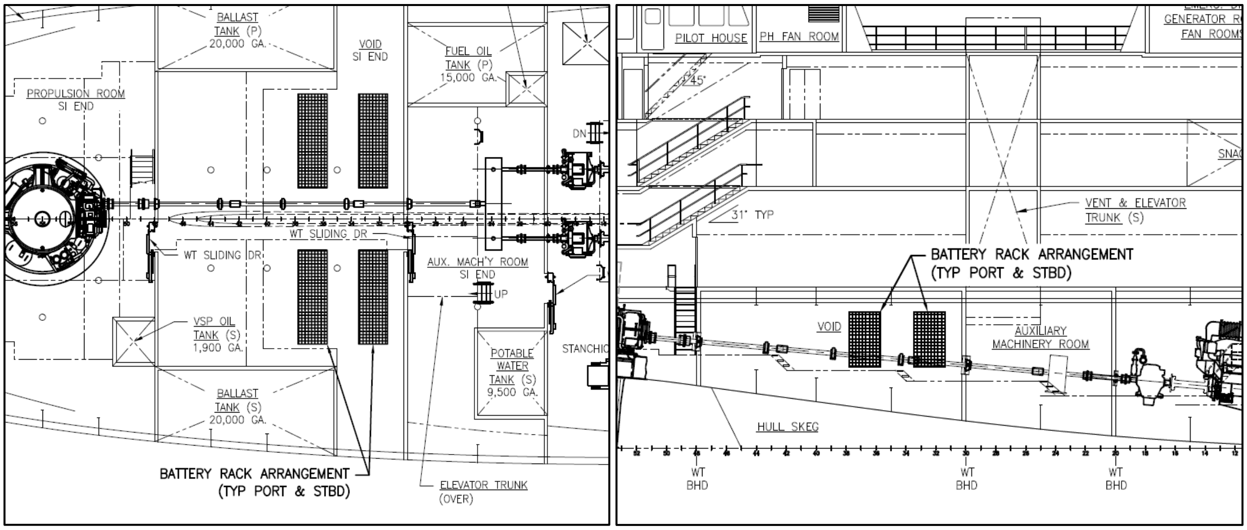


Figure 37 Notional battery arrangement on Ollis class vessel, mirrored fwd and aft (new motors not shown)

Note that due to load being transferred to the electric grid, sulfur dioxide emissions are predicted to increase approximately fifteenfold. Sulfur dioxide emissions from shoreside electric generation are driven by coal fired power plants, and New York State has proposed legislation that will likely force retirement of the plants by 2021. Therefore, in the future it is expected that electric grid sulfur dioxide emissions will drop significantly compared to the results provided in Table 37.

Recommendation

Implementing plug-in electric ferry operations at SIF will be costly, but this option provides the greatest potential fuel usage and emissions reductions – with two caveats. First, due to the very high cost of electricity in New York City, operational "fuel" costs will only decrease by roughly 9% from the ULSD baseline level, which does not outweigh the high capital cost. Second, while New York State's remaining coal plants continue to operate, per unit energy sulfur dioxide emissions from shore-based electricity generation facilities will greatly exceed the ULSD baseline levels.

Despite these caveats and the high implementation cost, the City should pursue plug-in electric technologies for all SIF classes expected to be in operation long-term. This recommendation is discussed further in Section 7.1.

The City's electricity rates are mostly driven by demand charges on the peak power draw, which are currently $14.75 per kW on average. The City should investigate any ability to decrease these demand rates in order to drive down overall cost of this option. Figure 38 shows how the 20-year present value operating cost (total diesel, electricity and maintenance) would vary based on a range of power demand rates compared to the baseline present value operations cost.

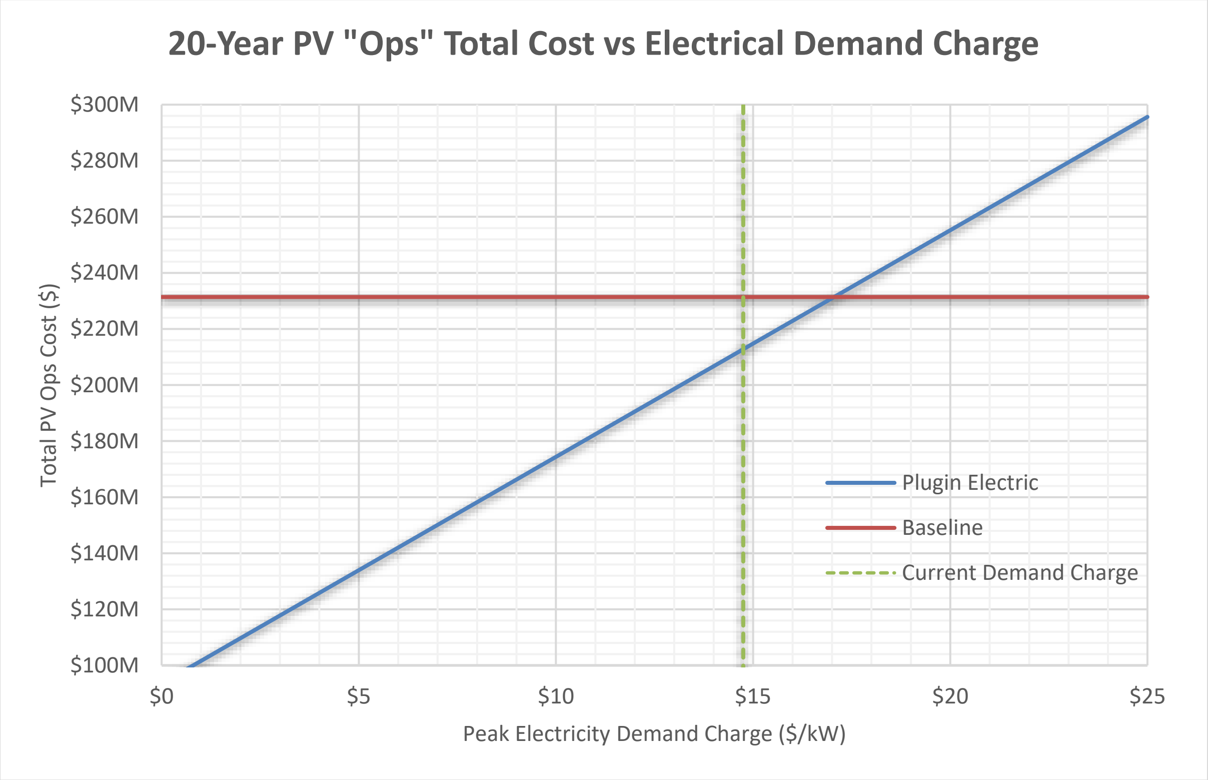


Figure 38 20-year present value operations cost variation compared to assumed electrical demand charge with a breakeven point shown at $17/kW

As mentioned above, proposed legislation would require that New York's coal-fired power plants be phased out of service by 2021, which would lower sulfur emissions to be in line with diesel engine operation with ULSD.

It is also realistic to assume that that total emissions from the electrical grid will continue to drop in the future, and likely at a much more significant rate over time than any incremental reductions possible on individual diesel engines. As battery and charging technologies advance in the coming years, this type of operation will become less costly and even more beneficial with respect to emissions.

→ Further investigation and implementation of plug-in electric operation is recommended.

6.1.8 Low Friction Hull Coatings

The cost and environmental impact of applying low friction hull coatings to SIF vessels were calculated as follows. First, a detailed analysis of the costs and benefits of low friction hull coatings was completed for the Ollis class ferries, which were chosen due to availability of information (See Appendix A.13). The estimated benefit from the detailed analysis was then applied to all other SIF classes. The low friction hull coating used for this analysis is Intersleek 1100SR coating with an Intersleek 731 tie coat. This option was chosen because it is the most advanced offering from International Paint, the same company that provides SIF's current coating, Interclene 245NA. Maintenance costs for switching coatings are estimated based on vessel surface area and vendor-provided coating costs, with added cost due to specialized installation requirements.

Assumptions

Other key assumptions are summarized below:

- Coating data (provided by vendor):

Table 39 International Marine Coatings data

Coating	Cost ($/gal)	Coverage (ft^2/gal)	Lifespan (yrs)
International Interclene 24NA	~$75	220	3
International Intersleek 731	~$150	253	Up to 10
International Intersleek 1100SR	~$246	171.5	Up to 10

- Power reductions are the same for all classes, based on Ollis class detailed calculations in Appendix A.13
- Power reductions occur only during transit phase of operations
- Surface roughness of Intersleek coating is ~70µm
- Surface roughness of baseline Interclene coating is ~150µm (Reference 76)

Based on the assumed surface roughness values, the required shaft power is reduced by roughly 3% during the transit phase of operations. The detailed analysis completed for Ollis class vessels takes data from the hull model tank testing (Reference 66) and uses it to calculate the change in power required for vessel propulsion when the surface roughness of the hull is varied. These calculations were completed in accordance with the 1978 ITTC Performance Prediction Method, (Reference 76).

The assumed surface roughness values are at coating application. Fouling will increase roughness of the legacy coating faster than the low friction coating. This means the new coatings’ power reduction benefits versus the legacy coatings will increase with time in operation. However, since this change over time will vary based on maintenance and surrounding conditions, it was not included in the analysis.

Complete information for the surface roughness analysis and other calculations for this option are provided in Appendix A.11.

Results

The 20-year lifecycle performance of the SIF fleet under these assumptions is given in Table 40. Although the low friction hull coating costs more at application, the increased lifespan and decreased fuel costs result in slight overall cost savings and emissions reductions.

Table 40 20-year performance of SIF fleet utilizing Intersleek low friction hull coatings

Metric	Units	Baseline	Low Friction Hull Coatings	Change		Cost Benefit ($/Unit)
Capital Cost	$		$0			
Operating Cost	NPV $	$231,000,000	$228,000,000	-$3,000,000	-1%	-
Total Cost	NPV $	$231,000,000	$228,000,000	-$3,000,000	-1%	-
Fuel	gal	82,000,000	80,000,000	-2,000,000	-2%	-
CO_2	MT	850,000	830,000	-20,000	-2%	-
NO_X	kg	5,300,000	5,200,000	-100,000	-2%	-
HC	kg	470,000	460,000	-10,000	-2%	-
PM	kg	110,000	110,000	-	-	-
CO	kg	920,000	910,000	-10,000	-1%	-
SO_2	kg	7,900	7,800	-100	-1%	-

Recommendation

Low friction hull coatings such as Intersleek 1100SR offer a low-cost option to reduce both total fuel consumption and emissions. While the initial cost of application of advanced coatings is approximately 6 times higher than legacy coatings, the increased coating lifespan and decreased fuel usage result in a 20-year cost savings, as well as reduced emissions. Additionally, with proper application techniques, the advanced hull coatings can be applied directly over the existing legacy coating during a standard maintenance period, which reduces operational impacts.

→ **Use of low friction hull coatings on SIF vessels is strongly recommended.**

6.1.9 Propulsive Split Operational Improvements

6.1.9.1 Molinari class

A study was completed on the *John G. Marchi*, one of the Molinari class vessels, investigating power reductions achieved by changing the propulsion power split from 83% aft and 17% forward to 90% aft and 10% forward. The study’s results, which can be seen in full in Reference 65, only apply to the three Molinari class vessels and are specific to fixed pitch propellers.

Assumptions

Other key assumptions are summarized below:

- Changing the power split reduces power required by 15%
- Equivalent power reductions will be possible across all three Molinari class vessels

Results

The 20-year lifecycle performance of the SIF fleet under these assumptions is given in Table 41. Results shown in Table 41 are fleetwide benefits resulting from a 15% power reduction during transit and maneuvering on the three Molinari class vessels, with no change to the other classes.

Table 41 20-year performance of SIF fleet with a 90/10% Molinari power split

Metric	**Units**	**Baseline**	**Power Split Molinari**	**Change**		**Cost Benefit ($/Unit)**
Capital Cost	$		$11,000			
Operating Cost	NPV $	$231,000,000	$223,000,000	-$8,000,000	-3%	-
Total Cost	NPV $	$231,000,000	$223,000,000	-$8,000,000	-3%	-
Fuel	gal	82,000,000	79,000,000	-3,000,000	-4%	-
CO_2	MT	850,000	810,000	-40,000	-5%	-
NO_X	kg	5,300,000	5,100,000	-200,000	-4%	-
HC	kg	470,000	440,000	-30,000	-6%	-
PM	kg	110,000	110,000	-	-	-
CO	kg	920,000	880,000	-40,000	-4%	-
SO_2	kg	7,900	7,600	-300	-4%	-

Recommendation

Changing the propulsion power split on the three Molinari class vessels to 90% aft and 10% forward would result in significant savings in fleetwide cost, fuel, and emissions over the 20-year lifecycle analyzed in this study. Implementation would only require programming updates to the propulsion control system in accordance with Reference 65, with no inherent risks.

→ Implementing a propulsion split update on Molinari class vessels is strongly recommended.

6.1.9.2 Voith Schneider Propelled Vessels

It is also possible that SIF's Voith Schneider propelled (VSP) vessels may save fuel by adjusting the power split between the forward and aft propellers. During model testing for the Ollis class vessels, the power split between forward and aft Voith propellers was 50%/50%. Model basin testing of the Ollis class design included a very brief investigation into power distribution (Reference 66). One test delivered slightly more power to the forward VSP, and one test delivered slightly more power to the aft VSP. Increasing power to the aft VSP by 4% (54/46 split aft/fwd) reduced overall power required by 2% compared to a 50%/50% baseline. The opposite split (46/54 fwd/aft) increased overall required power by 3%.

No additional work was done during model testing to determine if a more efficient power split was possible and what potential efficiency gains might be achievable. Given the initial implications for potential efficiency gains, more thorough investigation into the optimal power split for the Voith propelled vessels is recommended. This investigation should be accomplished through full-scale testing on one of the existing Voith Schneider propelled ferries.

6.1.10 Emissions Control Upgrades

In many cases, the advanced emissions controls techniques discussed in Section 4.2.3 to meet EPA Tier 3 and Tier 4 emissions can be retrofitted into existing lower tier engines. This often requires replacing a large number of engine parts and/or installing engine exhaust aftertreatment systems. For example, higher temperatures could require different material selection for pistons and cylinder liners, or a change from mechanical to electronic fuel injection could prompt new fuel injectors and associated control equipment. Performed independently these upgrades could be quite costly, but many of these components are replaced periodically as part of routine engine overhauls. Emissions upgrade kits purchased in conjunction with an engine overhaul can achieve significant emissions improvements with minimal added cost. Some upgrades require replacing components such as turbochargers, which would otherwise not be replaced at overhaul. These requirements increase the effective cost of an emissions upgrade.

This option assumes emissions upgrades available for the propulsion engines on Barberi and Molinari class vessels are implemented. These emission upgrades will only affect criteria emissions; CO_2 emissions are typically not affected.

Note: The Ollis class will enter service with EPA Tier 4 propulsion engines and EPA Tier 3 ship service generators, the highest ratings (i.e. - lowest emissions) currently available for these respective engine sizes.

Assumptions

Other key assumptions are summarized below:

- Molinari class propulsion engines are upgraded from EPA Tier 2 to Tier 3
- Barberi class propulsion engines upgrades reduce NOx emissions from EPA Tier 1 equivalent to Tier 2 equivalent

Full details for this option are shown in Appendix A-12.

Results

The 20-year lifecycle performance of the SIF fleet under these assumptions is given in Table 42.

Table 42 20-year performance of SIF fleet with upgraded engine emissions

Metric	Units	Baseline	Emission Control Upgrades	Change		Cost Benefit ($/Unit)
Capital Cost	$		$2,200,000			
Operating Cost	NPV $	$231,000,000	$232,000,000	+$1,000,000	+0%	-
Total Cost	NPV $	$231,000,000	$234,000,000	+$3,000,000	+1%	-
Fuel	gal	82,000,000	82,000,000	-	-	-
CO_2	MT	850,000	850,000	-	-	-
NO_x	kg	5,300,000	5,100,000	-200,000	-4%	$15
HC	kg	470,000	470,000	-	-	-
PM	kg	110,000	69,000	-41,000	-37%	$73
CO	kg	920,000	920,000	-	-	-
SO_2	kg	7,900	7,900	-	-	-

Recommendation

Voluntary EPA tier upgrades promise significant reductions in local criteria pollutants and have already been utilized effectively by SIF to dramatically reduce emissions from the fleet's propulsion engines. Further improvements may be achieved during upcoming Molinari and Barberi class engine overhauls.

→ Voluntary EPA tier upgrades for the Molinari and Barberi classes are recommended.

6.1.11 Non-Plug-in Hybrid Diesel Electric Plant II with Tier 3 Upgrades

A second diesel-battery hybrid option for the Molinari Class vessels was analyzed to capture a second set of assumptions compared to Section 6.1.6.

The Molinari Class vessels are diesel-electric (see Reference 1) and have *potential* for hybrid operation. The existing generating plant is operated well below the rated capacity and the diesel engines therefore operate below their best efficiency point. A hybrid system aims to increase plant efficiency by better matching diesel generator output with demand. During times of low load (maneuvering & dwell/pushing operations), spare capacity can be used to charge batteries and during times of peak load (transiting), stored energy can be used to supplement the generator output. This allows the diesel generators to operate near their best efficiency point throughout the load profile. This increased engine efficiency must outweigh the electrical losses incurred during battery charging and discharging to prove a net benefit.

The Molinari class vessels currently operate with two propulsion generators online, each loaded to approximately 65% during transit, 35% during maneuvering, and 15% during dwell times. Ideally, the vessels could reduce operation to a single propulsion generator with supplemental power from the batteries. Unfortunately, short maneuvering and dwell times during passenger loading and unloading do *not* provide sufficient excess power to balance the transit load, and additional power is needed. Upgrading the SSDG's to the maximum available Tier 3 rating may make a *two*-engine hybrid plant feasible.

In this analysis, a single propulsion generator and single ship service generator are assumed online during normal transits. Onboard electric batteries absorb excess power during maneuvering and passenger exchange and discharge supplemental power during peak transit loads. This leaves additional generators available in reserve for adverse weather conditions (requiring increased propulsion power) or equipment failure events.

Assumptions

Key assumptions are summarized below:

- Existing CAT 3408s (no EPA rating) are replaced with Tier 3 CAT 18s at the maximum available rating (550ekW)
- Existing propulsion diesel generators are upgraded to EPA Tier 3 equivalent
- Capital cost for this option assumes modification to the existing AC switchboard and electrical architecture with the addition of energy storage modules.
- Integrated propulsion and ship service electrical plants
- Hybrid system efficiency (DC converters and battery internal efficiency) is 91% when both charging and discharging the batteries.
- Battery system is sized for a 10-year lifetime. This considers the load profile associated with charging and discharging the batteries during each one-way trip.

Full details for this option are shown in Appendix A-13.

Results

The 20-year lifecycle performance of the SIF fleet under these assumptions is given in Table 43. Results shown in Table 43 are fleetwide benefits from modification of the three Molinari class vessels, with no change to the other classes.

A diesel hybrid system for the Molinari class is potentially feasible but with little margin (88% loading of online generators). This calculation depends heavily on the assumptions for electrical efficiencies of hybrid equipment, particularly electrical conversions between the generators (AC), batteries (DC), and propulsion motors (AC). Further analysis is required to determine details of the best integration strategy. Some runs are likely to require more energy than what is produced by the two operating engines. This could occur due to additional resistance from wind and seas, extra speed to keep the ferry on schedule, or shorter than average time at the dock. If only one such run occurs, it might be possible to manage the energy deficit with extra battery discharge. If multiple such runs occur consecutively, a second ship service generator could be periodically operated to provide the excess energy. This was not considered in emissions calculations.

To maintain operation as discussed above, the battery energy required for each one-way trip is roughly 300kWh.

Results assume the following battery characteristics:

- 910kw for 20 minutes (303kWh)
- 14 cycles per day
- 10-year life
- 1240kWh battery system

The Molinari class vessels have an unused vehicle deck that is a likely location for the new battery room.

Table 43 20-year performance of SIF fleet with change to integrated hybrid diesel electric plant on Molinari class with EPA Tier 3 engine upgrades and new ship service diesel generators

Metric	Units	Baseline	Diesel Hybrid Molinari	Change		Cost Benefit ($/Unit)
Capital Cost	$		$15,165,000			-
Operating Cost	NPV $	$231,000,000	$230,000,000	-$1,000,000	-0%	-
Total Cost	NPV $	$231,000,000	$245,000,000	+$14,000,000	+6%	
Fuel	gal	82,000,000	79,000,000	-3,000,000	-4%	$5
CO_2	MT	850,000	810,000	-40,000	-5%	$350
NO_X	kg	5,300,000	4,400,000	-900,000	-17%	$16
HC	kg	470,000	200,000	-270,000	-57%	$52
PM	kg	110,000	60,000	-50,000	-45%	$280
CO	kg	920,000	60,000	-860,000	-93%	$16
SO_2	kg	7,900	7,600	-300	-4%	$46,667

Recommendation

Upgrading the Molinari class vessel’s propulsion plants to an integrated non-plug-in hybrid plant architecture shows promise.

Replacement of the ship service generators, integration of the electrical distribution plant, and emissions upgrades to the propulsion generators provides an opportunity for significant reduction in criteria emissions and a modest reduction in carbon emissions and operating cost, when combine with hybrid technology.

→ **Diesel hybrid technology is recommended for further study on the Molinari class vessels.**

Further study of hybrid arrangements on the Molinari class vessels is required to determine the best integration strategy and expected benefits. This report makes assumptions about critical factors such as hybrid system efficiency. These assumptions must be validated with detailed engineering to confirm feasibility of the concept. This additional study should include several elements, including the following:

- Electrical engineering to determine the scope of modification or replacement of existing switchboards required to integrate the propulsion and ship service electrical plants.
- Coordination with equipment makers to propose specific equipment to allow confirmation of efficiencies, space requirements, and auxiliary system requirements
- Further validation of the operating profile assumptions, including verification of typical and above-average propulsion loads and estimating of additional ship-service load for hybrid equipment auxiliaries.
- Lifecycle cost optimization of the batteries considering replacement interval, potential benefits of recharging from shore power overnight or on layovers during the operating day.

6.2 New York City Ferries

6.2.1 Biodiesel

Assumptions

Assumptions for a NYCF biodiesel program are similar to those discussed in Section 6.1.1 for SIF. Based on the relatively young age of the NYCF fleet, it is not expected that fuel tank cleaning would be required as it would be for SIF. However, capital expenditures would be required to increase the size of fuel filters to improve water removal capability. This would apply to the ships as well as the shoreside fueling system at the NYCF homeport.

The Baudoin engines used on the NYCF are specifically limited to B10 in their engine documentation, so this value was used in the analysis. The impact on emissions rates is therefore half of that shown in the SIF analysis, which assumes B20. Since B10 is a less common product with lower demand and NYCF would be negotiating for fuel as a smaller customer, it is assumed that the $.05/gal price premium used for B20 would also apply to B10, even though there is less B100 mixed into the product.

Results

Under this option, the NYCF fleet would utilize approximately 66 million gallons of B10 over the next 20 years. The 20-year lifecycle performance of the NYCF fleet under these assumptions is given in Table 44.

Table 44 20-year performance of NYCF fleet utilizing B10 fuel

Metric	Units	Baseline	B-10	Change		Cost Benefit ($/Unit)
Capital Cost	$		$0			
Operating Cost	NPV $	$207,000,000	$211,000,000	+$4,000,000	+2%	-
Total Cost	NPV $	$207,000,000	$211,000,000	+$4,000,000	+2%	-
Fuel	gal	65,000,000	66,000,000	+1,000,000	+0.5%	-
CO_2	MT	660,000	620,000	-40,000	-6%	$25
NO_x	kg	5,000,000	5,000,000	-	-	-
HC	kg	100,000	100,000	-	-	-
PM	kg	110,000	104,000	-6,000	-5%	$167
CO	kg	770,000	710,000	-60,000	-8%	$17
SO_2	kg	6,100	5,500	-600	-10%	$1,667

Recommendation

The CO_2e for biodiesel usage at NYCF is even less than at SIF due to the engine manufacturer's restriction to B10. Nevertheless, B10 is still the most affordable alternative fuel in terms of cost/benefit for CO_2 reduction. However, given the operational risks and other factors discussed in Section 5.2, these benefits are considered marginal.

→ **A shift to biodiesel is not recommended.**

6.2.2 Renewable Diesel

There are no differences between renewable diesel assumptions for NYCF and SIF. As a practical matter, there could be difficulties in determining contractual terms for the use of more expensive fuel on NYCF due to the business relationship between the City, NYC EDC, and Hornblower.

Results

Table 45 summarizes the additional operating costs and reduction in emissions when using R50 with the NYC Ferries.

Table 45 20-year performance of NYCF fleet utilizing R50 fuel

Metric	Units	Baseline	R-50	Change		Cost Benefit ($/Unit)
Capital Cost	$		$0			
Operating Cost	NPV $	$207,000,000	$251,000,000	+$44,000,000	+21%	-
Total Cost	NPV $	$207,000,000	$251,000,000	+$44,000,000	+21%	-
Fuel	gal	65,000,000	65,000,000	-	-	-
CO_2	MT	660,000	440,000	-220,000	-33%	$200
NO_X	kg	5,000,000	4,900,000	-100,000	-2%	$440
HC	kg	104,000	90,000	-14,000	-13%	$3,143
PM	kg	110,000	96,000	-14,000	-13%	$3,143
CO	kg	770,000	650,000	-120,000	-16%	$367
SO_2	kg	6,000	3,000	-3,000	-50%	$14,667

Recommendation

Although expensive, renewable diesel offers a low risk means to achieve substantial CO_2 reduction. It can be utilized at higher blends than biodiesel and usage is limited only by available quantity and budget. Consideration should be given to full scale testing to confirm the changes in criteria emissions. Even if testing did not show significant local emission improvements, renewable diesel offers the largest readily achievable reduction in the SIF fleet global warming potential.

→ **Use of renewable diesel is strongly recommended.**

Varying quantities can be purchased as budgets dictate with negligible overhead costs required to periodically increase or decrease RD usage. The City should compare the cost of using renewable diesel on the ferries with other green initiatives and utilize as much renewable diesel as is financially feasible.

6.2.3 Low Friction Hull Coatings

Low friction hull coatings, as discussed in Section 5.9.1, are impractical for NYCF vessels, which already utilize advanced hull coatings and are already realizing the benefits in terms of reduced power demand and reduced fuel consumption. Consequently, this option was not investigated further.

6.2.4 EPA Tier 4 Upgrade

The NYCF Baudouin 6M26.3 propulsion engines for the 150 River class and the 12M26.3 propulsion engines for 350 Rockaway class are EPA Tier 3 certified.

Baudouin is in the process of securing EPA Tier 4 certification for their family of 6M and 12M marine rated engines. This extensive certification process is scheduled to be completed in 2019. Baudouin does have (an uncertified) Tier 4 engine operating on a route in the British Virgin Islands and will be installing Tier 4 engines on a vessel in San Francisco Bay area.

The Baudouin Tier 4 candidate engines use a selective catalytic reducer (SCR) to scrub the diesel engine exhaust gas of NOx. The SCR is similar in size to the muffler that is currently installed on the engines. In a retrofit, the muffler would be removed, and the SCR installed in its place. The sketch in Figure 39 shows the potential installation location of the SCR in a 150 River class vessel.

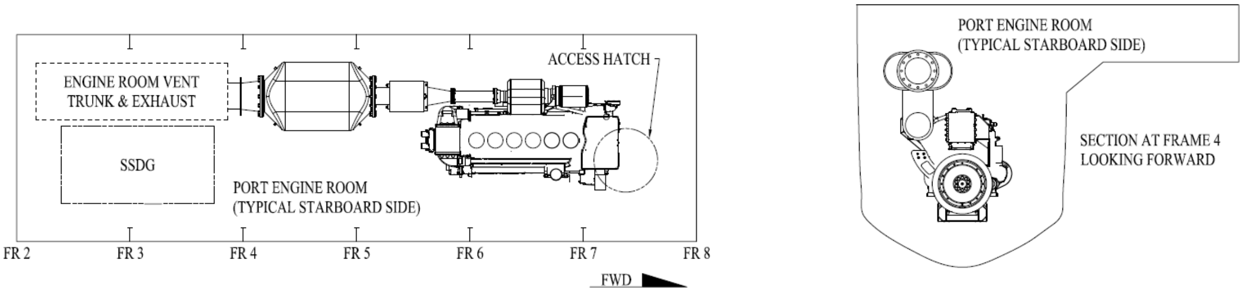


Figure 39 Potential installation location of SCR in a 150 River class vessel

In addition to the SCR, the system includes a urea storage and injection system to dose the exhaust gas. Urea is typically injected during all loads above 30%, and consumption can be assumed at 5-7% of the rate of diesel fuel consumption. The urea consumption varies based on the engine loading and would need to be further refined for the specific application. Addition of urea tanks would add weight to the vessel and may impact performance, an item requiring further investigation. Tanks would likely go inside the existing tank room, requiring temporary cutouts in the hull for installation.

There are two practical options for a Tier 4 upgrade for NYCF: upgrade the existing engines, or completely replace the engines.

Option 1: Existing Engine Upgrade

Upgrading the existing engines to Tier 4 is a complex process that includes replacing fuel injectors, pistons, and turbochargers and installing the urea system. Under this option, the engines can be upgraded to Tier 4 when a top end or major overhaul is required. Top end overhauls take place at 10,400 hours intervals and 12,000 hours intervals for the 6M and 12M respectively. Complete overhauls occur at 18,000-hour intervals, and 24,000 for the 6M and 12M respectively. The engine manufacturer stated they recommend replacing the engines after three complete overhauls. This would be at approximately 75,000 hours for the 6M and 96,000 hours for the 12M engines, at which stage engine replacement (Option 2 below) becomes the more practical option for upgrading to Tier 4.

Option 2: Engine Replacement

The second option for Tier 4 upgrades is wholesale replacement of the engine. The Baudouin representative said based on historical data, the small engines operate roughly 5,000 hours annually, and the 12M engines roughly 10,000 hours annually. Given the estimated operating hours of the engines, this replacement opportunity would occur at approximately 15 years for the 6M engines and 10 years for the 12M engines.

The SCR catalyst must be changed out every 12,000 hours for either model of engine. This is a conservative estimate, and the engine manufacturer expects this interval to increase to 20,000 hours once they have more installations and data to evaluate.

As discussed in Section 2.3.1, engines under 599 kW do not currently require Tier 4 certification. Upgrading the 6M engines would be voluntary. Conversely, a repower of the 12M engines could trigger a Tier 4 upgrade. Newbuild vessels are now required to have EPA Tier 4 engines installed if the installed power is greater than 599 kW.

Assumptions

In the lifecycle analysis, it is it assumed Tier 4 upgrades occur at the engine replacement intervals for each vessel. These estimates are reported in Appendix B.

The following metrics were provided by the engine manufacturer and are used to estimate the cost of the engine replacements. These values serve as ROM costs and will need to be refined if these projects move forward. All values are reported in 2019 dollars.

Table 46 Tier 4 engine upgrade costs

	6M Engine	12M Engine
Cost of new Tier 3 engine	$100,000	$192,000
Cost of new Tier 4 engine	$155,000	$270,000
Tier 4 upgrade during top end or full overhaul	$250,000	$800,000
Top end overhaul	35% of new engine cost	35% of new engine cost
Complete overhaul	60% of new engine cost	60% of new engine cost
Catalyst Changeout	$22,000	$44,000

The 12M engine requires two reactors, while the 6M only requires one per engine. This explains the increase in catalyst cost for the 12M engine.

Results

Table 47 summarizes the benefits of upgrading to Tier 4. Tier 4 engines are more fuel efficient then their Tier 3 counterparts, which is reflected in the table. However, the fuel cost savings is often offset by the cost of urea, which is estimated at $3.00/gal. The cost of urea is included in the fuel cost. It was estimated the urea consumption is 3% of the fuel consumption.

Table 47 20-year performance of NYCF fleet with EPA Tier 4 Upgrade

Metric	Units	Baseline	Emission Control Upgrades	Change		Cost Benefit ($/Unit)
Capital Cost	$		$3,800,000			
Operating Cost	NPV $	$207,000,000	$202,000,000	-$5,000,000	-2%	-
Total Cost	NPV $	$207,000,000	$206,000,000	-$1,000,000	-0%	-
Fuel	gal	65,000,000	60,000,000	-5,000,000	-8%	-
CO_2	MT	660,000	610,000	-50,000	-8%	-
NO_x	kg	5,000,000	1,000,000	-4,000,000	-80%	-
HC	kg	100,000	100,000	-	-	-
PM	kg	110,000	28,000	-82,000	-75%	-
CO	kg	770,000	770,000	-	-	-
SO_2	kg	6,100	5,700	-400	-7%	-

Recommendation

→ Upgrade all EPA Tier 3 engines to EPA Tier 4 during future repower projects.

Tier 4 upgrading is the most cost-effective way to reduce criteria emissions and provides a modest reduction in CO_2 from increased fuel efficiency. These modifications can also be accomplished during engine overhauls, at a higher cost. Depending the City's priorities, this timeline may be preferable. This recommendation applies to both the 6M and 12M engines.

6.2.5 All-Electric

A hypothetical electric NYCF fleet was analyzed to show the maximum reasonable benefit that could be achieved through electrification. This all-electric option has the greatest potential for emissions reduction but comes with many challenges. Some critical technology is not yet mature, and the Rockaway route may never be feasible with electric ferries due to the high energy demand and long distances between piers. Demanding schedules, short dwell times, exposed piers, and limited crew add to the difficulty. Significant shoreside and pier infrastructure upgrades are needed, requiring careful coordination with the City and utility district.

Table 48 demonstrates the low power density of batteries relative to diesel fuel. Battery requirements significantly exceed the allowable additional weight margin the vessels can accommodate if once per day charging is required. In order to maintain current operations, commercial battery power density will need to increase by 30 to 50 times over what is currently available. This necessitates frequent charging of the vessels along each route and the installation of several charging stations, as described in Section 7.2.

Several manufacturers are developing shoreside charging facilities, but no off-the-shelf configurations have been developed for this application. This technology is rapidly developing, however, and a future fleet scenario was analyzed to determine the potential benefits.

Table 48 All-electric battery sizing for NYCF assuming daily charging, similar to existing operation

Route	Energy [kWhr/day]	Battery Capacity [kWhr]	Weight[1] [tons]	% Exceeding Allowable Weight	Specific Battery Weight Required[2] (MJ/kg)
East River	6,030	24,130	240	3,117%	12
Rockaway	11,130	44,515	440	4,702%	22
South Brooklyn	5,895	23,580	235	3,044%	11
Astoria	5,695	22,775	225	2,937%	11
Soundview	7,675	30,690	305	3,992%	15
Lower East Side	6,715	26,855	265	3,480%	13

[1] Assuming 0.4 MJ/kg; [2] Required to satisfy allowable weight (i.e. 0% exceedance)

Assumptions

The lifecycle analysis assumes a fully electric fleet makeup beginning in year 2020. This timeline is intended to show the maximum possible benefit of the option compared to alternatives. In reality, electric conversion of the fleet will take significant planning, engineering, and technological development before implementation is possible.

Metrics from several electric feasibility studies were compiled and used in preliminary sizing calculations. After evaluating several battery manufacturers, the following values were used for this analysis:

- Depth of Discharge margin: 4.0
- Specific Volume: 200 MJ/m^3
- Specific Weight: 0.4 MJ/kg

The specific weight of the propulsion batteries is critical, as the aluminum catamarans are weight sensitive. Adding weight beyond the vessel’s design limits will significantly increase the energy required for the vessel to maintain speed and therefore maintain schedule. The depth of discharge margin of 4.0 implies the batteries cycle within 25% of their rated power. Current battery densities therefore require charging at several stops along the electrified routes. The following assumptions were used in the lifecycle analysis:

- Average charging duration: 15min (current dwell times average 4min)
- River class charging power per vessel: 1.2MW
- Rockaway class charging power per vessel: 2.0MW

Results

The analysis of electrified routes considered charging several times along the route, with charging stations installed at various (but not all) stops along a route, a configuration analogous to an electric rapid-charging bus station. This option would require high capital cost to install several shoreside charging facilities, each of which would need to be able to provide enough energy for the next leg segment within a very short time period. Several manufacturers are developing shoreside charging facilities, but no off-the-shelf configurations have been developed for this type of rapid charging with quick attach and detach periods. However, this technology is under development, and a future fleet scenario was developed to determine if potential capital and operational lifecycle cost savings exist.

The results of the lifecycle analysis are shown in the following Table 49. These estimates show a substantial decrease in emissions and a modest decrease in NPV. These estimates are further detailed in Appendix B.

Table 49 20-year performance of NYCF fleet with an electric upgrade

Metric	Units	Baseline	All-Electric	Change		Cost Benefit ($/Unit)
Capital Cost	$		$43,100,000			
Operating Cost	NPV $	$207,000,000	$129,000,000	-$78,000,000	-38%	-
Total Cost	NPV $	$207,000,000	$172,000,000	-$35,000,000	-17%	-
Fuel (Diesel)	gal	65,000,000	-	-$65,000,000	-100%	-
Fuel (Energy)	GJ	-	910,110,000	-	-	-
CO$_2$	MT	660,000	180,000	-480,000	-73%	-
NO$_x$	kg	5,000,000	200,000	-4,800,000	-96%	-
HC	kg	100,000	10,000	-90,000	-90%	-
PM	kg	110,000	10,000	-100,000	-91%	-
CO	kg	770,000	130,000	-640,000	-83%	-
SO$_2$	kg	6,100	107,400	+101,300	+1661%	-

***The theoretical SO$_2$ emissions rate is dramatically influenced by the few remaining coal plants in New York. The remaining coal plants are likely to be decommissioned by 2021, reducing SO2 emissions to approximately zero.*

Recommendation

→ **Further investigation of plug-in electric operation is recommended.**

The current state of technology makes a plug-in electric fleet technically infeasible for NYCF's fleet, schedule, or mooring conditions, and is therefore not recommended for short-term retrofits of the vessels. However, this technology is rapidly developing and provides the best way to meet the City's 80x50 goal. Electrification of the fleet should be studied in detail for future consideration.

6.2.6 Hybrid

As discussed in Section 5.6.3, diesel hybrid configurations are generally described as *series* or *parallel*. Hybrid propulsion plants can sometimes increase efficiency by allowing the diesel engines to operate at their most efficient load. Since electrical losses will always occur, the increase in efficiency from the optimized diesel operations must be greater than the net electrical losses. Another factor that must be considered is the increase in weight and cost that hybrids can incur. For the right kind of operation, and the right kind of vessel, hybrid propulsion can be an effective means of reducing fuel consumption.

A parallel hybrid design includes a generator, power-take-off/power-take-in reduction gear, electrical switchgear, and a battery bank. Space and weight limitations prohibit installing this amount of equipment on both the 150 River class and 350 Rockaway class, so this option has not been evaluated further in the lifecycle analysis.

A series hybrid propulsion configuration was also considered for the NYCF. While technically feasible, it was determined that this configuration would not provide fuel or emissions savings, so it was not brought forward to the lifecycle assessment.

Assumptions

The battery sizing metric assumptions from Section 6.2.5 are also used in this section:

- Depth of Discharge margin: 4.0
- Specific Volume: 200 MJ/m^3
- Specific Weight: 0.4 MJ/kg

The preliminary electrical system efficiency is assumed to be 90%. This value must be refined with equipment selection but serves as a realistic estimate for the overall system efficiency.

The hybrid calculations were performed for round trip energy use. Layover and deadheading periods use the following assumptions:

- Layover is not included in time spent charging batteries for hybrid propulsion arrangements, as this contingency time may not be consistent, and should not be relied upon to size propulsion batteries.
- Deadheading, being a high operating point for a long period of time, skews the feasibility of a hybrid solution drastically. This can be mitigated by deadheading at a slower speed, for longer time period. Using this methodology, it is assumed in the hybrid calculations that this period of deadheading is completed under the power of the generator.

The hybrid calculations assume that when the vessel is loading and unloading passengers (pushing the dock) the batteries will be charging from the generators. While the vessel is in transit, the batteries will provide peak shaving, reducing the overall size of the generators required and allowing the generators to operate at their most efficient load.

Results

Two Caterpillar generator sizes are used in the preliminary calculations, the C7.1, rated for 218.6 bkW and the C9.3, rated for 275 bkW. Each engine burns 216 and 215 g/kWhr, which is greater than both the 6M and 12M engines.

Considering the operational profile and energy demands, electrical losses through a hybrid system, engine sizing and brake specific fuel consumption, there is no gain in fuel efficiency or emissions reduction. The added cost and complexity of the hybrid system can only be justified if the fuel savings and emissions savings are significant. This is not the case with the NYCF vessels. Calculations to support these conclusions are available in Appendix B.

Recommendations

→ Neither a parallel hybrid nor series hybrid system is recommended for NYCF.

A diesel hybrid configuration will increase the fleet’s fuel consumption and emissions and is not recommended for this application. This option has not been evaluated further in the lifecycle analysis.

6.2.7 Plug-in Hybrid

A plug-in hybrid propulsion configuration was considered for the NYCF. While technically feasible, it was determined this configuration will not provide fuel or emissions savings for the fleet and was not brought forward to the lifecycle assessment.

The goal of this option is to reduce the size of the diesel mechanical propulsion equipment and improve fuel consumption by providing energy from shoreside facilities. This outcome was not possible given NYCF vessel sizes and operational profiles.

Assumptions

Two complementary approaches were taken to evaluate plug-in hybrid feasibility for the NYCF fleet. First, the total battery weight that could be fit within the available volume on board the 150 and 350 class vessels was calculated. Second, an amount of added weight the vessels could reasonably accommodate was assumed, and the amount of battery power that could be generated within that given weight limit was calculated.

In both cases, it was assumed the batteries would be housed in the Forward Void, below the Main Deck. For the 350 Rockaway vessels, the empty volume forward of the tanks was also used. In both cases, it was assumed the batteries fill 50% of the void space.

The battery metrics for all-electric and series hybrid outlined in Sections 6.2.5 and 6.2.6 were used to approximate battery size, weight and depth of discharge.

Results

Table 50 shows the values calculated using vessel volume as a constraint for battery size. Approximately 360 kWhrs and 555 kWhrs of batteries could physically within the volume available on the 150 and 350 class vessels, respectively, resulting in 14 tons of added weight on the 150 class vessels 22 tons of added weight on the 350 class. The weight of the additional electrical equipment (PTO/PTI, switchboard, cabling, etc.) was not considered. This battery weight alone is approximately 20% of total vessel weight for either class; such a large weight increase would greatly increase vessel resistance and is not feasible.

Table 50 Volume constrained plug-in hybrid option

Class	Installed Capacity [kWhr]	Useful Battery Energy [kWhr]	Weight [tons]	Volume [ft^3]	Volume Limit [ft^3]	Daily Fuel Offset [gal]
River 150	1,444	360	14.5	920	930	9.5
Rockaway 150	1,444	360	14.5	920	930	9.5
Rockaway 350	2,222	555	22	1,450	1,415	15

The second method is weight constrained to investigate how much battery capacity could be added while staying within a reasonable weight limit. It was assumed that a 10% weight increase above the maximum deadweight is reasonable. As Table 51 shows, the 150 and 350 class vessels could take on approximately 150 kWhrs and 200 kWhrs of useful battery capacity, respectively. These values would be reduced once the weight of the additional electrical equipment was considered. On the average route, this amount of energy could provide propulsion power for approximately 2-3 legs of a vessel's route. The daily fuel offset represents the equivalent amount of diesel the batteries would be replacing.

Table 51 Weight constrained plug-in hybrid option

	Installed Capacity [kWhr]	Useful Battery Energy [kWhr]	Weight [tons]	Volume [ft^3]	Weight Limit [tons]	Daily Fuel Offset [gal]
River 150	600	170	6.5	425	7.5	4.5
Rockaway 150	670	185	7.4	475	7.5	5.0
Rockaway 350	825	230	9	580	90	6.1

In addition to the sizing calculations performed above, a plug-in series system would suffer from the same inefficiencies as the series hybrid described in Section 6.2.6. The main difference between the two is that the first discharge of the batteries is powered by shoreside energy rather than a charge from the generator. Table 50 and Table 51 indicate how minor this fuel savings would be.

Recommendations

The NYCF vessels cannot carry enough battery energy to positively impact their fuel consumption and emissions if a diesel plant is retained on board. This option has not been evaluated further in the lifecycle analysis.

→ Plug-in hybrid operation is not recommended.

6.2.8 Fuel Cells

Fuel cells are an attractive option for NYCF due to their ability to eliminate local emissions on the ferries. Given the immaturity of the technology, this option was evaluated for feasibility only at a preliminary level. Retrofitting the existing vessels to replace the diesel engines with fuel cells would be very challenging, and details of these challenges are discussed in Section 5.8. As such, it is preferable to design and build purpose-built fuel cell vessels, as is the case with the Incat-Crowther *Water-Go-Round* newbuild vessel.

Assumptions

Metrics from the *Zero-V* and *SF-Breeze* (References 61 and 73) studies were used to determine the approximate fuel cell capacity, weight, and size for vessels of the 150 and 350 class type. Both these concept studies use liquid hydrogen and Hydrogenics PEM fuel cells, so these propulsion options are used in this analysis. The following metrics were used in this approximation:

Properties of Hydrogen

- LHV of Hydrogen: 119.96 MJ/kg H_2
- Density of Hydrogen: 701.8 kg/m^3

Properties of Fuel Cells – Hydrogenics HD30, 120kW rack

- Average Fuel Cell Efficiency: 45%
- Gravimetric Power Density: 0.15 kW/kg
- Volumetric Power Density: 73.97 kW/m^3

Properties of Auxiliary Equipment

- Gardner Cryogenics Empty Tank Mass: 8.7 kg/kg LH_2
- Outer Tank Volume: 24.8 L/kg LH_2
- Approximate Thermax Vaporizer Weight: 2000 lbs

Retrofitting the existing NYCF vessels for fuel cell propulsion would be very complex and is not recommended. A retrofit would require removing the main engines, diesel fuel tanks, and supporting auxiliary equipment. A preliminary weight estimate for these propulsion components is given below for each the 150 and 350 class vessel types. The auxiliary equipment includes items such fuel pumps, lube oil pumps, and piping.

Table 52 NYCF propulsion weight estimate

Item	150 River Class (weight, tons)	350 Rockaway (weight, tons)
Engines	3.94	7.09
Fuel	5.20	6.93
Auxiliary Equipment (7% of Engine weight)	0.275	0.496
Subtotal	9.41	14.51
Margin (10%)	0.94	1.45
Total	**10.35**	**15.96**

This preliminary weight estimate shows there are approximately 10.3 tons on the 150 River class Vessels and 16 tons on the 350 Rockaway vessels that can be removed and replaced with fuel cell equipment and hydrogen storage.

Results

Preliminary calculations revealed that a fuel cell configuration may be possible for the NYCF fleet. This conclusion was developed by considering the shortest and longest routes for the smaller vessels, using the current schedule on the Lower East Side and Soundview routes. The installed power for each class of vessel remains identical to their current configuration.

The fuel cell weight and volume, and vaporizer weight are consistent for each vessel configuration.

Table 53 Lower East Side fuel cell propulsion approximate weight estimate

Item	One Round Trip	Two Round Trips	Three Round Trips
Fuel Cell Volume (ft^3)	572	572	572
Tank Volume (gal)	226	452	572
Fuel Cell Weight (tons)	8.8	8.8	8.8
Vaporizer Weight (tons)	2	2	2
Tank Weight (tons)	0.33	0.66	0.99
Fuel Weight (tons)	0.04	0.08	0.11
Design Margin (10%)	1.12	1.15	1.19
Total (tons)	**12.29**	**12.69**	**13.10**

Table 54 Soundview fuel cell propulsion approximate weight estimate

Item	One Round Trip	Two Round Trips	Three Round Trips
Fuel Cell Volume (ft^3)	572	572	572
Tank Volume (gal)	458	916	1374
Fuel Cell Weight (tons)	8.8	8.8	8.8
Vaporizer Weight (tons)	2	2	2
Tank Weight (tons)	0.67	1.34	2.01
Fuel Weight (tons)	0.08	0.15	0.23
Design Margin (10%)	1.15	1.23	1.30
Total (tons)	**12.70**	**13.53**	**14.35**

Table 55 Rockaway fuel cell propulsion approximate weight estimate

Item	One Round Trip	Two Round Trips	Three Round Trips
Fuel Cell Volume (ft^3)	982	982	982
Tank Volume (gal)	825	1649	2474
Fuel Cell Weight (tons)	15.12	15.12	15.12
Vaporizer Weight (tons)	2	2	2
Tank Weight (tons)	1.21	2.41	3.62
Fuel Weight (tons)	0.14	0.28	0.42
Design Margin (10%)	1.85	1.98	2.12
Total (tons)	**20.32**	**21.80**	**23.28**

In all three cases, the calculations show the dominating criteria is the weight of the fuel cell system installation, rather than the size/weight of the LH_2 fuel and tank. The one and two round trip cases appear to be feasible from a vessel weight/displacement perspective. Nevertheless, locating the LH_2 tank(s) for the vessel is challenging, and its difficulty should not be underestimated.

This analysis is limited in that vessel stability and the arrangement of the propulsion equipment, fuel storage, and bunkering system have not been analyzed in detail. These aspects are significant and should be evaluated in a more in-depth study prior to considering implementation. As fuel cell vessels are still in their prototyping phase, this was not included in the scope of this report.

Recommendations

→ **Due to regulatory hurdles, low fuel availability, and technical feasibility, a fuel cell propulsion retrofit is not recommended for NYCF at this time.**

As fuel cell technology develops, the hydrogen supply chain becomes greener, and more prototype vessels are built, this technology may become increasingly promising for the marine industry. Currently, although the elimination of local emissions is attractive, the global emissions produced during hydrogen production (discussed in Section 5.8.4) make this option difficult to recommend on an emissions reduction basis. It is also too new and untested in marine applications to serve as a feasible retrofit option for current vessels, even aside from the costs and technical complexity of such an endeavor.

However, this technology should be monitored going forward for promising marine developments. Purpose-built fuel cell vessels may be technologically feasible for NYCF, with modifications to vessel arrangements and schedule. Should fuel cells develop into an attractive future fleet option, an in-depth feasibility study must be conducted to optimize vessel design and operations.

6.2.9 Natural Gas

Section 5.4.2.2 reviewed the gas engines currently available. While there are no options currently suitable for retrofit into the NYCF fleet, new offerings in the future might be acceptable. A future iteration of the NYCF fleet could also be purpose-designed with available gas engines. Some basic estimates are provided below to examine the feasibility and benefit of natural gas propulsion for NYCF.

Fuel Storage

Both LNG and CNG could potentially provide adequate fuel storage for the NYCF fleet. The MTU Series 4000 M05-N is similar in power to the existing Baudouin 12M engines on the Rockaway and 350 class ferries. Unlike the EMD DIG engines discussed in Section 5.4.2.3, this engine does not require a high-pressure fuel supply and would not need large onboard gas compressors to utilize CNG.

Rough estimates of the required gas storage volume were made using the relative energy content of diesel, CNG, and LNG. A single NYCF ferry operating on one of the East River routes typically consumes approximately 500 gallons of diesel fuel per day. Approximately 1400 kg of natural gas contains the same energy as 500 gallons of diesel. The required tank size was estimated by including a 15% margin and, for LNG, accounting for maximum and minimum fill levels (Section 5.4.3.3). Results are given in Table 56. Fuel tank length assumes tanks with a 1.5-meter diameter (the same as the existing diesel tanks).

Table 56 Estimated natural gas fuel tank sizes for NYCF – two tanks per ship

	CNG @200 bar	**LNG @163°C**	**Remarks**
Energy Required (MJ/day)	68,000	68,000	Based on 500 gal diesel, LHV 136 MJ/gal
LHV (MJ/kg)	47	49	Liquefaction removes inert gasses
Weight (kg)	1445	1372	
Density (kg/m^3)	180	468	
Total Tank Volume (m^3)	9.2	4.2	Both tanks, including 15% margin and limits
Each Tank Length (m)	3.3	1.8	Cylindrical tanks/hemisphere ends, d=1.45m

Fitting these tanks belowdecks in the existing NYCF designs is not feasible. On the larger Rockaway class ferries, the current diesel tanks are approximately 2m long, but the lengths estimated above do not account for tank insulation, structure, or gas handling equipment that is normally collocated with the tank. Alternatively, fuel tanks could be arranged near the pilothouse topside. Placing 0.85m diameter tanks would be reasonable. This would require 4m long tanks for LNG or 8.4m long tanks for CNG. A sketch is shown in Figure 40 to illustrate the scale of the required tank sizes. Actual arrangements would require further review of ship stability, auxiliary equipment space requirements, and hazardous zone regulations and would likely require elimination of some or all of the topside seating.

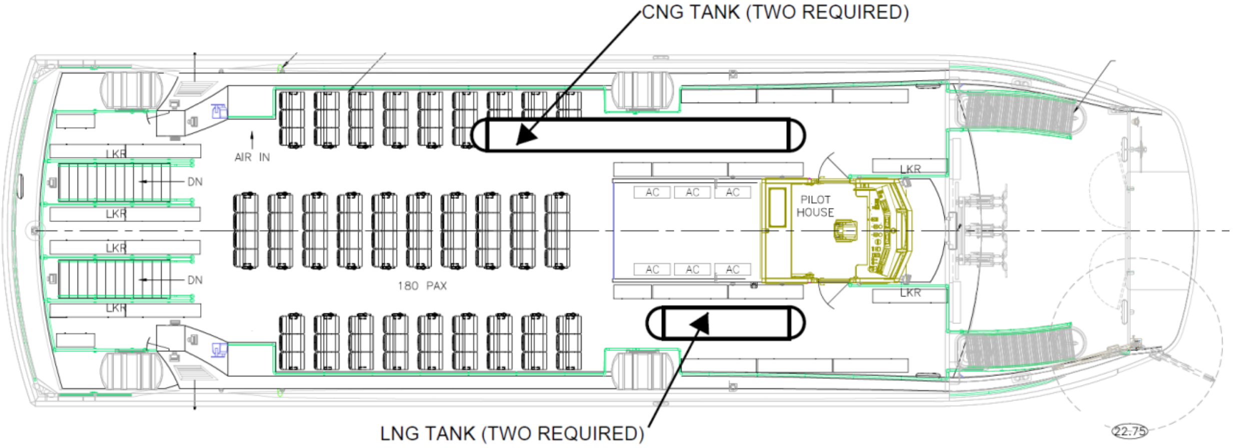


Figure 40 Sketch of required sizes for topside natural gas tanks on NYCF

Bunkering

Assuming no change in the NYC fire code, the only practical option to bunker the NYCF system using LNG is with a purpose-built barge that could be refilled from a small LNG supply ship. The logistics of transporting LNG up the east river to the Brooklyn Navy Yard would require careful consideration of regulations, safety, and public opinion. Alternatively, natural gas compressors and storage could be installed on shore if a CNG-fueled ferry was developed. Shoreside compression and storage capability as was discussed for SIF in Section 5.4.5.2, NYCF would require a similarly sized system, approximately $1 million for compressors alone, plus storage and distribution systems. Finally, the logistics of rapidly bunkering the fleet would be a challenge. Current practice is for all ferries to take fuel each night at the end of second shift. Approximately 10,000 gallons of fuel are distributed to 20 ferries in a few hours. Replicating this for gas fuel would be challenging, especially for LNG (see further discussion of LNG bunkering complexity in Section 5.4.3.3). The impact of hazardous zones during the bunkering evolutions would also need to be examined. Some CNG road vehicle fleets use automated systems that slowly fuel multiple vehicles simultaneously. Vehicles are connected to the system in the evening and fueling continues through the night. If found to be acceptable from a safety and regulatory perspective, these systems might be adaptable to NYCF.

Engineering Complexity

The current crewing concept for the NYCF might present some challenges for a natural gas-powered ferry. Gas propulsion plants, particularly LNG plants, are more complex than the existing diesel plants. The design of the engines, fuel systems, and other miscellaneous equipment could necessitate an additional watchstander to monitor and control the engineering plant. Reference 95 provides guidance on minimum manning requirements but does not specifically address this situation. Instead, final approval of the manning plan rests with the local Officer in Charge, Marine Inspection (OCMI). Even though a reduced manning concept might receive "conceptual approval" during the design development, the OCMI could determine that an additional watchstander is required.

Results

The gas engines currently available are not suitable for retrofit into the existing NYCF hulls. Future NYCF ships could be designed for gas fuel, but several regulatory factors would need to be resolved. These values use a gas conversion of 130 MJ of gas for each gallon of diesel. This value is higher than the Staten Island Ferries estimates because the smaller gas engines are less efficient. This value was estimated using the Mitsubishi all-gas engine, which is market ready but not suitable for installation onboard the NYCF vessels.

Table 57 20-year performance of NYCF fleet with gas engines upgrade

Option	Diesel Reduction	Gas Usage	Change in Cost	Change in CO_2e
All Gas	-65M gal	8.5M GJ	-\$78M[1]	-60,000 MT (-9%)

[1] Change in operating cost only. Capital cost not included.

Recommendation

Significant cost and emissions savings can be achieved with a natural gas conversion. However, the small size of the ferries results in a complex conversion, and there are currently no suitable engines for NYCF.

→ **Converting the NYCF fleet to natural gas is not recommended at this time.**

Section 7 Future Fleet Blueprint

Using the analysis performed in Section 6, a blueprint for the future of both ferry fleets is described here. If the City desires to fundamentally change the future greenhouse gas emissions of its ferry fleets, a bold approach is required. Even combining the best elements of the various options presented above, a combustion-based ferry system cannot achieve the 80x50 goal.

Criteria emissions will naturally improve as older ferries are replaced with new vessels designed to meet strict Tier 4 emissions standards, and the best non-electric option, renewable diesel, offers a one-third reduction in GHG emissions. While impressive for an option that can be implemented immediately, renewable diesel falls well short of the 80% goal.

What does it take to get to 80% reduction?

Grid electrical power in New York state is already 50% carbon free from hydroelectric, wind, and nuclear sources. The remaining 50% comes primarily from natural gas, and combustion at the utility scale is significantly more efficient than in a marine diesel engine. For the same carbon emissions, a shoreside natural gas power plant can produce over 1.75 times more energy (Reference 96) than a marine diesel engine. The combination of these effects results in an average CO_2 production rate of 200 g/kwh for the utility while the SIF fleet averages 730 g/kwh – over 3.5 times greater.

Shifting ferry power to the electric grid would reduce greenhouse gas emissions by 70%.

A Molinari class ferry emits over one metric ton of CO_2 during a one-way trip from Staten Island to Manhattan. Using utility power, emissions from the same Molinari class one-way trip would be reduced to roughly 300 kg (0.3 MT). A River class NYCF ferry produces a half metric ton of CO_2 during a weekend round trip and a similar 70% reduction would be achieved by electrifying.

While both examples fall slightly short of the 80% OneNYC target, it seems all but certain that the utility will improve enough in the near future to meet the goal. In fact, the RGGI guarantees ongoing reductions in the carbon intensity of regional power.

From the ferries' perspective, a conversion to plug-in power should be considered an investment in continuous future emissions improvements. Future innovations in green energy will naturally focus on land-based electrical power generation, as the larger market size promises investors greater payoffs than the marine sector can offer. Furthermore, engineering and regulatory challenges in the marine sector will slow technology advancement in favor of land-based improvements. As shown in Section 6, a conventional ferry can make only incremental improvements to its emissions profile without large capital expenditures. A plug-in ferry can leverage incremental improvements in the land-side power sector and maintain cutting edge emissions performance throughout its lifetime.

7.1 Staten Island Ferries

7.1.1 What does a future electric SIF fleet look like?

An electric ferry fleet would be based on the plug-in hybrid and plug-in electric technologies described in Section 5.6. Implementation of these technologies for the Molinari, Ollis, and future midsize ferries was discussed in Section 6.1.7.

The likely propulsion arrangement of future electric ferries would be a plug-in hybrid diesel-electric plant. Electric propulsion motors would receive power from an integrated ship's electrical bus. This integrated bus would be capable of receiving power from an onboard battery bank, high-capacity shore power connection, or onboard diesel generators.

Normal operations for this type of propulsion system would involve charging the battery bank from shore power each time the ferry pulls into the slip. This frequent charging would be necessary to get all power from shore and operate the ferries with the diesel engines secured, maximizing the environmental benefit and minimizing diesel engine maintenance costs. A notional operations schedule given this charging frequency is shown in Table 58.

Table 58 Notional electric ferry schedule during peak periods

Ferry	Whitehall				St. George			
	Arrive	Commence Charging	Commence Disconnect	Depart	Arrive	Commence Charging	Commence Disconnect	Depart
1	7:52	7:53	7:59	8:00	8:22	8:23	8:29	8:30
	8:52	8:53	8:59	9:00	9:22	9:23	9:29	9:30
2	8:07	8:08	8:14	8:15	8:37	8:38	8:44	8:45
	9:07	9:08	9:14	9:15	9:37	9:38	9:44	9:45
3	8:22	8:23	8:29	8:30	8:52	8:53	8:59	9:00
	9:22	9:23	9:29	9:30	9:52	9:53	9:59	10:00
4	8:37	8:38	8:44	8:45	9:07	9:08	9:14	9:15
	9:37	9:38	9:44	9:45	10:07	10:08	10:14	10:15

A key decision will be how much diesel backup power to retain. One approach would be to design a fully capable diesel-electric ferry that also has a full-size battery bank and charging capability. Although the most flexible, it would also be the most expensive. In general, diesel use would be limited to abnormal situations such as power outages. On the other hand, having the onboard diesel generators normally provide some power would afford significant design flexibility. The amount of power provided by the onboard generators would be traded against the capacity of the shore power connection, size of the battery bank, electrical demand fees, and other related factors. Significant lifecycle cost savings might be obtained through some compromise with emissions.

One reasonable design point could be to equip these electric ferries with onboard power generation capability equal to approximately half of the design speed brake power requirement. Assuming a design speed of 16 knots and a typical cubic relationship between speed and power, this would allow backup operation on the onboard generators at approximately 12.5 knots.

Another possible design is the Ollis class plug-in conversion discussed in Section 6.1.7. This design replaces all four diesel engines with electric motors. In the event of an absence of grid power, there would be no remaining backup propulsion power. Fully operational shoreside infrastructure would be required before putting such a ferry in to service, and large shore-based backup generators would be required to maintain ferry operations during a utility outage.

Nearly as important as the ferries themselves, an electric future fleet would depend on sophisticated shoreside infrastructure. The ferry slips would be upgraded with high-capacity automated shore power connections such as those discussed in Section 5.6.4.3. Various cost and design factors could prompt the use of shoreside battery banks. These connections would be needed on at least two slips each at St. George and Whitehall terminals. Electrifying a third slip at each side may be necessary depending on layover schedules and periodic terminal maintenance.

7.1.2 What action is needed to enable this future?

→ Initiate a Preliminary Design Investigation (PDI) into shoreside electrical infrastructure

The cost and capability of the shoreside infrastructure is a crucial element of this blueprint. High electrical demand charges are a major driver for the high electrical energy costs discussed in Section 6.1.7. Exploration of the shoreside infrastructure must include the utilities as key stakeholders – any options that affect demand charges will have major impacts to the lifecycle cost of a plug-in ferry system. One option to reduce lifecycle costs might be to incorporate shoreside batteries to facilitate lower demand from the grid. In this scenario, the shore terminal would place a lower constant power demand on the grid. When a ferry isn’t charging, the power would be used to charge batteries. The shore batteries would be discharged through the automated shore power connection during ferry charging to achieve high power levels without a corresponding increase in the electrical demand cost.

Backup power options should also be explored during the PDI. Large shore generators could be used to maintain the reliability of the ferry system in a loss of utility power, eliminating or reducing the size of backup generators onboard the ferries.

Finally, pier arrangement details must be closely investigated. This includes factors such as the physical space required for the components just discussed, the suitability of the existing pier structures to mount automated shore power equipment, the feasibility of integrating automated mooring equipment, impact of tides and currents, and evaluation of operational scenarios including pier maintenance and overlapping ferry departures and arrivals.

→ Design a Molinari class Hybrid Conversion

The PDI recommended above will need an electric ferry design to derive information needed to assess the shore infrastructure. As existing diesel-electric ferries in the SIF fleet, the Molinari class provides the best starting point for these assumptions. The Ollis class would require a more significant conversion to be plug-in capable, and the midsized Austen replacement class will require less space and power and are therefore a less limiting case for the shore infrastructure. This Molinari class hybrid design also has the advantage of being executable in the near term.

The Molinari class ferries will be due for a midlife overhaul in approximately 2024. This overhaul could be used to convert at least one of these ferries to plug-in hybrids.

This conversion and subsequent operation and maintenance of hybrid Molinari class ferries would provide SIF with invaluable experience on the advantages and disadvantages of certain aspects of plug-in hybrid systems, as well as building partnerships with key equipment vendors. The Molinari hybrids could retain full-speed propulsion capability using installed diesel engines. This would allow the hybrid conversion to occur in parallel with the shore infrastructure PDI and independently of budget and schedule concerns for constructing shoreside infrastructure, eventually transitioning to hybrid operation when shore equipment is ready. These conversions would be a costly undertaking on a ferry already at midlife. The decision to execute a conversion should be evaluated in the future using more detailed feasibility information from the PDI and the hybrid conversion design, considering both the cost and how the conversion timing impacts the ability to gain valuable operating experience early enough to inform future electric ship designs.

As with any new technology, SIF should expect to encounter new challenges and difficulties in implementing battery and plug-in systems. Setting out to identify and solve these challenges on the Molinari class might provide a beneficial look into the future by allowing the City to build a more optimal electric ferry that builds on the experience gained from a plug-in hybrid Molinari class.

7.1.3 How do the existing ferries fit with this future?

The Barberi class has insufficient service life remaining to reasonably consider a hybrid conversion, particularly since the existing plant is diesel mechanical. Similarly, it is unlikely that converting the Austen class is worthwhile, although their smaller size could potentially prove beneficial for trialing a technology at lower capital cost.

As discussed above, the Molinari class could be converted to plug-in series hybrids to gain experience to inform later vessel designs. Even if the shore infrastructure is delayed and the plug-in option is not used right away, the onboard plant could be operated as a diesel electric hybrid to gain experience in energy management and the use and maintenance of shipboard batteries.

A major conversion would be required to electrify the Ollis class ferries. This could be the fully electric conversion discussed in Section 6.1.7 or a parallel hybrid design that replaces only some of the engines. Although both options are feasible from a high level, a conversion from diesel-mechanical to plug-in electric would be more complex and costly than converting the diesel-electric Molinari class.

The future midsize ferries would be designed at least as plug-in ready; utilization after construction would depend on the development of shore infrastructure.

7.1.4 Is this future fleet compatible with other alternative fuels?

Depending on the design of the ships and shoreside infrastructure, a future plug-in ferry might still need to produce some energy using onboard fuels. Where diesel engines are installed, renewable diesel would be just as viable as for the current ferries. Use of renewable diesel would be complementary to the low-carbon utility power.

In addition to the challenges discussed in Section 5.2, biodiesel has poorer long-term storage stability than other fuels (Reference 44). While this would not be a concern if the fleet was continuously turning over fuel as it does now, biodiesel carried as a backup fuel on a plug-in ferry would potentially suffer from stability problems before being used.

Natural gas fueled engines would not necessarily have any additional technical barriers to overcome in a hybrid ferry compared to those options discussed in Sections 5 and 6. Arrangements would be difficult, since the supporting systems for both gas and hybrid propulsion would compete for space. Most significantly, gas propulsion is only worthwhile where sufficient fuel consumption allows the cost advantage of gas fuel to offset higher capital costs. Since the hybrid ferries would get most power from the grid, it is unlikely that gas engines could be economical for a hybrid.

Similar economic arguments would likely apply to fuel cells, although there are few examples on which to base cost estimates. As with gas, the competing space requirements would potentially be problematic. On the other hand, any ferry with an integrated electric propulsion plant, including a hybrid, would be more able to incorporate fuel cells than a mechanical propulsion concept. The installed batteries would also provide ample buffer to accommodate limitations on the fuel cell's rate of power change.

Automated mooring, as discussed above, is potentially an important technology for a plug-in hybrid ferry. Although the mooring system and automatic shore power system would compete for both topside ferry space and pier space, such a system would eliminate the pushing load, thereby reducing the total power demand and associated electrical power demand fees during ferry charging. The improved consistency of the mooring arrangement would also be an important factor for the complexity and safety of the automated charging system connection.

7.1.5 Natural Gas

The above discussion on electric ferries offers a blueprint towards emissions reduction. The other goal of this study was to identify means to reduce fuel costs. Although several minor upgrades to reduce fuel cost are discussed in Section 6.1, we did not identify any fundamental change to the future fleet blueprint that would enable more significant cost savings. Although natural gas is not recommended at this time, this recommendation hinges on several key assumptions that result in the following conclusions:

- SIF fuel use gives a 20-year payback period for $10M in LNG conversion capital costs.
- The technical viability of an SIF LNG conversion is marginal based on arrangement and stability difficulties.
- Significant regulatory uncertainty results in high risk. This includes USCG, which has not yet approved an LNG powered passenger ship design in the US, and the NYC fire code, which requires amendment to allow the most desirable LNG fueling methods.
- Lack of methane regulation results in uncertainty in the real environmental benefit of gas engines.
- No new LNG engines were evaluated, only EMD's gas conversion options.

The impending global cap on sulfur in marine fuels may still drive significant innovation and economies of scale for marine gas propulsion technology. If such innovation occurs, especially in combination with sustained high oil prices and gas production advances, gas powered SIF ferries could provide a path to meaningful fuel cost reductions.

7.2 New York City Ferry

7.2.1 What does a future electric NYCF fleet look like?

Electric technologies – including batteries, electric drives, and automated shore power connections – are not currently mature enough for the small, high speed, low displacement catamarans operated by NYCF. However, as these technologies advance, it is likely that viable plug-in electric solutions will become available.

As Section 6.2.6 showed, hybrid arrangements are not feasible for these ferries, and therefore a plug-in NYCF fleet would be fully electric. In this scenario, the existing vessels would exchange their diesel engines, fuel tanks, and some auxiliary equipment for batteries, propulsion motors, and required electrical equipment. One generator would remain, and enough diesel fuel for the vessel to return to homeport in an emergency. In this scenario, a charging station at the homeport charges the batteries overnight, and additional charging stations would be installed along the routes to provide top-up energy throughout the day. This could be similar to the quick charging of a transit bus along its route. Several land-based rapid charging systems are in development (Figure 41) though no similar marine versions currently exist – a major hurdle to overcome. Rapid shore charging is a major challenge for marine vessels and for this fleet in particular. The exposed nature of the existing piers, short dwell times, and limited crew all contribute to the difficulty.

Figure 41 Automatic electric bus charging stations, 600kW max capacity (source: ABB)

The most logical locations for charging stations are places where multiple ferries have stops; for example, Wall Street, East 34th Street, and Sunset Park for southbound vessels (Figure 42). The longer routes will prove more difficult to electrify because of their isolation and high energy demands on a single leg. The Rockaway route would need a dramatic increase in battery density (Table 59) or change in vessel design for a plug-in solution to be feasible due to the long leg from Sunset park to Rockaway Beach. Several other routes are feasible but problematic due to their isolated nature (Soundview, Coney Island, St. George) and need for dedicated charging stations (Figure 42).

A lifecycle assessment of this option was performed and showed significant reduction in emissions and fuel consumption. The capital cost to convert all vessels to electrical and install shoreside charging stations is estimated at $35M. It would be most practical to electrify the vessels when they require a midlife repower. Estimating this repower effort to begin in approximately 10 years would allow time for batteries and autonomous charging technology to mature and reduce in price.

Figure 42 NYCF route map with theoretical future charging stations overlaid; refueling is current done at the Brooklyn Navy Yard – NYCF's homeport

Battery Assumptions

Metrics from several electric feasibility studies were compiled and used in preliminary sizing calculations. After evaluating several battery manufacturers, the following values were used for the analysis:

- Depth of Discharge margin: 4.0
- Specific Volume: 200 MJ/m^3

- Specific Weight: 0.4 MJ/kg

The specific weight of the propulsion batteries is critical, as the aluminum catamarans are weight sensitive. Adding weight beyond the vessel's design limits will significantly increase the energy required for the vessel to maintain speed and therefore maintain schedule. The depth of discharge margin of 4.0 implies the batteries cycle within 25% of their rated power.

Charging Locations and Schedule

A future fleet of all-electric vessels will likely require service modifications for NYCF. As the technology develops to make electrification more feasible, the City should perform a detailed ridership study in tandem with exploring feasible charging locations. This will require modifying route terminals and spending more time pushing the dock. These calculations assume installation of four charging stations at $2M each. Using today's battery technology, the smaller River class 150 vessels could carry enough power for 2-3 legs before needing to be recharged. A depth of discharge of 25% (or a margin of 4, described above) will necessitate replacing batteries every 5-years. Battery replacement represents the majority of the maintenance costs.

Feasibility

An electric plug-in fleet requires several battery characteristic improvements, including cycle life, depth of discharge, power density (both volumetric and gravimetric), and charging/discharging rates. Additionally, schedule changes are required to allow longer dwell times for charging. Considering an average round trip of 3000 MJ and keeping the depth of discharge at 25%, the battery energy density will need to improve almost threefold to achieve 1.1 MJ/kg. Current marine certified battery technology has an energy density of 0.4 MJ/kg. In order to achieve an average full day of operation, a 150 River class vessel would require an energy density of approximately 7.7 MJ/kg. Volumetric density must be improved for an all-electric fleet that does not charge throughout its route.

Charging and discharging rates for these high-cycle batteries are typically around 3C. C-rates are described in Section 5.6. An adjustment in schedule would be required to fully charge the propulsion batteries, both to the transit times and to the dwell times. Further investigation of an electric fleet requires optimizing the battery configuration to balance the charging/discharging rates with the installed energy.

Table 59 below summarizes the weight of the required battery bank for twice-per-round-trip charging. The energy consumption for each round trip includes the auxiliary generator energy requirements. The installed battery capacity is four times higher than the required energy because of the batteries' depth of discharge requirement, discussed in detail in Section 5.6.2. The energy requirement for each route assumes the vessel is on the most energy intensive day. For example, the East River route's energy consumption value is for weekend operations, where the route is extended to Governor's Island.

Table 59 All-electric battery sizing for NYCF assuming two charging periods per round trip

Route	Energy [kWhr]	Battery Capacity [kWhr]	Weight [tons]	% Exceeding Allowable	[1]Assumed Specific Battery Weight (MJ/kg)
East River	276	1,104	11	0%	0.50
Rockaway	618	2,473	24	0%	0.75[2]
South Brooklyn	255	1,019	10	0%	0.46
Astoria	215	858	8	0%	0.39
Soundview	342	1,370	14	0%	0.42[2]
Lower East Side	172	687	7	0%	0.31

[1]Current battery specific weight = 0.4 MJ/kg; [2]Route assumed to use the 350-Rockaway class vessel

The estimated weight of the fuel, engines, fuel tanks and auxiliary equipment for the 150 River class vessel is 12 tons, and for the 350 Rockaway vessels approximately 17.5 tons (see Appendix B). Using current battery technology, the smaller vessels can carry approximately 285 kWhr of battery energy, while the larger vessels could carry approximately 450 kWhr. 285 kWhrs provides enough energy for only a few legs along a typical vessel route, and therefore mid-route charging would be required.

The long eastern leg on the Rockaway route cannot be done with only 450 kWhr of installed energy, so electric propulsion is not feasible on this route with current battery technology. The Soundview route is shown as feasible above, but it shares limited stops, so charging infrastructure may be prohibitively complicated and expensive. This barrier is shared with the expansion routes (Coney Island and St. George).

7.2.2 What can be done in the short term?

Renewable diesel offers the most practical criteria and GHG emissions reduction for the existing ferries and can be introduced immediately. The City should begin buying as much renewable diesel as budgets allow. The benefits of renewable diesel for NYCF are detailed in Section 6.1.2.

An alternative way to reduce criteria emissions is to convert the existing diesel engines from EPA Tier 3 to Tier 4. This is invasive and expensive, however, and will be most feasible at vessel midlife when existing engines are due for replacement. Tier upgrades are described in detail in Sections 4.2.3 and 6.2.4.

The absence of a short-term plug-in solution means that diesel-mechanical propulsion will serve NYCF vessels for now. The vessels are already lightweight aluminum, painted with drag reducing coatings, and optimized to maximize passenger capacity however, and there is little more that can be done to reduce the energy necessary to push the vessels through the water. The River class vessels have been de-pitched to raise the bollard thrust and lessen the need for high engine load while maneuvering during docking operations. NYCF reports this lowers the maximum operating speed of the vessel by 1.5 knots. Additionally, all three vessel classes have limited their engine RPM by 3-5% below the manufacturers' factory ratings to conserve fuel.

7.2.3 Natural Gas

A secondary goal of this study was to identify means to reduce fuel costs, and the recommendations did not identify any fundamental change to the future fleet blueprint that would enable more significant cost savings. Although natural gas is not feasible at this time due to the limited availability of marine gas-powered propulsion engines of appropriate size, natural gas ferries may be feasible in the future. Section 6.2.9 estimates that a 70% reduction in fuel cost and 30% reduction in CO_2e is possible if the entire fleet could be converted to run on natural gas. Future consideration of this option must contend with the difficulties outlined in Section 6.2.9.

References

1. NYC Sustainability, NYC, https://www1.nyc.gov/site/sustainability/codes/80x50.page, accessed 11/12/2018.
2. *Reduction of GHG Emissions from Ships: Third IMO GHG Study 2014 – Final Report*, IMO, MEPC 67/INF.3, 25 July 2014.
3. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, IPCC, 2015.
4. Current price development oil and gas, DNVGL, https://www.dnvgl.com/maritime/lng/current-price-development-oil-and-gas.html, accessed 11/19/2018.
5. Ship & Bunker; "FortisBC Begin First Published Posting of LNG Bunker Prices," https://shipandbunker.com/news/world/772235-ship-bunker-fortisbc-begin-first-published-posting-of-lng-bunker-prices, accessed 11/19/2018.
6. *Jumbo Mark II Class Hybrid System Integration Study*, Elliott Bay Design Group, Rev 0, 12/21/2017.
7. *WSF Medium Voltage Shore Power Feasibility Study*, Glosten, Inc, Rev -, 9 February 2018.
8. *New York Electricity Profile 2016*, US Energy Information Administration, https://www.eia.gov/electricity/state/newyork/index.php, accessed 11/21/2018.
9. *New York State Profile and Energy Estimates*, US Energy Information Administration, https://www.eia.gov/state/data.php?sid=NY#SupplyDistribution, accessed 11/21/2018.
10. *Renewable Hydrocarbon Biofuels*, Department of Energy Alternative Fuels Data Center, https://afdc.energy.gov/fuels/emerging_hydrocarbon.html, accessed 11/26/2018.
11. *Toxicological Profile for Fuel Oils*, U.S. Department of Health and Human Services, June 1995.
12. *California Code of Regulations, Title 13, Division 3, § 2282,*
13. *Renewable Diesel Fuel*, National Renewable Energy Laboratory, July 18, 2016.
14. *DCAS to Expand Use of 99% Petroleum-Free Renewable Diesel in City Vehicles*, NYC DCAS, http://www.nyc.gov/html/dcas/downloads/pdf/fleet/Press-Release-DCAS-to-Expand-Use-of-Renewable-Diesel-in-City-Fleet-Vehicles.pdf, accessed 11/26/2018.
15. *Biodiesels Produced From Certain Feedstocks Have Distinct Properties From Petroleum Diesel*, US Energy Information Administration, aeoeia.gov/todayinenergy/detail.php?id=36052, accessed 11/26/2018.
16. *Washington State Ferry Biodiesel Research & Demonstration Project*, Washington State University, Final Report, April 30, 2009.
17. *Quantification of the Cold Flow Properties of Biodiesels Blended with ULSD*, Iowa Central Community College.
18. *Economics of Biofuels*, US Environmental Protection Agency, https://www.epa.gov/environmental-economics/economics-biofuels, accessed 11/28/2018.

19. *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions*, US Environmental Protection Agency, EPA420-P-02-001, October 2002.
20. *At the Forefront of Green Engine Technology*, MAN Diesel & Turbo, 5510-0178-00ppr, April 2016.
21. *Benefits of Methanol as a Marine Fuel*, Methanex.
22. *Methanol as a Marine Fuel*, Lennart Haraldson, Wartsila, January 28, 2015.
23. *Improving Methanol Production Efficiency and Reducing Carbon Dioxide Emissions*, Methanol Institute.
24. *Methanol as a Marine Fuel*, International Maritime Organization, 2016
25. *Alternative Fuel Price Report, US Department of Energy*, https://afdc.energy.gov/fuels/prices.html, accessed 11/29/2018.
26. *Methanex Monthly Average Regional Posted Contract Price History*, Methanex, October 31, 2018.
27. *Stena Germanic RoPax Ferry*, https://www.ship-technology.com/projects/stena-germanica-ropax-ferry/, accessed 11/28/2018.
28. *Using Methanol Fuel in the MAN B&W ME-LGI Series*, MAN Diesel and Turbo, 5510-0172-00ppr, August 2014.
29. *Methanol as Engine Fuel: Challenges and Opportunities*, Tony Stojcevski, Wartsila, 6/29/2016.
30. *Facts about Formaldehyde*, US EPA, https://www.epa.gov/formaldehyde/facts-about-formaldehyde, accessed 11/29/2018.
31. *Methanex, the power of agility*, Methanex, https://www.methanex.com/, accessed 11/29/2018.
32. *Environmental Issues*, Energy by Nature Ng-Tech, *http://emsh-ngtech.com/methanol/environmental-issues/*, accessed 11/28/2018.
33. *Life-Cycle Energy Use and Greenhouse Gas Emissions of Methanol Pathways from the GREET Model*, Michael Want and Uisung Lee, Argonne National Laboratory, July 31, 2017.
34. *2016 Billion-Ton Report – Advancing Domestic Resources for a Thriving Bioeconomy*, US Department of Energy, Volume 1, July 2016
35. *Low Carbon Fuel Standard*, California Air Resources Board, https://www.arb.ca.gov/fuels/lcfs/lcfs.htm, accessed 11/29/2018.
36. Bromberg L., Cheng, W.; “Methanol as an alternative transportation fuel in the US: Options for sustainable and/or energy-secure transportation,” *Sload Automotive Laboratory, MIT*, Final Report, November 2010.
37. DCAS Fuel Price Sheet.
38. *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*, US Environmental Protection Agency, EPA-420-R-10-006, February 2010.

39. *Hydrotreated Vegetable Oil (HVO) as a Renewable Diesel Fuel: Trade-off between NOx, Particulate Emission, and Fuel Consumption of a Heavy-Duty Engine*, SAE International, 2008-01-2500.

40. *Biodiesel Characterization and NOx Mitigation Study,* California Air Resources Board, October 2011.

41. *Economy and Emissions Impacts from Solazyme Fuel in UPS Delivery Vehicles,* National Renewable Energy Laboratory, NREL/TP-5400-68896, August 2018.

42. *New York City Fire Code,* NYC, Title 29.

43. https://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm

44. *The Use of Biodiesel Fuels in the U.S. Marine Industry,* MARAD, DTMA1D05007, TO090000055, April 2010.

45. Fritz, S.; Hedrick, J.; "Locomotive Emissions Measurements for Various Blends of Biodiesel Fuel," SAE International, 2013-24-0106, 8 September 2013.

46. *Detail Specification: Fuel, Naval Distillate*, Naval Sea System Command, MIL-DTL-16884N, 22 April 2014.

47. *How Hydrogen Empowers the Energy Transition*, The Hydrogen Council, January 2017

48. *Destination: Hydrogen,* Air Liquide, 2017

49. *Multi-State ZEV Task Force,* ZEV States, https://www.zevstates.us/, accessed 1/18/2019

50. *First Came the Hydrogen Cars. Now, the Refilling Stations,* New York Times, May 18th, 2018.

51. *2018 Hydrogen and Fuel Cell Development Plan,* Northeast Electrochemical Energy Storage Cluster, 2018

52. *Hydrogen Production,* U.S. Department of Energy, September 2004.

53. *Alternative Fuels Data Center, Maps and Data*, U.S. Department of Energy, accessed 1/18/2019.

54. *Fact of the Month May 2018,* Fuel Cell Technologies Office, https://www.energy.gov/eere/fuelcells/fact-month-may-2018-10-million-metric-tons-hydrogen-produced-annually-united-states, accessed 18/1/2019.

55. *Joint Agency Staff Report on Assembly Bill 8: 2017 Annual Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California,* California Energy Commission, December 2017.

56. *Air Liquide Announces location of Several Hydrogen Fueling Stations in Northeast USA,* Air Liquide, https://www.airliquide.com/united-states-america/air-liquide-announces-locations-several-hydrogen-fueling-stations-northeast, 7 April 2016.

57. *Hydrogen Production and Distribution,* U.S. Department of Energy, https://afdc.energy.gov/fuels/hydrogen_production.html, accessed 1/18/2018.

58. *MAN Cryo Takes Further Step Towards Cleaner Shipping in World-First,* MAN Energy Solutions, https://marine.man-es.com/news/news-details/2018/12/05/man-cryo-takes-further-step-towards-cleaner-shipping-in-world-first, 1/18/2019.

59. *A Ferry That Runs on Hydrogen Fuel Cells is Coming to San Francisco*, Grist, https://grist.org/article/a-ferry-that-runs-on-hydrogen-fuel-cells-is-coming-to-san-francisco/, 3/8/2019.

60. *The Water-Go-Round*, Golden Gate Zero Emission Marine Water-Go-Round Project, https://watergoround.com/, 3/8/2019.

61. *Feasibility of the SF-Breeze: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry*, National Laboratories, September 2016.

62. *California Clean Vehicle Rebate Program*, CVRP Eligible Vehicles, California Air Resources Board, https://cleanvehiclerebate.org/eng/eligible-vehicles, accessed 3/8/2019.

63. *Volkswagen Clean Air Act Civil Settlement*, EPA, https://www.epa.gov/enforcement/volkswagen-clean-air-act-civil-settlement, accessed 3/8/2019.

64. *Cost to Refill*, California Fuel Cell Partnership, https://cafcp.org/content/cost-refill, accessed 3/8/2019.

65. *Staten Island Ferry John J. Marchi Optimization of Propulsion Motor Configuration – Test Results*, Marine Design Dynamics, Inc., July 13, 2018.

66. *Double-Ended Passenger Ferry (97 M); Performance Tests with Voith Schneider Propulsors*, Maritime Research Institute Netherlands (MARIN), 28459-2-BT/DT, Final Report, February 2016.

67. *Fathom Focus – Hull Coatings for Vessel Performance*, Fathom Shipping & Hempel, September 2013

68. *BU-205: Types of Lithium-Ion*, Battery University, https://batteryuniversity.com/index.php/learn/article/types_of_lithium_ion, accessed 3/15/2019

69. *Costs Associated with Compressed Natural Gas Vehicle Fueling Infrastructure*, US Department of Energy, September 2014.

70. *Annual Energy Outlook 2018 Case Descriptions*, US Energy Information Administration, August 2018.

71. *Fuel Cell Basics*, Fuel Cell and Hydrogen Energy Association, http://www.fchea.org/fuelcells, accessed 4/1/2019.

72. *Study on the Use of Fuel Cells in Shipping*, EMSA European Maritime Safety Agency, DNV-GL, Version 0.1, January 2017.

73. *Sandia Zero-V Design Study Report*, Glosten, Rev -, 25/11/2017

74. *HyPM HD 30 – 30kW Hydrogen Fuel Cell Power Module*, Hydrogenics Specification Sheet, February 2014.

75. *Large-Scale programme for Energy Research*, The Research Council of Norway, https://www.forskningsradet.no/en/Funding/ENERGIX/1253979664347/p1184150364108?visAktive=true, accessed 4/1/2019.

76. *ITTC-Recommended Procedures and Guidelines; 1978 ITTC Performance Prediction Method*, International Towing Tank Conference, Rev. 02, 09/2011.

77. 2014 National Emissions Inventory (NEI) Data, US Environmental Protection Agency, https://www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data, accessed 04/10/2019
78. *Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels,* ASTM D6751, 2018.
79. *Standard Specification for Diesel Fuel Oil, Biodiesel Blend (B6 to B20)*, ASTM D7467, 2018.
80. *New York City Ferries Summer Schedule (V6)*, NYCF, August 2018.
81. *17075.05 Fuel Study Shipcheck Trip Report*, Glosten, Rev -, 8 January 2019.
82. *New York City Ferries Fuel Tracking*, NYCF, August 2018.
83. *Annual Energy Outlook 2019,* US Energy Information Administration, 24 January 2019.
84. "Magnus Effect at Flettner Rotor Boat.svg;" Unaltered image used under Creative Commons BY-SA 3.0 license; Author Dan-yell, 18 September 2013. https://commons.wikimedia.org/wiki/File:Flettnerrotor.png
85. *Standard Specification for Diesel Fuel Oils,* ASTM D975, 2019.
86. *F-49 Daily Schedule – Weekday*, NYCDOT Staten Island Ferry, R-0, 15 January 2011.
87. *Life-Cycle Costing Manual for the Federal Energy Management Program*, NIST, HBK 135, 1995.
88. *Annual Energy Outlook 2019*, US Energy Information Administration, 24 January 2019.
89. *Longitudinal study of the performance characteristics and environmental impacts of renewable diesel fuels in marine engines*, Scripps Institution of Oceanography, DTMA-91-H-2013-0001.
90. *Renewable Diesel for Marine Applications, Final Report*, MARAD, 13 August 2013.
91. *Equivalency Determination - Design Criteria for Natural Gas Fuel Systems,* USCG (CD-ENG), Policy Letter 01-12 CH-1, 12 July 2017.
92. *International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code)*, International Maritime Organization, Resolution MSC.391(95), 11 June 2015.
93. *LNG as a marine fuel in the EU*, University Maritime Advisory Services, 22 June 2018.
94. *NYC Ferry*, New York City Ferries, New York City Ferries, https://www.ferry.nyc/, 1 October 2018.
95. *USCG Marine Safety Manual, Vol. III: Marine Industry Personnel*, United States Coast Guard, COMDTINST M16000.8B, July 30th, 2014.
96. De Gouw, J. A.; Parrish, D. D.; Frost, G. J.; Trainer, M.; "Reduced emissions of CO_2, NOx, and SO_2 from U.S. power plants owing to switch from coal to natural gas with combined cycle technology," *Earth's Future,* AGU Publications, Volume 2 (Issue 2), February 2014.

Appendix A SIF Data

Appendix A.1

SIF LCCA and Emissions Comparisons

Any **formulas** that differ from Baseline are outlined in green

Reference Information

Real Disc. Rate	1%		
Diesel Density	3.218	kg/gal	
kgCO2perkgDiesel	3.206		
kgSO2perkgDiesel	3.00E-05		
kgCO2perMJGas	0.050	Source EPA - see onenote	
Methane GWP	28		
DieselLHV	145	MJ/gal	EIA

		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Ships	Barberi/Kennedy	3	2	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0
	Molinari	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Ollis	0	1	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Austen	2	2	2	2	2	2	2	2	2	2	1	0	0	0	0	0	0	0	0	0	0
	Future Midsize	0	0	0	0	0	0	0	0	0	0	1	2	3	3	3	3	3	3	3	3	3
	Total	8	8	9	9	9	9	9	9	8	8	8	8	9	9	9	9	9	9	9	9	9
Trips/week	Barberi	296	197	46	46	46	46	46	46	0	0	0	0	0	0	0	0	0	0	0	0	0
	Molinari	296	296	273	273	273	273	273	273	296	296	296	296	296	296	296	296	296	296	296	296	296
	Ollis	0	99	273	273	273	273	273	273	296	296	296	296	296	296	296	296	296	296	296	296	296
	Austen	190	190	190	190	190	190	190	190	190	190	95	0	0	0	0	0	0	0	0	0	0
	Future Midsize	0	0	0	0	0	0	0	0	0	0	95	190	190	190	190	190	190	190	190	190	190
	Total	782	782	782	782	782	782	782	782	782	782	782	782	782	782	782	782	782	782	782	782	782

Fuel Costs

based on AEO2019, 2018 dollars

Electricity $14.75 per kW (demand rate) - constant in real 2018 dollars

		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Diesel	(per gallon)	$ 2.56	$ 2.56	$ 2.54	$ 2.57	$ 2.62	$ 2.66	$ 2.68	$ 2.76	$ 2.78	$ 2.87	$ 2.89	$ 2.92	$ 2.96	$ 2.99	$ 3.00	$ 3.02	$ 3.06	$ 3.05	$ 3.07	$ 3.09	$ 3.10
Electricity	(per kwh)	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04
LNG	(per GJ)	$ 11.20	$ 11.04	$ 11.03	$ 11.13	$ 11.28	$ 11.53	$ 11.62	$ 11.62	$ 11.69	$ 11.67	$ 11.71	$ 11.70	$ 11.82	$ 11.88	$ 11.93	$ 11.96	$ 12.03	$ 12.06	$ 12.06	$ 12.07	$ 12.10

Baseline (4.3.1)

Fuel and Emissions		**Total**
Diesel	gal	82M
Fuel Energy	GJ	12M
NOx	MT	5297
HC	MT	467
PM	MT	115
CO	MT	923
CO2	MT	846K
SO2	MT	7.9
Costs - 20 yr NPV		$231.4M
Costs - Ops NPV		$231.4M
Costs - Capital		-

		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Diesel	(gal/year)	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M
NOx	(tons/year)	439	376	270	270	270	270	270	270	251	251	232	213	213	213	213	213	213	213	213	213	213
HC	(tons/year)	27	26	23	23	23	23	23	23	23	23	22	21	21	21	21	21	21	21	21	21	21
PM	(tons/year)	10.4	8.6	5.6	5.6	5.6	5.6	5.6	5.6	5.1	5.1	4.9	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
CO	(tons/year)	49	46	40	40	40	40	40	40	40	40	43	47	47	47	47	47	47	47	47	47	47
CO2	(tons/year)	39955	40017	40173	40173	40173	40173	40173	40173	40141	40141	40279	40418	40418	40418	40418	40418	40418	40418	40418	40418	40418
SO2	(tons/year)	0.374	0.374	0.376	0.376	0.376	0.376	0.376	0.376	0.376	0.376	0.377	0.378	0.378	0.378	0.378	0.378	0.378	0.378	0.378	0.378	0.378
Capital		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$9.9M	$9.9M	$9.9M	$10.0M	$10.2M	$10.4M	$10.4M	$10.7M	$10.8M	$11.2M	$11.3M	$11.5M	$11.6M	$11.7M	$11.7M	$11.8M	$12.0M	$12.0M	$12.0M	$12.1M	$12.2M
Maintenance		$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M
Ops Subtotal		$11.0M	$11.0M	$11.0M	$11.1M	$11.3M	$11.5M	$11.5M	$11.8M	$11.9M	$12.3M	$12.4M	$12.5M	$12.7M	$12.8M	$12.8M	$12.9M	$13.1M	$13.0M	$13.1M	$13.2M	$13.2M
Total		$11.0M	$11.0M	$11.0M	$11.1M	$11.3M	$11.5M	$11.5M	$11.8M	$11.9M	$12.3M	$12.4M	$12.5M	$12.7M	$12.8M	$12.8M	$12.9M	$13.1M	$13.0M	$13.1M	$13.2M	$13.2M
PV Total	(discounted to 2020)	$11.0M	$10.9M	$10.8M	$10.8M	$10.9M	$10.9M	$10.9M	$11.0M	$11.0M	$11.2M	$11.2M	$11.2M	$11.2M	$11.2M	$11.2M	$11.1M	$11.1M	$11.0M	$11.0M	$10.9M	$10.9M
PV Ops	(discounted to 2020)	$11.0M	$10.9M	$10.8M	$10.8M	$10.9M	$10.9M	$10.9M	$11.0M	$11.0M	$11.2M	$11.2M	$11.2M	$11.2M	$11.2M	$11.2M	$11.1M	$11.1M	$11.0M	$11.0M	$10.9M	$10.9M
PV Fuel		$9.9M																				$10.0M

Opt 1 - Emission Control Upgrades (6.1.10)

Fuel and Emissions		**Total**	vs baseline	
Diesel	gal	82M	+0%	239K
NOx	MT	5123	-3%	-174
HC	MT	469	+0%	2
PM	MT	69	-40%	-46
CO	MT	919	-0%	-3
CO2e	MT	848K	+0%	2,461
SO2	MT	7.9	+0%	0.0
Costs - 20 yr NPV		$234.2M	+1%	$2.8M
Costs - Ops NPV		$232.0M	+0%	$.6M
Costs - Capital		$2.2M		

		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Diesel	(gal/year)	4.0M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M
NOx	(tons/year)	372	331	259	259	259	259	259	259	251	251	232	213	213	213	213	213	213	213	213	213	213
HC	(tons/year)	28	26	23	23	23	23	23	23	23	23	22	21	21	21	21	21	21	21	21	21	21
PM	(tons/year)	8.1	6.3	3.5	3.5	3.5	3.5	3.5	3.5	2.8	2.8	2.6	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
CO	(tons/year)	48	45	40	40	40	40	40	40	40	40	43	47	47	47	47	47	47	47	47	47	47
CO2	(tons/year)	40905	40650	40319	40319	40319	40319	40319	40319	40141	40141	40279	40418	40418	40418	40418	40418	40418	40418	40418	40418	40418
SO2	(tons/year)	0.383	0.380	0.377	0.377	0.377	0.377	0.377	0.377	0.376	0.376	0.377	0.378	0.378	0.378	0.378	0.378	0.378	0.378	0.378	0.378	0.378
Capital		$2.2M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$10.1M	$10.1M	$9.9M	$10.0M	$10.3M	$10.4M	$10.5M	$10.8M	$10.8M	$11.2M	$11.3M	$11.5M	$11.6M	$11.7M	$11.7M	$11.8M	$12.0M	$12.0M	$12.0M	$12.1M	$12.2M
Maintenance		$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M
Ops Subtotal		$11.2M	$11.2M	$11.0M	$11.1M	$11.3M	$11.5M	$11.6M	$11.9M	$11.9M	$12.3M	$12.4M	$12.5M	$12.7M	$12.8M	$12.8M	$12.9M	$13.1M	$13.0M	$13.1M	$13.2M	$13.2M
Total		$13.4M	$11.2M	$11.0M	$11.1M	$11.3M	$11.5M	$11.6M	$11.9M	$11.9M	$12.3M	$12.4M	$12.5M	$12.7M	$12.8M	$12.8M	$12.9M	$13.1M	$13.0M	$13.1M	$13.2M	$13.2M
PV Total	(discounted to 2020)	$13.4M	$11.1M	$10.8M	$10.8M	$10.9M	$10.9M	$10.9M	$11.1M	$11.0M	$11.2M	$11.2M	$11.2M	$11.2M	$11.2M	$11.2M	$11.1M	$11.1M	$11.0M	$11.0M	$10.9M	$10.9M
PV Ops	(discounted to 2020)	$11.2M	$11.1M	$10.8M	$10.8M	$10.9M	$10.9M	$10.9M	$11.1M	$11.0M	$11.2M	$11.2M	$11.2M	$11.2M	$11.2M	$11.2M	$11.1M	$11.1M	$11.0M	$11.0M	$10.9M	$10.9M
PV Fuel		$10.1M																				$10.0M

Opt 2 - B20 Biodiesel (6.1.1)

Fuel and Emissions		**Total**	vs baseline	
B20	gal	83M	+1%	820K
NOx	MT	5403	+2%	106
HC	MT	397	-15%	-70
PM	MT	98	-15%	-17
CO	MT	784	-15%	-138
CO2	MT	761K	-10%	-84,575
SO2	MT	6.3	-20%	-1.6
Costs - 20 yr NPV		$237.7M	+3%	$6.2M
Costs - Ops NPV		$237.3M	+3%	$5.9M
Costs - Capital		$.4M		

Fuel costs include extra $.05/gal

Gallons of B100 blended 17M

		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
B20	(gal/year)	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	4.0M	4.0M	4.0M	4.0M	4.0M	4.0M	4.0M	4.0M	4.0M	4.0M
NOx	(tons/year)	448	384	275	275	275	275	275	275	256	256	237	217	217	217	217	217	217	217	217	217	217
HC	(tons/year)	23	22	19	19	19	19	19	19	20	20	19	18	18	18	18	18	18	18	18	18	18
PM	(tons/year)	8.8	7.3	4.8	4.8	4.8	4.8	4.8	4.8	4.3	4.3	4.2	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
CO	(tons/year)	42	39	34	34	34	34	34	34	34	34	37	40	40	40	40	40	40	40	40	40	40
CO2	(tons/year)	35959	36015	36156	36156	36156	36156	36156	36156	36127	36127	36251	36376	36376	36376	36376	36376	36376	36376	36376	36376	36376
SO2	(tons/year)	0.299	0.300	0.301	0.301	0.301	0.301	0.301	0.301	0.300	0.300	0.302	0.303	0.303	0.303	0.303	0.303	0.303	0.303	0.303	0.303	0.303
Capital		$.4M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$10.2M	$10.2M	$10.2M	$10.3M	$10.5M	$10.7M	$10.7M	$11.0M	$11.1M	$11.5M	$11.6M	$11.8M	$11.9M	$12.0M	$12.1M	$12.2M	$12.3M	$12.3M	$12.4M	$12.4M	$12.5M
Maintenance		$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M
Ops Subtotal		$11.3M	$11.3M	$11.3M	$11.4M	$11.6M	$11.8M	$11.8M	$12.1M	$12.2M	$12.6M	$12.7M	$12.9M	$13.0M	$13.1M	$13.1M	$13.2M	$13.4M	$13.4M	$13.4M	$13.5M	$13.6M
Total		$11.7M	$11.3M	$11.3M	$11.4M	$11.6M	$11.8M	$11.8M	$12.1M	$12.2M	$12.6M	$12.7M	$12.9M	$13.0M	$13.1M	$13.1M	$13.2M	$13.4M	$13.4M	$13.4M	$13.5M	$13.6M
PV Total	(discounted to 2020)	$11.7M	$11.2M	$11.1M	$11.1M	$11.1M	$11.2M	$11.1M	$11.3M	$11.3M	$11.5M	$11.5M	$11.5M	$11.5M	$11.5M	$11.4M	$11.4M	$11.4M	$11.3M	$11.2M	$11.2M	$11.1M
PV Ops	(discounted to 2020)	$11.3M	$11.2M	$11.1M	$11.1M	$11.1M	$11.2M	$11.1M	$11.3M	$11.3M	$11.5M	$11.5M	$11.5M	$11.5M	$11.5M	$11.4M	$11.4M	$11.4M	$11.3M	$11.2M	$11.2M	$11.1M
PV Fuel		$10.2M																				$10.2M

Reference Data - values referenced from other sheets here to simplify lifecycle formulas to the left

Baseline (4.3.1)

Fuel and emissions per trip. Capital and maintenance cost per year

	gal	CO	PM	NOx	HC	CO2	SO2	Capital	Maintenance
Barberi	113	1.2	0.39	14.5	0.33	1167	0.0109	$ -	$ 65,515
Molinari	109	1.6	0.25	10.8	1.08	1128	0.0106	$ -	$ 345,734
Ollis	114	0.6	0.04	2.3	0.08	1179	0.0110	$ -	$ 474,404
Austen	45	0.5	0.06	5.0	0.53	469	0.0044	$ -	$ 97,484
Future Midsize	48	1.2	0.02	1.2	0.32	497	0.0047	$ -	$ 101,199

Opt 1 - Emission Control Upgrades (6.1.10)

Fuel and emissions per trip. Capital and maintenance cost per year

	gal	CO	PM	NOx	HC	CO2	SO2	Capital	Maintenance
Barberi	119	1.1	0.39	10.1	0.39	1229	0.0115	$ 100,000	$ 65,515
Molinari	109	1.6	0.10	10.8	1.08	1128	0.0106	$ 2,070,000	$ 345,734
Ollis	114	0.6	0.04	2.3	0.08	1179	0.0110	$ -	$ 474,404
Austen	45	0.5	0.06	5.0	0.53	469	0.0044	$ -	$ 97,484
Future Midsize	48	1.2	0.02	1.2	0.32	497	0.0047	$ -	$ 101,199

Opt 2 - B20 Biodiesel (6.1.1)

Fuel and emissions per trip. Capital and maintenance cost per year

	gal	CO	PM	NOx	HC	CO2	SO2	Capital	Maintenance
Barberi	114	1.0	0.33	14.8	0.28	1050	0.0087	$ 25,442	$ 65,515
Molinari	110	1.4	0.21	11.0	0.92	1015	0.0084	$ 268,011	$ 345,734
Ollis	115	0.5	0.04	2.3	0.07	1061	0.0088	$ 63,679	$ 474,404
Austen	46	0.5	0.05	5.1	0.45	422	0.0035	$ 30,672	$ 97,484
Future Midsize	49	1.0	0.02	1.2	0.28	447	0.0037	$ -	$ 101,199

Appendix A.1

SIF LCCA and Emissions Comparisons

Opt 3 - R50 Renewable Diesel (6.1.2)

Fuel and Emissions		**Total**	vs baseline	
R50	gal	82M	-	0K
NOx	MT	5165	-2%	-132
HC	MT	397	-15%	-70
PM	MT	98	-15%	-17
CO	MT	784	-15%	-138
CO2	MT	571K	-33%	-274,869
SO2	MT	4.0	-50%	-4.0
Costs - 20 yr NPV		$287.2M	+24%	$55.7M
Costs - Ops NPV		$287.2M	+24%	$55.7M
Costs - Capital		-		

Fuel costs include extra $1.50/gal

Gallons of R100 blended	41M

R50	(gal/year)	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M
NOx	(tons/year)	428	367	263	263	263	263	263	263	244	244	226	208	208	208	208	208	208	208	208	208	208
HC	(tons/year)	23	22	19	19	19	19	19	19	20	20	19	18	18	18	18	18	18	18	18	18	18
PM	(tons/year)	8.8	7.3	4.8	4.8	4.8	4.8	4.8	4.8	4.3	4.3	4.2	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
CO	(tons/year)	42	39	34	34	34	34	34	34	34	34	37	40	40	40	40	40	40	40	40	40	40
CO2	(tons/year)	26969	27011	27117	27117	27117	27117	27117	27117	27095	27095	27189	27282	27282	27282	27282	27282	27282	27282	27282	27282	27282
SO2	(tons/year)	0.187	0.187	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.189	0.189	0.189	0.189	0.189	0.189	0.189	0.189	0.189	0.189
Capital		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$12.8M	$12.9M	$12.8M	$12.9M	$13.1M	$13.3M	$13.4M	$13.7M	$13.7M	$14.1M	$14.2M	$14.4M	$14.5M	$14.6M	$14.7M	$14.8M	$14.9M	$14.9M	$15.0M	$15.0M	$15.1M
Maintenance		$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M
Ops Subtotal		$13.9M	$13.9M	$13.9M	$14.0M	$14.2M	$14.4M	$14.5M	$14.7M	$14.8M	$15.2M	$15.3M	$15.5M	$15.6M	$15.7M	$15.8M	$15.9M	$16.0M	$16.0M	$16.1M	$16.1M	$16.2M
Total		$13.9M	$13.9M	$13.9M	$14.0M	$14.2M	$14.4M	$14.5M	$14.7M	$14.8M	$15.2M	$15.3M	$15.5M	$15.6M	$15.7M	$15.8M	$15.9M	$16.0M	$16.0M	$16.1M	$16.1M	$16.2M
PV Total	(discounted to 2020)	$13.9M	$13.8M	$13.6M	$13.6M	$13.7M	$13.7M	$13.6M	$13.7M	$13.7M	$13.9M	$13.9M	$13.9M	$13.9M	$13.8M	$13.7M	$13.7M	$13.7M	$13.5M	$13.4M	$13.3M	$13.3M
PV Ops	(discounted to 2020)	$13.9M	$13.8M	$13.6M	$13.6M	$13.7M	$13.7M	$13.6M	$13.7M	$13.7M	$13.9M	$13.9M	$13.9M	$13.9M	$13.8M	$13.7M	$13.7M	$13.7M	$13.5M	$13.4M	$13.3M	$13.3M
PV Fuel		$12.8M																				$12.4M

Opt 3 - R50 Renewable Diesel (6.1.2)

	Fuel and emissions per trip. Capital and maintenance cost per year								
	gal	CO	PM	NOx	HC	CO2	SO2	Capital	Maintenance
Barberi	113	1.0	0.33	14.1	0.28	788	0.0055	$ -	$ 65,515
Molinari	109	1.4	0.21	10.5	0.92	761	0.0053	$ -	$ 345,734
Ollis	114	0.5	0.04	2.2	0.07	796	0.0055	$ -	$ 474,404
Austen	45	0.5	0.05	4.9	0.45	317	0.0022	$ -	$ 97,484
Future Midsize	48	1.0	0.02	1.2	0.28	336	0.0023	$ -	$ 101,199

Opt 4a - DGB LNG Molinari (6.1.3)

Fuel and Emissions		**Total**	vs baseline	
Diesel	gal	67M	-18%	-15M
LNG	GJ	1.8M	-	
Fuel Total	GJ	11.5M	-3%	-0.3M
NOx	MT	5297	-	0
HC	MT	467	-	0
PM	MT	115	-	0
CO	MT	923	-	0
CO2e	MT	846K	-0%	-208
SO2	MT	6.5	-18%	-1.4
Costs - 20 yr NPV		$242.3M	+5%	$10.9M
Costs - Ops NPV		$212.3M	-8%	-$19.1M
Costs - Capital		$30.0M		

Diesel	(gal/year)	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M	3.2M
LNG	(GJ/year)	88K	88K	81K	81K	81K	81K	81K	81K	88K	88K	88K	88K	88K	88K	88K	88K	88K	88K	88K	88K	88K
NOx	(tons/year)	439	376	270	270	270	270	270	270	251	251	232	213	213	213	213	213	213	213	213	213	213
HC	(tons/year)	27	26	23	23	23	23	23	23	23	23	22	21	21	21	21	21	21	21	21	21	21
PM	(tons/year)	10.4	8.6	5.6	5.6	5.6	5.6	5.6	5.6	5.1	5.1	4.9	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
CO	(tons/year)	49	46	40	40	40	40	40	40	40	40	43	47	47	47	47	47	47	47	47	47	47
CO2	(tons/year)	39945	40007	40164	40164	40164	40164	40164	40164	40131	40131	40269	40408	40408	40408	40408	40408	40408	40408	40408	40408	40408
SO2	(tons/year)	0.304	0.305	0.312	0.312	0.312	0.312	0.312	0.312	0.306	0.306	0.307	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309	0.309
Capital		$30.0M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$9.0M	$9.1M	$9.1M	$9.2M	$9.4M	$9.5M	$9.6M	$9.8M	$9.8M	$10.1M	$10.2M	$10.4M	$10.5M	$10.6M	$10.6M	$10.7M	$10.8M	$10.8M	$10.9M	$10.9M	$11.0M
Maintenance		$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M
Ops Subtotal		$10.1M	$10.2M	$10.2M	$10.3M	$10.5M	$10.6M	$10.7M	$10.9M	$10.9M	$11.2M	$11.3M	$11.5M	$11.6M	$11.7M	$11.7M	$11.8M	$11.9M	$11.9M	$12.0M	$12.0M	$12.1M
Total		$40.1M	$10.2M	$10.2M	$10.3M	$10.5M	$10.6M	$10.7M	$10.9M	$10.9M	$11.2M	$11.3M	$11.5M	$11.6M	$11.7M	$11.7M	$11.8M	$11.9M	$11.9M	$12.0M	$12.0M	$12.1M
PV Total	(discounted to 2020)	$40.1M	$10.1M	$10.0M	$10.0M	$10.1M	$10.1M	$10.1M	$10.2M	$10.1M	$10.2M	$10.2M	$10.3M	$10.3M	$10.3M	$10.2M	$10.2M	$10.2M	$10.0M	$10.0M	$9.9M	$9.9M
PV Ops	(discounted to 2020)	$10.1M	$10.1M	$10.0M	$10.0M	$10.1M	$10.1M	$10.1M	$10.2M	$10.1M	$10.2M	$10.2M	$10.3M	$10.3M	$10.3M	$10.2M	$10.2M	$10.2M	$10.0M	$10.0M	$9.9M	$9.9M
PV Fuel		$9.0M																				$9.0M

Opt 4a - DGB LNG Molinari (6.1.3)

	Fuel and emissions per trip. Capital and maintenance cost per year									
	gal diesel	GJ gas	CO	PM	NOx	HC	CO2e	SO2	Capital	Maintenance
Barberi	113		1.2	0.39	14.5	0.33	1167	0.0109	$ -	$ 65,515
Molinari	62	5.70	1.6	0.25	10.8	1.08	1127	0.0060	$ 30,000,000	$ 345,734
Ollis	114		0.6	0.04	2.3	0.08	1179	0.0110	$ -	$ 474,404
Austen	45		0.5	0.06	5.0	0.53	469	0.0044	$ -	$ 97,484
Future Midsize	48		1.2	0.02	1.2	0.32	497	0.0047	$ -	$ 101,199

Opt 4b - DIG LNG Ollis/Midsize (6.1.3)

Fuel and Emissions		**Total**	vs baseline	
Diesel	gal	49M	-40%	
LNG	GJ	3.9M		
Total Fuel Energy	GJ	11.0M	-7%	-0.8M
NOx	MT	5297	-	0
HC	MT	467	-	0
PM	MT	115	-	0
CO	MT	923	-	0
CO2e	MT	777K	-8%	-68,363
SO2	MT	4.7	-40%	-3.2
Costs - 20 yr NPV		$234.5M	+1%	$3.1M
Costs - Ops NPV		$187.6M	-19%	-$43.8M
Costs - Capital		$48.0M		

Diesel	(gal/year)	3.9M	3.4M	2.5M	2.5M	2.5M	2.5M	2.5M	2.5M	2.4M	2.4M	2.2M	2.0M	2.0M	2.0M	2.0M	2.0M	2.0M	2.0M	2.0M	2.0M	2.0M
LNG	(GJ/year)	-	60K	165K	165K	165K	165K	165K	165K	179K	179K	206K	232K	232K	232K	232K	232K	232K	232K	232K	232K	232K
NOx	(tons/year)	439	376	270	270	270	270	270	270	251	251	232	213	213	213	213	213	213	213	213	213	213
HC	(tons/year)	27	26	23	23	23	23	23	23	23	23	22	21	21	21	21	21	21	21	21	21	21
PM	(tons/year)	10.4	8.6	5.6	5.6	5.6	5.6	5.6	5.6	5.1	5.1	4.9	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
CO	(tons/year)	49	46	40	40	40	40	40	40	40	40	43	47	47	47	47	47	47	47	47	47	47
CO2	(tons/year)	39955	38877	37017	37017	37017	37017	37017	37017	36722	36722	36677	36633	36633	36633	36633	36633	36633	36633	36633	36633	36633
SO2	(tons/year)	0.374	0.325	0.239	0.239	0.239	0.239	0.239	0.239	0.228	0.228	0.210	0.192	0.192	0.192	0.192	0.192	0.192	0.192	0.192	0.192	0.192
Capital		$36.0M	-	-	-	-	-	-	-	-	$12.0M	-	-	-	-	-	-	-	-	-	-	-
Fuel		$9.9M	$9.3M	$8.1M	$8.2M	$8.4M	$8.5M	$8.6M	$8.8M	$8.7M	$8.9M	$8.7M	$8.5M	$8.6M	$8.7M	$8.7M	$8.8M	$8.9M	$8.9M	$8.9M	$9.0M	$9.0M
Maintenance		$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M
Ops Subtotal		$11.0M	$10.4M	$9.2M	$9.3M	$9.5M	$9.6M	$9.7M	$9.8M	$9.7M	$9.9M	$9.8M	$9.6M	$9.7M	$9.8M	$9.8M	$9.9M	$10.0M	$10.0M	$10.0M	$10.0M	$10.1M
Total		$47.0M	$10.4M	$9.2M	$9.3M	$9.5M	$9.6M	$9.7M	$9.8M	$9.7M	$21.9M	$9.8M	$9.6M	$9.7M	$9.8M	$9.8M	$9.9M	$10.0M	$10.0M	$10.0M	$10.0M	$10.1M
PV Total	(discounted to 2020)	$47.0M	$10.3M	$9.0M	$9.0M	$9.1M	$9.1M	$9.1M	$9.2M	$9.0M	$20.1M	$8.9M	$8.6M	$8.6M	$8.6M	$8.5M	$8.5M	$8.5M	$8.4M	$8.4M	$8.3M	$8.3M
PV Ops		$11.0M	$10.3M	$9.0M	$9.0M	$9.1M	$9.1M	$9.1M	$9.2M	$9.0M	$9.1M	$8.9M	$8.6M	$8.6M	$8.6M	$8.5M	$8.5M	$8.5M	$8.4M	$8.4M	$8.3M	$8.3M
PV Fuel		$9.9M																				$7.4M

Opt 4b - DIG LNG Ollis/Midsize (6.1.3)

	Fuel and emissions per trip. Capital and maintenance cost per year									
	gal diesel	GJ gas	CO	PM	NOx	HC	CO2e	SO2	Capital	Maintenance
Barberi	113		1.2	0.39	14.5	0.33	1167	0.0109	$ -	$ 65,515
Molinari	109		1.6	0.25	10.8	1.08	1128	0.0106	$ -	$ 345,734
Ollis	15	11.64	0.6	0.04	2.3	0.08	957	0.0014	$ 36,000,000	$ 474,404
Austen	45		0.5	0.06	5.0	0.53	469	0.0044	$ -	$ 97,484
Future Midsize	8	5.39	1.2	0.02	1.2	0.32	460	0.0008	$ 12,000,000	$ 101,199

* Additional capital cost for midsize projected to 2029

Opt 4c - All DIG LNG (Partial - see 6.1.3)

Fuel and Emissions		**Total**	vs baseline	
Diesel	gal	4M	-95%	-78M
LNG	GJ	8.2M		
Total Fuel Energy	GJ	8.8M	-26%	-3.1M
CO2e	MT	704K	-17%	-142,241
Costs - 20 yr NPV		$117.8M	-49%	-$113.6M
Costs - Ops NPV		$117.8M	-49%	-$113.6M
Costs - Capital		-		

Note: this is a partial calculation of fuel savings only, to support discussion of speed changes in Section 6.1.3 of the report

Diesel	(gal/year)	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M	0.2M
LNG	(GJ/year)	387K	388K	389K	389K	389K	389K	389K	389K	389K	389K	390K	392K	392K	392K	392K	392K	392K	392K	392K	392K	392K
CO2	(tons/year)	30795	31673	33153	33153	33153	33153	33153	33153	33429	33429	33788	34148	34148	34148	34148	34148	34148	34148	34148	34148	34148
Capital		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$4.8M	$4.8M	$4.8M	$4.8M	$4.9M	$5.0M	$5.0M	$5.1M	$5.1M	$5.1M	$5.1M	$5.2M	$5.2M	$5.2M	$5.3M	$5.3M	$5.3M	$5.3M	$5.3M	$5.3M	$5.3M
Maintenance		$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M
Ops Subtotal		$5.9M	$5.9M	$5.9M	$5.9M	$6.0M	$6.1M	$6.1M	$6.1M	$6.2M	$6.2M	$6.2M	$6.2M	$6.3M	$6.3M	$6.3M	$6.4M	$6.4M	$6.4M	$6.4M	$6.4M	$6.4M
Total		$5.9M	$5.9M	$5.9M	$5.9M	$6.0M	$6.1M	$6.1M	$6.1M	$6.2M	$6.2M	$6.2M	$6.2M	$6.3M	$6.3M	$6.3M	$6.4M	$6.4M	$6.4M	$6.4M	$6.4M	$6.4M
PV Total	(discounted to 2020)	$5.9M	$5.8M	$5.8M	$5.7M	$5.8M	$5.8M	$5.8M	$5.7M	$5.7M	$5.7M	$5.6M	$5.6M	$5.6M	$5.6M	$5.5M	$5.5M	$5.5M	$5.4M	$5.4M	$5.3M	$5.3M
PV Ops		$5.9M	$5.8M	$5.8M	$5.7M	$5.8M	$5.8M	$5.8M	$5.7M	$5.7M	$5.7M	$5.6M	$5.6M	$5.6M	$5.6M	$5.5M	$5.5M	$5.5M	$5.4M	$5.4M	$5.3M	$5.3M
PV Fuel		$4.8M																				$4.4M

Opt 4c - All DIG LNG (Partial - see 6.1.3)

	Fuel and emissions per trip. Capital and maintenance cost per year									
	gal diesel	GJ gas	CO	PM	NOx	HC	CO2	SO2	Capital	Maintenance
Barberi	113	11					835			$ 65,515
Molinari	109	11					897			$ 345,734
Ollis	114	11					1007			$ 474,404
Austen	45	5					417			$ 97,484
Future Midsize	48	5					490			$ 101,199
gal to GJ conversion		0.1	GJ/gal							

SIF LCCA and Emissions Comparisons

Opt 5 - Low Friction Hull Coatings (6.1.8)

Fuel and Emissions		Total	vs baseline	
Diesel	gal	80M	-2%	-1.6M
NOx	MT	5230	-1%	-67
HC	MT	461	-1%	-6
PM	MT	113	-1%	-2
CO	MT	910	-1%	-13
CO2	MT	830K	-2%	-16,097
SO2	MT	7.8	-2%	-0.2
Costs - 20 yr NPV		$227.6M	-2%	-$3.8M
Costs - Ops NPV		$227.6M	-2%	-$3.8M
Costs - Capital		-		

Diesel	(gal/year)	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M
NOx	(tons/year)	432	371	266	266	266	266	266	266	248	248	229	210	210	210	210	210	210	210	210	210	210
HC	(tons/year)	27	25	22	22	22	22	22	22	23	23	22	21	21	21	21	21	21	21	21	21	21
PM	(tons/year)	10.2	8.5	5.5	5.5	5.5	5.5	5.5	5.5	5.0	5.0	4.8	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
CO	(tons/year)	48	45	39	39	39	39	39	39	39	39	43	46	46	46	46	46	46	46	46	46	46
CO2	(tons/year)	39331	39339	39405	39405	39405	39405	39405	39405	39354	39354	39495	39635	39635	39635	39635	39635	39635	39635	39635	39635	39635
SO2	(tons/year)	0.368	0.368	0.369	0.369	0.369	0.369	0.369	0.369	0.368	0.368	0.370	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.371
Capital		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$9.7M	$9.8M	$9.7M	$9.8M	$10.0M	$10.2M	$10.2M	$10.5M	$10.6M	$10.9M	$11.1M	$11.2M	$11.4M	$11.5M	$11.5M	$11.6M	$11.8M	$11.7M	$11.8M	$11.9M	$11.9M
Maintenance		$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M
Ops Subtotal		$10.8M	$10.9M	$10.8M	$10.9M	$11.1M	$11.3M	$11.3M	$11.6M	$11.7M	$12.0M	$12.2M	$12.3M	$12.5M	$12.6M	$12.6M	$12.7M	$12.8M	$12.8M	$12.9M	$13.0M	$13.0M
Total		$10.8M	$10.9M	$10.8M	$10.9M	$11.1M	$11.3M	$11.3M	$11.6M	$11.7M	$12.0M	$12.2M	$12.3M	$12.5M	$12.6M	$12.6M	$12.7M	$12.8M	$12.8M	$12.9M	$13.0M	$13.0M
PV Total	(discounted to 2020)	$10.8M	$10.8M	$10.6M	$10.6M	$10.7M	$10.7M	$10.7M	$10.8M	$10.8M	$11.0M	$11.0M	$11.0M	$11.1M	$11.0M	$11.0M	$11.0M	$11.0M	$10.8M	$10.8M	$10.7M	$10.7M
PV Ops	(discounted to 2020)	$10.8M	$10.8M	$10.6M	$10.6M	$10.7M	$10.7M	$10.7M	$10.8M	$10.8M	$11.0M	$11.0M	$11.0M	$11.1M	$11.0M	$11.0M	$11.0M	$11.0M	$10.8M	$10.8M	$10.7M	$10.7M
PV Fuel		$9.7M																				$9.8M

Opt 5 - Low Friction Hull Coatings (6.1.8)

Fuel and emissions per trip. Capital and maintenance cost per year

	gal	CO	PM	NOx	HC	CO2	SO2	Capital	Maintenance
Barberi	112	1.2	0.38	14.2	0.33	1152	0.0108	$ -	$ 66,015
Molinari	107	1.6	0.25	10.6	1.06	1108	0.0104	$ -	$ 349,234
Ollis	112	0.6	0.04	2.3	0.08	1154	0.0108	$ -	$ 477,627
Austen	45	0.5	0.06	5.0	0.53	460	0.0043	$ -	$ 98,184
Future Midsize	47	1.2	0.02	1.2	0.32	488	0.0046	$ -	$ 102,449

Opt 6 - Integrated Bus Molinari (6.1.4)

Fuel and Emissions		Total	vs baseline	
Diesel	gal	81M	-1%	-1.1M
NOx	MT	4858	-8%	-439
HC	MT	446	-5%	-21
PM	MT	114	-1%	-1
CO	MT	910	-1%	-12
CO2	MT	835K	-1%	-11,001
SO2	MT	7.8	-1%	-0.1
Costs - 20 yr NPV		$234.0M	+1%	+$2.6M
Costs - Ops NPV		$227.2M	-2%	-$4.2M
Costs - Capital		$6.8M		

Diesel	(gal/year)	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M
NOx	(tons/year)	417	355	250	250	250	250	250	250	229	229	211	192	192	192	192	192	192	192	192	192	192
HC	(tons/year)	26	25	22	22	22	22	22	22	22	22	21	20	20	20	20	20	20	20	20	20	20
PM	(tons/year)	10.3	8.5	5.6	5.6	5.6	5.6	5.6	5.6	5.0	5.0	4.8	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
CO	(tons/year)	48	45	39	39	39	39	39	39	39	39	43	46	46	46	46	46	46	46	46	46	46
CO2	(tons/year)	39419	39481	39679	39679	39679	39679	39679	39679	39605	39605	39744	39882	39882	39882	39882	39882	39882	39882	39882	39882	39882
SO2	(tons/year)	0.369	0.369	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.371	0.372	0.373	0.373	0.373	0.373	0.373	0.373	0.373	0.373	0.373	0.373
Capital		$6.8M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$9.8M	$9.8M	$9.8M	$9.9M	$10.1M	$10.2M	$10.3M	$10.6M	$10.7M	$11.0M	$11.1M	$11.3M	$11.4M	$11.5M	$11.6M	$11.7M	$11.8M	$11.8M	$11.9M	$11.9M	$12.0M
Maintenance		$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M
Ops Subtotal		$10.8M	$10.8M	$10.8M	$10.9M	$11.1M	$11.3M	$11.3M	$11.6M	$11.7M	$12.0M	$12.2M	$12.3M	$12.4M	$12.6M	$12.6M	$12.7M	$12.8M	$12.8M	$12.9M	$12.9M	$13.0M
Total		$17.5M	$10.8M	$10.8M	$10.9M	$11.1M	$11.3M	$11.3M	$11.6M	$11.7M	$12.0M	$12.2M	$12.3M	$12.4M	$12.6M	$12.6M	$12.7M	$12.8M	$12.8M	$12.9M	$12.9M	$13.0M
PV Total	(discounted to 2020)	$17.5M	$10.7M	$10.6M	$10.6M	$10.7M	$10.7M	$10.7M	$10.8M	$10.8M	$11.0M	$11.0M	$11.0M	$11.0M	$11.0M	$11.0M	$10.9M	$10.9M	$10.8M	$10.8M	$10.7M	$10.7M
PV Ops	(discounted to 2020)	$10.8M	$10.7M	$10.6M	$10.6M	$10.7M	$10.7M	$10.7M	$10.8M	$10.8M	$11.0M	$11.0M	$11.0M	$11.0M	$11.0M	$11.0M	$10.9M	$10.9M	$10.8M	$10.8M	$10.7M	$10.7M
PV Fuel		$9.8M																				$9.8M

Opt 6 - Integrated Bus Molinari (6.1.4)

Fuel and emissions per trip. Capital and maintenance cost per year

	gal	CO	PM	NOx	HC	CO2	SO2	Capital	Maintenance
Barberi	113	1.2	0.39	14.5	0.33	1167	0.0109	$ -	$ 65,515
Molinari	106	1.6	0.25	9.4	1.01	1093	0.0102	$ 6,750,000	$ 270,519
Ollis	114	0.6	0.04	2.3	0.08	1179	0.0110	$ -	$ 474,404
Austen	45	0.5	0.06	5.0	0.53	469	0.0044	$ -	$ 97,484
Future Midsize	48	1.2	0.02	1.2	0.32	497	0.0047	$ -	$ 101,199

Opt 7 - Int Bus & Var Spd Molinari (6.1.5)

Fuel and Emissions		Total	vs baseline	
Diesel	gal	78M	-5%	-4.1M
NOx	MT	5013	-5%	-284
HC	MT	473	+1%	6
PM	MT	100	-13%	-15
CO	MT	910	-1%	-12
CO2	MT	804K	-5%	-41,875
SO2	MT	7.5	-5%	-0.4
Costs - 20 yr NPV		$252.1M	+9%	+$20.7M
Costs - Ops NPV		$219.5M	-5%	-$11.9M
Costs - Capital		$32.6M		

Diesel	(gal/year)	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M
NOx	(tons/year)	425	362	257	257	257	257	257	257	237	237	218	199	199	199	199	199	199	199	199	199	199
HC	(tons/year)	27	26	23	23	23	23	23	23	23	23	22	21	21	21	21	21	21	21	21	21	21
PM	(tons/year)	9.6	7.9	5.0	5.0	5.0	5.0	5.0	5.0	4.3	4.3	4.2	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
CO	(tons/year)	48	45	39	39	39	39	39	39	39	39	43	46	46	46	46	46	46	46	46	46	46
CO2	(tons/year)	37916	37978	38291	38291	38291	38291	38291	38291	38102	38102	38240	38379	38379	38379	38379	38379	38379	38379	38379	38379	38379
SO2	(tons/year)	0.355	0.355	0.358	0.358	0.358	0.358	0.358	0.358	0.357	0.357	0.358	0.359	0.359	0.359	0.359	0.359	0.359	0.359	0.359	0.359	0.359
Capital		$32.6M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$9.4M	$9.4M	$9.4M	$9.5M	$9.7M	$9.9M	$10.0M	$10.2M	$10.3M	$10.6M	$10.7M	$10.9M	$11.0M	$11.1M	$11.1M	$11.3M	$11.4M	$11.4M	$11.4M	$11.5M	$11.5M
Maintenance		$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M	$1.0M
Ops Subtotal		$10.4M	$10.5M	$10.4M	$10.6M	$10.7M	$10.9M	$11.0M	$11.2M	$11.3M	$11.6M	$11.7M	$11.9M	$12.0M	$12.1M	$12.2M	$12.3M	$12.4M	$12.4M	$12.4M	$12.5M	$12.6M
Total		$43.0M	$10.5M	$10.4M	$10.6M	$10.7M	$10.9M	$11.0M	$11.2M	$11.3M	$11.6M	$11.7M	$11.9M	$12.0M	$12.1M	$12.2M	$12.3M	$12.4M	$12.4M	$12.4M	$12.5M	$12.6M
PV Total	(discounted to 2020)	$43.0M	$10.3M	$10.2M	$10.2M	$10.3M	$10.4M	$10.3M	$10.5M	$10.4M	$10.6M	$10.6M	$10.7M	$10.7M	$10.6M	$10.6M	$10.6M	$10.6M	$10.4M	$10.4M	$10.3M	$10.3M
PV Ops	(discounted to 2020)	$10.4M	$10.3M	$10.2M	$10.2M	$10.3M	$10.4M	$10.3M	$10.5M	$10.4M	$10.6M	$10.6M	$10.7M	$10.7M	$10.6M	$10.6M	$10.6M	$10.6M	$10.4M	$10.4M	$10.3M	$10.3M
PV Fuel		$9.4M																				$9.5M

Opt 7 - Int Bus & Var Spd Molinari (6.1.5)

Fuel and emissions per trip. Capital and maintenance cost per year

	gal	CO	PM	NOx	HC	CO2	SO2	Capital	Maintenance
Barberi	113	1.2	0.39	14.5	0.33	1167	0.0109	$ -	$ 65,515
Molinari	96	1.6	0.20	9.9	1.10	995	0.0093	$ 32,571,000	$ 270,519
Ollis	114	0.6	0.04	2.3	0.08	1179	0.0110	$ -	$ 474,404
Austen	45	0.5	0.06	5.0	0.53	469	0.0044	$ -	$ 97,484
Future Midsize	48	1.2	0.02	1.2	0.32	497	0.0047	$ -	$ 101,199

Opt 8a - Diesel Hybrid Molinari (6.1.6)

Fuel and Emissions		Total	vs baseline	
Diesel	gal	78M	-4%	-3.7M
NOx	MT	5601	+6%	304
HC	MT	491	+5%	24
PM	MT	99	-14%	-16
CO	MT	909	-2%	-14
CO2	MT	808K	-4%	-37,884
SO2	MT	7.6	-4%	-0.4
Costs - 20 yr NPV		$259.4M	+12%	+$28.0M
Costs - Ops NPV		$222.8M	-4%	-$8.6M
Costs - Capital		$36.7M		

Diesel	(gal/year)	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M
NOx	(tons/year)	454	391	283	283	283	283	283	283	266	266	247	228	228	228	228	228	228	228	228	228	228
HC	(tons/year)	28	27	24	24	24	24	24	24	24	24	23	22	22	22	22	22	22	22	22	22	22
PM	(tons/year)	9.6	7.8	4.9	4.9	4.9	4.9	4.9	4.9	4.3	4.3	4.1	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
CO	(tons/year)	48	45	39	39	39	39	39	39	39	39	42	46	46	46	46	46	46	46	46	46	46
CO2	(tons/year)	38110	38172	38471	38471	38471	38471	38471	38471	38296	38296	38435	38573	38573	38573	38573	38573	38573	38573	38573	38573	38573
SO2	(tons/year)	0.357	0.357	0.360	0.360	0.360	0.360	0.360	0.360	0.358	0.358	0.360	0.361	0.361	0.361	0.361	0.361	0.361	0.361	0.361	0.361	0.361
Capital		$36.7M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$9.4M	$9.5M	$9.5M	$9.6M	$9.8M	$9.9M	$10.0M	$10.3M	$10.3M	$10.7M	$10.8M	$10.9M	$11.1M	$11.2M	$11.2M	$11.3M	$11.4M	$11.4M	$11.5M	$11.5M	$11.6M
Maintenance		$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M
Ops Subtotal		$10.6M	$10.6M	$10.6M	$10.7M	$10.9M	$11.1M	$11.1M	$11.4M	$11.5M	$11.8M	$11.9M	$12.1M	$12.2M	$12.3M	$12.3M	$12.4M	$12.6M	$12.5M	$12.6M	$12.7M	$12.7M
Total		$47.2M	$10.6M	$10.6M	$10.7M	$10.9M	$11.1M	$11.1M	$11.4M	$11.5M	$11.8M	$11.9M	$12.1M	$12.2M	$12.3M	$12.3M	$12.4M	$12.6M	$12.5M	$12.6M	$12.7M	$12.7M
PV Total	(discounted to 2020)	$47.2M	$10.5M	$10.4M	$10.4M	$10.5M	$10.5M	$10.5M	$10.6M	$10.6M	$10.8M	$10.8M	$10.8M	$10.8M	$10.8M	$10.7M	$10.7M	$10.7M	$10.6M	$10.5M	$10.5M	$10.4M
PV Ops	(discounted to 2020)	$10.6M	$10.5M	$10.4M	$10.4M	$10.5M	$10.5M	$10.5M	$10.6M	$10.6M	$10.8M	$10.8M	$10.8M	$10.8M	$10.8M	$10.7M	$10.7M	$10.7M	$10.6M	$10.5M	$10.5M	$10.4M
PV Fuel		$9.4M																				$9.5M

Opt 8a - Diesel Hybrid Molinari (6.1.6)

Fuel and emissions per trip. Capital and maintenance cost per year

	gal	CO	PM	NOx	HC	CO2	SO2	Capital	Maintenance
Barberi	113	1.2	0.39	14.5	0.33	1167	0.0109	$ -	$ 65,515
Molinari	98	1.6	0.20	11.7	1.15	1008	0.0094	$ 36,666,000	$ 387,974
Ollis	114	0.6	0.04	2.3	0.08	1179	0.0110	$ -	$ 474,404
Austen	45	0.5	0.06	5.0	0.53	469	0.0044	$ -	$ 97,484
Future Midsize	48	1.2	0.02	1.2	0.32	497	0.0047	$ -	$ 101,199

Appendix A.1

SIF LCCA and Emissions Comparisons

Opt 9d - Molinari, Ollis, Midsize Plugin (6.1.7)

Fuel and Emissions		**Total**	vs baseline	
Diesel	gal	9M	-89%	-72.8M
Electricity	kWh	1058M		
NOx	MT	1340	-75%	-3957
HC	MT	76	-84%	-391
PM	MT	33	-71%	-82
CO	MT	262	-72%	-661
CO2	MT	311K	-63%	-534694
SO2	MT	128.6	+1525%	121
Costs - 20 yr NPV		$373.7M	+62%	+$142.3M
Costs - Ops NPV		$212.8M	-8%	-$18.6M
Costs - Capital		$162.0M		

Diesel	(gal/year)	2.2M	1.6M	0.7M	0.7M	0.7M	0.7M	0.7M	0.7M	0.4M	0.4M	0.2M	0.0M	0.0M	0.0M	0.0M	0.0M	0.0M	0.0M	0.0M	0.0M	0.0M
Electricity	(kWh/year)	23M	32M	46M	46M	46M	46M	46M	46M	49M	49M	54M	58M	58M	58M	58M	58M	58M	58M	58M	58M	58M
NOx	(tons/year)	278	206	94	94	94	94	94	94	61	61	37	13	13	13	13	13	13	13	13	13	13
HC	(tons/year)	11	9	6	6	6	6	6	6	6	6	3	0	0	0	0	0	0	0	0	0	0
PM	(tons/year)	6.8	4.9	2.0	2.0	2.0	2.0	2.0	2.0	1.1	1.1	0.9	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
CO	(tons/year)	27	22	15	15	15	15	15	15	13	13	11	9	9	9	9	9	9	9	9	9	9
CO2	(tons/year)	27254	23076	16708	16708	16708	16708	16708	16708	14721	14721	13250	11778	11778	11778	11778	11778	11778	11778	11778	11778	11778
SO2	(tons/year)	3	4	6	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7
Capital		$150.0M	-	-	-	-	-	-	-	-	$12.0M	-	-	-	-	-	-	-	-	-	-	-
Fuel		$5.6M	$4.1M	$1.8M	$1.8M	$1.9M	$1.9M	$1.9M	$2.0M	$1.2M	$1.3M	$.6M	-	-	-	-	-	-	-	-	-	-
Electricity (Energy)		$.9M	$1.2M	$1.7M	$1.7M	$1.7M	$1.7M	$1.7M	$1.7M	$1.8M	$1.8M	$2.0M	$2.2M	$2.2M	$2.2M	$2.2M	$2.2M	$2.2M	$2.2M	$2.2M	$2.2M	$2.2M
Electricity (Demand)		$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M	$6.3M
Maintenance		$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M	$1.8M
Ops Subtotal		$14.5M	$13.4M	$11.6M	$11.6M	$11.6M	$11.7M	$11.7M	$11.8M	$11.2M	$11.2M	$10.7M	$10.2M	$10.2M	$10.2M	$10.2M	$10.2M	$10.3M	$10.3M	$10.3M	$10.3M	$10.2M
Total		$164.5M	$13.4M	$11.6M	$11.6M	$11.6M	$11.7M	$11.7M	$11.8M	$11.2M	$23.2M	$10.7M	$10.2M	$10.2M	$10.2M	$10.2M	$10.2M	$10.3M	$10.3M	$10.3M	$10.3M	$10.2M
PV Total	(discounted to 2020)	$164.5M	$13.2M	$11.3M	$11.2M	$11.2M	$11.1M	$11.0M	$11.0M	$10.3M	$21.2M	$9.7M	$9.2M	$9.1M	$9.0M	$8.9M	$8.8M	$8.7M	$8.7M	$8.6M	$8.5M	$8.4M
PV Ops	(discounted to 2020)	$14.5M	$13.2M	$11.3M	$11.2M	$11.2M	$11.1M	$11.0M	$11.0M	$10.3M	$10.2M	$9.7M	$9.2M	$9.1M	$9.0M	$8.9M	$8.8M	$8.7M	$8.7M	$8.6M	$8.5M	$8.4M
PV Electrici	(discounted to 2020)	$7.1M	$7.4M	$7.8M	$7.7M	$7.6M	$7.6M	$7.5M	$7.4M	$7.5M	$7.4M	$7.5M	$7.5M	$7.5M	$7.4M	$7.3M	$7.3M	$7.2M	$7.1M	$7.1M	$7.0M	$6.9M
PV Fuel		$5.6M																				$1.8M

Opt 9d - Molinari, Ollis, Midsize Plugin (6.1.7)

Fuel and emissions per trip. Capital and maintenance cost per year

	gal	kWh	CO	PM	NOx	HC	CO2	SO2	Capital	Maintenance
Barberi	113		1.2	0.39	14.5	0.33	1167	0.0109	$ -	$ 65,515
Molinari	0	1516	0.2	0.02	0.3	0.01	302	0.1789	$ 75,000,000	$ 700,000
Ollis	0	1687	0.3	0.02	0.4	0.01	353	0.2087	$ 75,000,000	$ 764,127
Austen	45		0.5	0.06	5.0	0.53	469	0.0044	$ -	$ 97,484
Future Midsize	0	858	0.1	0.01	0.2	0.01	171	0.1013	$ 12,000,000	$ 191,667

Highest Electric Demand: 17.7 MW

* Additional capital cost for midsize projected to 2029

Opt 10 - Power Split Molinari (6.1.9)

Fuel and Emissions		**Total**	vs baseline	
Diesel	gal	79M	-4%	-3.2M
NOx	MT	5071	-4%	-226
HC	MT	442	-5%	-24
PM	MT	109	-5%	-6
CO	MT	884	-4%	-38
CO2	MT	812K	-4%	-33,525
SO2	MT	7.6	-4%	-0.3
Costs - 20 yr NPV		$223.1M	-4%	-$8.3M
Costs - Ops NPV		$223.0M	-4%	-$8.4M
Costs - Capital		$.0M		

Diesel	(gal/year)	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.7M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M
NOx	(tons/year)	428	365	259	259	259	259	259	259	240	240	221	202	202	202	202	202	202	202	202	202	202
HC	(tons/year)	26	25	21	21	21	21	21	21	22	22	21	20	20	20	20	20	20	20	20	20	20
PM	(tons/year)	10.1	8.3	5.4	5.4	5.4	5.4	5.4	5.4	4.8	4.8	4.6	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
CO	(tons/year)	47	44	38	38	38	38	38	38	38	38	41	45	45	45	45	45	45	45	45	45	45
CO2	(tons/year)	38322	38384	38666	38666	38666	38666	38666	38666	38508	38508	38647	38786	38786	38786	38786	38786	38786	38786	38786	38786	38786
SO2	(tons/year)	0.359	0.359	0.362	0.362	0.362	0.362	0.362	0.362	0.360	0.360	0.362	0.363	0.363	0.363	0.363	0.363	0.363	0.363	0.363	0.363	0.363
Capital		$.0M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$9.5M	$9.5M	$9.5M	$9.6M	$9.8M	$10.0M	$10.1M	$10.3M	$10.4M	$10.7M	$10.8M	$11.0M	$11.1M	$11.2M	$11.3M	$11.4M	$11.5M	$11.5M	$11.5M	$11.6M	$11.7M
Maintenance		$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M
Ops Subtotal		$10.6M	$10.6M	$10.6M	$10.7M	$10.9M	$11.1M	$11.1M	$11.4M	$11.5M	$11.8M	$11.9M	$12.1M	$12.2M	$12.3M	$12.3M	$12.5M	$12.6M	$12.6M	$12.6M	$12.7M	$12.8M
Total		$10.6M	$10.6M	$10.6M	$10.7M	$10.9M	$11.1M	$11.1M	$11.4M	$11.5M	$11.8M	$11.9M	$12.1M	$12.2M	$12.3M	$12.3M	$12.5M	$12.6M	$12.6M	$12.6M	$12.7M	$12.8M
PV Total	(discounted to 2020)	$10.6M	$10.5M	$10.4M	$10.4M	$10.5M	$10.5M	$10.5M	$10.6M	$10.6M	$10.8M	$10.8M	$10.8M	$10.8M	$10.8M	$10.7M	$10.7M	$10.7M	$10.6M	$10.6M	$10.5M	$10.4M
PV Ops	(discounted to 2020)	$10.6M	$10.5M	$10.4M	$10.4M	$10.5M	$10.5M	$10.5M	$10.6M	$10.6M	$10.8M	$10.8M	$10.8M	$10.8M	$10.8M	$10.7M	$10.7M	$10.7M	$10.6M	$10.6M	$10.5M	$10.4M
PV Fuel		$9.5M																				$9.6M

Opt 10 - Power Split Molinari (6.1.9)

Fuel and emissions per trip. Capital and maintenance cost per year

	gal	CO	PM	NOx	HC	CO2	SO2	Capital	Maintenance
Barberi	113	1.2	0.39	14.5	0.33	1167	0.0109	$ -	$ 65,515
Molinari	99	1.5	0.23	10.1	1.00	1022	0.0096	$ 11,250	$ 345,734
Ollis	114	0.6	0.04	2.3	0.08	1179	0.0110	$ -	$ 474,404
Austen	45	0.5	0.06	5.0	0.53	469	0.0044	$ -	$ 97,484
Future Midsize	48	1.2	0.02	1.2	0.32	497	0.0047	$ -	$ 101,199

Opt 11 - One Minute (Partial - see 5.9.2)

Fuel and Emissions		**Total**	vs baseline	
Diesel	gal	82M	-1%	-427K
Costs - 20 yr NPV		$230.3M	-0%	-$1.1M
Costs - Ops NPV		$230.3M	-0%	-$1.1M
Costs - Capital		-		

Note: this is a partial calculation of fuel savings only, to support discussion of speed changes in Section 5.9.2 of the report

Diesel	(gal/year)	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M	3.9M
NOx	(tons/year)	439	376	270	270	270	270	270	270	251	251	232	213	213	213	213	213	213	213	213	213	213
HC	(tons/year)	27	26	23	23	23	23	23	23	23	23	22	21	21	21	21	21	21	21	21	21	21
PM	(tons/year)	10.4	8.6	5.6	5.6	5.6	5.6	5.6	5.6	5.1	5.1	4.9	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
CO	(tons/year)	49	46	40	40	40	40	40	40	40	40	43	47	47	47	47	47	47	47	47	47	47
CO2	(tons/year)	39955	40017	40173	40173	40173	40173	40173	40173	40141	40141	40279	40418	40418	40418	40418	40418	40418	40418	40418	40418	40418
SO2	(tons/year)	0.374	0.374	0.376	0.376	0.376	0.376	0.376	0.376	0.376	0.376	0.377	0.378	0.378	0.378	0.378	0.378	0.378	0.378	0.378	0.378	0.378
Capital		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$9.8M	$9.9M	$9.9M	$10.0M	$10.2M	$10.3M	$10.4M	$10.7M	$10.8M	$11.1M	$11.2M	$11.4M	$11.5M	$11.6M	$11.7M	$11.8M	$11.9M	$11.9M	$12.0M	$12.0M	$12.1M
Maintenance		$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M	$1.1M
Ops Subtotal		$10.9M	$11.0M	$10.9M	$11.0M	$11.2M	$11.4M	$11.5M	$11.8M	$11.9M	$12.2M	$12.3M	$12.5M	$12.6M	$12.7M	$12.8M	$12.9M	$13.0M	$13.0M	$13.1M	$13.1M	$13.2M
Total		$10.9M	$11.0M	$10.9M	$11.0M	$11.2M	$11.4M	$11.5M	$11.8M	$11.9M	$12.2M	$12.3M	$12.5M	$12.6M	$12.7M	$12.8M	$12.9M	$13.0M	$13.0M	$13.1M	$13.1M	$13.2M
PV Total	(discounted to 2020)	$10.9M	$10.9M	$10.7M	$10.7M	$10.8M	$10.9M	$10.8M	$11.0M	$10.9M	$11.1M	$11.2M	$11.2M	$11.2M	$11.2M	$11.1M	$11.1M	$11.1M	$11.0M	$10.9M	$10.9M	$10.8M
PV Ops	(discounted to 2020)	$10.9M	$10.9M	$10.7M	$10.7M	$10.8M	$10.9M	$10.8M	$11.0M	$10.9M	$11.1M	$11.2M	$11.2M	$11.2M	$11.2M	$11.1M	$11.1M	$11.1M	$11.0M	$10.9M	$10.9M	$10.8M
PV Fuel		$9.8M																				$9.9M

Opt 11 - One Minute (Partial - see 5.9.2)

Fuel and emissions per trip. Capital and maintenance cost per year

	gal	CO	PM	NOx	HC	CO2	SO2	Capital	Maintenance
Barberi	113	1.2	0.39	14.5	0.33	1167	0.0109	$ -	$ 65,515
Molinari	109	1.6	0.25	10.8	1.08	1128	0.0106	$ -	$ 345,734
Ollis	114	0.6	0.04	2.3	0.08	1179	0.0110	$ -	$ 474,404
Austen	45	0.5	0.06	5.0	0.53	469	0.0044	$ -	$ 97,484
Future Midsize	48	1.2	0.02	1.2	0.32	497	0.0047	$ -	$ 101,199

Opt 8b - Tier 3 Hybrid Molinari II (6.1.11)

Fuel and Emissions		**Total**	vs baseline	
Diesel	gal	79M	-4%	-3.3M
NOx	MT	4412	-17%	0.0M
HC	MT	197	-58%	0K
PM	MT	61	-47%	-7
CO	MT	636	-31%	-284
CO2	MT	814K	-4%	-34K
SO2	MT	7.6	-4%	0K
				-$231.4M
Costs - 20 yr NPV		$245.2M	+6%	$13.8M
Costs - Ops NPV		$230.1M	-1%	-1.4M
Costs - Capital		$15.2M		

Diesel	(gal/year)	3.7M	3.7M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.7M	3.7M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M	3.8M
NOx	(tons/year)	396	333	230	230	230	230	230	230	208	208	189	170	170	170	170	170	170	170	170	170	170
HC	(tons/year)	14	13	10	10	10	10	10	10	10	10	9	8	8	8	8	8	8	8	8	8	8
PM	(tons/year)	7.7	6.0	3.2	3.2	3.2	3.2	3.2	3.2	2.4	2.4	2.3	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
CO	(tons/year)	35	32	27	27	27	27	27	27	26	26	29	33	33	33	33	33	33	33	33	33	33
CO2	(tons/year)	38431	38493	38767	38767	38767	38767	38767	38767	38617	38617	38756	38894	38894	38894	38894	38894	38894	38894	38894	38894	38894
SO2	(tons/year)	0.360	0.360	0.363	0.363	0.363	0.363	0.363	0.363	0.361	0.361	0.363	0.364	0.364	0.364	0.364	0.364	0.364	0.364	0.364	0.364	0.364
Capital		$15.2M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$9.5M	$9.6M	$9.6M	$9.7M	$9.9M	$10.0M	$10.1M	$10.4M	$10.4M	$10.7M	$10.9M	$11.0M	$11.1M	$11.3M	$11.3M	$11.4M	$11.5M	$11.5M	$11.6M	$11.6M	$11.7M
Maintenance		$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M	$1.4M
Ops Subtotal		$10.9M	$11.0M	$11.0M	$11.1M	$11.3M	$11.4M	$11.5M	$11.8M	$11.8M	$12.2M	$12.3M	$12.4M	$12.6M	$12.7M	$12.7M	$12.8M	$13.0M	$12.9M	$13.0M	$13.1M	$13.1M
Total		$26.1M	$11.0M	$11.0M	$11.1M	$11.3M	$11.4M	$11.5M	$11.8M	$11.8M	$12.2M	$12.3M	$12.4M	$12.6M	$12.7M	$12.7M	$12.8M	$13.0M	$12.9M	$13.0M	$13.1M	$13.1M
PV Total	(discounted to 2020)	$26.1M	$10.9M	$10.8M	$10.8M	$10.8M	$10.9M	$10.8M	$11.0M	$10.9M	$11.1M	$11.1M	$11.2M	$11.2M	$11.1M	$11.1M	$11.0M	$11.1M	$10.9M	$10.9M	$10.8M	$10.8M
PV Ops	(discounted to 2020)	$10.9M	$10.9M	$10.8M	$10.8M	$10.8M	$10.9M	$10.8M	$11.0M	$10.9M	$11.1M	$11.1M	$11.2M	$11.2M	$11.1M	$11.1M	$11.0M	$11.1M	$10.9M	$10.9M	$10.8M	$10.8M
PV Fuel		$9.5M																				

Opt 8b - Tier 3 Hybrid Molinari II (6.1.11)

Fuel and emissions per trip. Capital and maintenance cost per year

	gal	CO	PM	NOx	HC	CO2	SO2	Capital	Maintenance
Barberi	113	1.22	0.39	14.5	0.33	1167	0.0109	$ -	$ 65,515
Molinari	100	0.72	0.08	8.0	0.23	1029	0.0096	$ 15,165,000	$ 684,374
Ollis	114	0.61	0.04	2.3	0.08	1179	0.0110	$ -	$ 474,404
Austen	45	0.53	0.06	5.0	0.53	469	0.0044	$ -	$ 97,484
Future Midsize	48	1.22	0.02	1.2	0.32	497	0.0047	$ -	$ 101,199

SIF Baseline

Baseline input data is formatted in orange

Baseline formulas are formatted in gray

Format changed input data or formulas

Unconfirmed data is in yellow (baseline or option-specific)

Summary

	Barberi	Molinari	Ollis	Austen	Midsize
Fuel/trip (gal)	113	109	114	45	48
Emissions/trip (kg)					
CO2	1167	1128	1179	469	497
SO2	0.011	0.011	0.011	0.004	0.005
NOx	14.5	10.8	2.3	5.0	1.2
CO	1.2	1.6	0.6	0.5	1.2
HC	0.3	1.1	0.1	0.5	0.3
PM	0.4	0.2	0.0	0.1	0.0
Cost Estimate					
Capital ($)	$ -	$ -	$ -	$ -	$ -
Maintenance ($/yr)	$ 65,515	$ 345,734	$ 474,404	$ 97,484	$ 101,199

Baseline Route Profile

	Total Shaft Power by Class (kw)				
Phase	Molinari	Barberi	Ollis	Austen	Midsize
Transit	3640	3700	4400	1965	2312
Manv	1943	1566	1862	832	979
Push	729	520	618	276	325
Gensets	170	200	200	130	150

Notes:

Power levels above are generator powers where applicable. Efficiency applied below

Molinari profile based on total generator loading reported at the HMI, documented in shipcheck notes

Barberi power based on HMI readings of % power, modified by notes from Ollis design discussions and Barberi tank test data

Austen power based on SIF reporting

Midsize power extrapolated from Barberi and Ollis using Holtrop estimate. Full details in writeup by TSL

Engines and Conversion Efficiencies

	Molinari		Barberi		Ollis		Austen		Midsize	
Engines	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG
# Running	2	1	4	1	4	1	2	1	2	1
MCR (kw)	2983	370	1305	340	1861	430	2350	175	1491	340
MCR (hp)	4000	496	1750	456	2496	577	3151	235	1999	456
Elec. Efficiency	0.96	0.92	1	0.92	1	0.92	1	0.92	1	0.92

Notes:

Molinari operates 2 of 3 installed propulsion generators. All other classes normally operate all propulsion engines.

Electrical efficiency applied to estimate engine load from switchboard readings. Efficiency based on similar generators

Austen propulsion engines are derated based on VSP limits. Full rating used here to accurately calculate SFC

SFC Equations (ref fuel consumption/emissions workbook)

		a	b	c	Description (x=%MCR)	Reference for fit
Molinari	Propulsion	7800	-1.33	182	Power fit with constant offset: ax^b+c	Manufacturer data from 25%-100% MCR. Fit includes additional points <25% calculated from past study data provided by SIF
	SSDG	34600	-1.84	243	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Barberi	Propulsion	0.05	-8.36	581	Quadratic fit: ax^2+bx+c	Manufacturer data sheet. Sheet based on engine RPM and cubic propeller law. % of rated RPM used to estimate %MCR
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Ollis	Propulsion	2512	-1.30	193	Power fit with constant offset: ax^b+c	FAT for Ollis engines documented by SIF owner's representative
	SSDG	5130	-1.26	246	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 C18
Austen	Propulsion	104	-0.44	184	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 3516
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Midsize	Propulsion	0.02	-3.14	290	Quadratic fit: ax^2+bx+c	Simplified from manufacturer's data sheet
	SSDG	0.019	-3.31	406	Quadratic fit: ax^2+bx+c	Based on CAT Tier 3 C18

Engine Load Point, SFC

	Molinari	Barberi	Ollis	Austen	Midsize	Notes
	bkw per engine					Load per engine calculated from route profile, electrical efficiency, and number of engines operating
Transit	1896	925	1100	983	1156	
Manv	1012	392	466	416	489	
Push	380	130	155	138	162	
Gensets	185	217	217	141	163	
	% MCR					Based on engine ratings listed above
Transit	64	71	59	42	78	
Manv	34	30	25	18	33	
Push	13	10	8	6	11	
Gensets	50	64	51	81	48	
	SFC (g/kwh)					Calculated from %MCR using fit curve types and coefficients listed above
Transit	213	238	206	204	167	
Manv	254	375	231	214	208	
Push	447	503	354	232	258	
Gensets	269	241	283	236	290	

Brake-Specific Criteria Emissions Factors (BSEF) Load-Dependent Fit Equations

Enter cycle weighted emissions target (g/kwh) in orange cells (EPA limit or other value)

Molinari	*Prop.*		a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	6.5	NOx	0.0013	-0.20	13.0	6.5	20.2	NOx	0.0040	-0.61	40.4	20.1
	1.1	CO	0.0002	-0.03	2.2	1.1	1.3	CO	0.0003	-0.04	2.6	1.3
	0.70	HC	0.0001	-0.02	1.4	0.70	1.27	HC	0.0003	-0.04	2.5	1.27
	0.17	PM	0.0000	-0.01	0.3	0.17	0.44	PM	0.0001	-0.01	0.9	0.44
Barberi	*Prop.*		a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	10.2	NOx	0.0020	-0.31	20.4	10.1	20.2	NOx	0.0040	-0.61	40.4	20.1
	0.9	CO	0.0002	-0.03	1.8	0.9	1.3	CO	0.0003	-0.04	2.6	1.3
	0.17	HC	0.0000	-0.01	0.3	0.17	1.27	HC	0.0003	-0.04	2.5	1.27
	0.28	PM	0.0001	-0.01	0.6	0.28	0.44	PM	0.0001	-0.01	0.9	0.44
Ollis	*Prop.*		a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
	0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
	0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
	0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10
Austen	*Prop.*		a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	5.0	NOx	0.0010	-0.15	10.0	5.0	20.2	NOx	0.0040	-0.61	40.4	20.1
	0.6	CO	0.0001	-0.02	1.2	0.6	1.3	CO	0.0003	-0.04	2.6	1.3
	0.60	HC	0.0001	-0.02	1.2	0.60	1.27	HC	0.0003	-0.04	2.5	1.27
	0.04	PM	0.0000	0.00	0.1	0.04	0.44	PM	0.0001	-0.01	0.9	0.44
Midsize	*Prop.*		a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
	0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
	0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
	0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10

Notes:

Orange target values are based on manufacturer's certified data, where available. Where unavailable, values published by the EPA for the equivalent engine model were used.

At Tier 4, the HC limit is 10% of the combined HC+NOx limit. This ratio was used to estimate HC emissions for earlier tiers where no HC data was reported.

Quadratic fit curve coefficients are calculated above to estimate the load dependence of emissions factors. The general shape of these curves is based on a CAT 3516 Tier 3 engine for which complete emissions vs. load data was available.

The "Cycle Average" uses the BSEF predicted by the quadratic fit coefficients for specific load points with the weighting factors specified in the EPA rules for calculating emissions. See 40 CFR §1042 for additional details.

BSEF at Operating Profile Load Points

(g/kwh)	Molinari	Barberi	Ollis	Austen	Midsize
		NOx			
Transit	5.9	9.0	1.0	5.5	1.0
Manv	7.9	13.1	1.5	7.7	1.4
Push	10.7	17.6	1.9	9.2	1.9
Gensets	20.2	18.2	5.1	17.8	5.3
		CO			
Transit	1.0	0.8	0.3	0.7	1.0
Manv	1.3	1.1	0.4	0.9	1.4
Push	1.8	1.5	0.5	1.1	1.9
Gensets	1.3	1.2	1.3	1.1	5.3
		HC			
Transit	0.63	0.15	0.01	0.66	0.26
Manv	0.85	0.22	0.01	0.92	0.37
Push	1.16	0.29	0.02	1.10	0.51
Gensets	1.28	1.15	0.61	1.12	1.33
		PM			
Transit	0.15	0.25	0.02	0.04	0.02
Manv	0.21	0.36	0.03	0.06	0.02
Push	0.28	0.48	0.04	0.07	0.03
Gensets	0.17	0.39	0.10	0.39	0.11

Note: calculated from quadratic coefficients on previous sheet and the engine's operating point (%MCR) at that phase of the operating profile

Total Energy, Fuel, Emissions Per Trip

Route profile (time per phase, minutes)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	19	18	19	15	15
Manv	3	4	3	7	7
Push	8	8	8	8	8
Gensets	30	30	30	30	30

Total Trip Energy (all engines) (kwh)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1201	1110	1393	491	578
Manv	101	104	93	97	114
Push	101	69	82	37	43
Gensets	92	109	109	71	82
Total	1496	1392	1678	696	817

Notes:
Route profile times were based on shipcheck notes.
Energy calculated from product of profile times and power

Total Trip Fuel (kg)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	256	264	286	100	96
Manv	26	39	22	21	24
Push	45	35	29	9	11
Gensets	25	26	31	17	24
Total	352	364	368	146	155

Total Trip Fuel (gal)

	Molinari	Barberi	Ollis	Austen	Midsize
Fuel	109	113	114	45	48

CO2 and SO2 per Trip

	Molinari	Barberi	Ollis	Austen	Midsize
CO2 (kg)	1128	1167	1179	469	497
SO2 (kg)	0.011	0.011	0.011	0.004	0.005

Fuel calculated from each engine's SFC, power level, and time
kg CO2 = 3.206 · kg diesel (MEPC 67/INF.3: Third IMO GHG Study, MGO value)
SO2 from mass balance using 15 ppm S oxidized to SO2

Diesel density = 3.218 kg/gal

Criteria Emissions per Trip (kg)

kg = BSEF · power level · no. engines

NOx

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	7.0	9.9	1.4	2.7	0.6
Manv	0.8	1.4	0.1	0.7	0.2
Push	1.1	1.2	0.2	0.3	0.1
Gensets	1.9	2.0	0.6	1.3	0.4

CO

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1.2	0.9	0.4	0.3	0.6
Manv	0.1	0.1	0.0	0.1	0.2
Push	0.2	0.1	0.0	0.0	0.1
Gensets	0.1	0.1	0.1	0.1	0.4

HC

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.76	0.17	0.01	0.32	0.15
Manv	0.09	0.02	0.00	0.09	0.04
Push	0.12	0.02	0.00	0.04	0.02
Gensets	0.12	0.12	0.07	0.08	0.11

PM

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.18	0.27	0.03	0.02	0.010
Manv	0.02	0.04	0.00	0.01	0.003
Push	0.03	0.03	0.00	0.00	0.001
Gensets	0.02	0.04	0.01	0.03	0.009

Capital Cost Estimate

Equipment	Molinari Qty	Molinari Cost (ea)	Molinari Cost	Barberi Qty	Barberi Cost (ea)	Barberi Cost	Ollis Qty	Ollis Cost (ea)	Ollis Cost	Austen Qty	Austen Cost (ea)	Austen Cost	Midsize Qty	Midsize Cost (ea)	Midsize Cost
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Subtotal			$ -			$ -			$ -			$ -			$ -
Installation (@50%)			$ -			$ -			$ -			$ -			$ -
Total			$ -			$ -			$ -			$ -			$ -

Maintenance Cost Estimate

Item	Interval	Units	Molinari Cost (ea)	Molinari Cost	Barberi Cost (ea)	Barberi Cost	Ollis Cost (ea)	Ollis Cost	Austen Cost (ea)	Austen Cost	Midsize Cost (ea)	Midsize Cost
Main Propulsion Diesel Engine (engine hrs/yr)			15054		3796		27664		4940		4940	
Lube Oil Change	4000	hrs	$ 6,500	$ 24,462	$ 6,500	$ 6,169	$ 6,500	$ 44,954	$ 6,500	$ 8,028	$ 6,500	$ 8,028
Minor Overhaul	8000	hrs	$ 37,000	$ 69,623	$ 37,000	$ 17,558	$ 37,000	$ 127,947	$ 37,000	$ 22,848	$ 37,000	$ 22,848
Major Overhaul	30000	hrs	$ 242,000	$ 121,433	$ 242,000	$ 30,624	$ 242,000	$ 223,158	$ 242,000	$ 39,849	$ 242,000	$ 39,849
Alternator Overhaul	10	yrs	$ 50,000	$ 45,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Ship Service Diesel Generator (engine hrs/yr)			7527		949		6916		2470		2470	
Lube Oil Change	1000	hrs	$ 500	$ 3,763	$ 500	$ 475	$ 500	$ 3,458	$ 500	$ 1,235	$ 500	$ 1,235
Minor Overhaul	20000	hrs	$ 50,000	$ 18,817	$ 50,000	$ 2,373	$ 50,000	$ 17,290	$ 50,000	$ 6,175	$ 50,000	$ 6,175
Major Overhaul	20000	hrs	$ 100,000	$ 37,634	$ 100,000	$ 4,745	$ 100,000	$ 34,580	$ 100,000	$ 12,350	$ 100,000	$ 12,350
Alternator Overhaul	10	yrs	$ 25,000	$ 15,000	$ 25,000	$ 2,143	$ 25,000	$ 13,810	$ 25,000	$ 5,000	$ 25,000	$ 7,143
General												
Hull Coating	3	yrs	$ 10,000	$ 10,000	$ 10,000	$ 1,429	$ 10,000	$ 9,206	$ 6,000	$ 2,000	$ 7,500	$ 3,571
Average ($/yr)				$ 345,734		$ 65,515		$ 474,404		$ 97,484		$ 101,199

Notes

Hours/year are an average value from 2020-2040

SIF B20 Analysis

Baseline input data is formatted in orange

Baseline formulas are formatted in gray

Format changed input data or formulas

Unconfirmed data is in yellow (baseline or option-specific)

Summary

	Barberi	Molinari	Ollis	Austen	Midsize
Fuel/trip (gal)	114	110	115	46	49
Emissions/trip (kg)					
CO2	1050	1015	1061	422	447
SO2	0.009	0.008	0.009	0.004	0.004
NOx	14.8	11.0	2.3	5.1	1.2
CO	1.0	1.4	0.5	0.5	1.0
HC	0.3	0.9	0.1	0.5	0.3
PM	0.3	0.2	0.0	0.0	0.0
Cost Estimate					
Capital ($)	$ 25,442	$ 268,011	$ 63,679	$ 30,672	$ -
Maintenance ($/yr)	$ 65,515	$ 345,734	$ 474,404	$ 97,484	$ 101,199

Baseline Route Profile

Total Shaft Power by Class (kw)

Phase	Molinari	Barberi	Ollis	Austen	Midsize
Transit	3640	3700	4400	1965	2312
Manv	1943	1566	1862	832	979
Push	729	520	618	276	325
Gensets	170	200	200	130	150

Notes:

Power levels above are generator powers where applicable. Efficiency applied below

Molinari profile based on total generator loading reported at the HMI, documented in shipcheck notes

Barberi power based on HMI readings of % power, modified by notes from Ollis design discussions and Barberi tank test data

Austen power based on SIF reporting

Midsize power extrapolated from Barberi and Ollis using Holtrop estimate. Full details in writeup by TSL

Engines and Conversion Efficiencies

	Molinari		Barberi		Ollis		Austen		Midsize	
Engines	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG
# Running	2	1	4	1	4	1	2	1	2	1
MCR (kw)	2983	370	1305	340	1861	430	2350	175	1491	340
MCR (hp)	**4000**	**496**	**1750**	**456**	**2496**	**577**	**3151**	**235**	**1999**	**456**
Elec. Efficiency	0.96	0.92	1	0.92	1	0.92	1	0.92	1	0.92

Notes:

Molinari operates 2 of 3 installed propulsion generators. All other classes normally operate all propulsion engines.

Electrical efficiency applied to estimate engine load from switchboard readings. Efficiency based on similar generators

SFC Equations (ref fuel consumption/emissions workbook)

		a	b	c	Description (x=%MCR)	Reference for fit
Molinari	Propulsion	7800	-1.33	182	Power fit with constant offset: ax^b+c	Manufacturer data from 25%-100% MCR. Fit includes additional points <25% calculated from past study data provided by SIF
	SSDG	34600	-1.84	243	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Barberi	Propulsion	0.05	-8.36	581	Quadratic fit: ax^2+bx+c	Manufacturer data sheet. Sheet based on engine RPM and cubic propeller law. % of rated RPM used to estimate %MCR
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Ollis	Propulsion	2512	-1.30	193	Power fit with constant offset: ax^b+c	FAT for Ollis engines documented by SIF owner's representative
	SSDG	5130	-1.26	246	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 C18
Austen	Propulsion	104	-0.44	184	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 3516
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Midsize	Propulsion	0.02	-3.14	290	Quadratic fit: ax^2+bx+c	Simplified from manufacturer's data sheet
	SSDG	0.019	-3.31	406	Quadratic fit: ax^2+bx+c	Based on CAT Tier 3 C18

Engine Load Point, SFC

	Molinari	Barberi	Ollis	Austen	Midsize	Notes
bkw per engine						Load per engine calculated from route profile, electrical efficiency, and number of engines operating
Transit	1,896	925	1,100	983	1,156	
Manv	1,012	392	466	416	489	
Push	380	130	155	138	162	
Gensets	185	217	217	141	163	
% MCR						Based on engine ratings listed above
Transit	64	71	59	42	78	
Manv	34	30	25	18	33	
Push	13	10	8	6	11	
Gensets	50	64	51	81	48	
SFC (g/kwh)						Calculated from %MCR using fit curve types and coefficients listed above
Transit	213	238	206	204	167	
Manv	254	375	231	214	208	
Push	447	503	354	232	258	
Gensets	269	241	283	236	290	

Brake-Specific Criteria Emissions Factors (BSEF) Load-Dependent Fit Equations

Enter cycle weighted emissions target in orange cells (EPA limit or other value)

Molinari	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
6.5	NOx	0.0013	-0.20	13.0	6.5	20.2	NOx	0.0040	-0.61	40.4	20.1
1.1	CO	0.0002	-0.03	2.2	1.1	1.3	CO	0.0003	-0.04	2.6	1.3
0.70	HC	0.0001	-0.02	1.4	0.70	1.27	HC	0.0003	-0.04	2.5	1.27
0.17	PM	0.0000	-0.01	0.3	0.17	0.44	PM	0.0001	-0.01	0.9	0.44
Barberi	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
10.2	NOx	0.0020	-0.31	20.4	10.1	20.2	NOx	0.0040	-0.61	40.4	20.1
0.9	CO	0.0002	-0.03	1.8	0.9	1.3	CO	0.0003	-0.04	2.6	1.3
0.17	HC	0.0000	-0.01	0.3	0.17	1.27	HC	0.0003	-0.04	2.5	1.27
0.28	PM	0.0001	-0.01	0.6	0.28	0.44	PM	0.0001	-0.01	0.9	0.44
Ollis	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10
Austen	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
5.0	NOx	0.0010	-0.15	10.0	5.0	20.2	NOx	0.0040	-0.61	40.4	20.1
0.6	CO	0.0001	-0.02	1.2	0.6	1.3	CO	0.0003	-0.04	2.6	1.3
0.60	HC	0.0001	-0.02	1.2	0.60	1.27	HC	0.0003	-0.04	2.5	1.27
0.04	PM	0.0000	0.00	0.1	0.04	0.44	PM	0.0001	-0.01	0.9	0.44
Midsize	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10

Notes:

Orange target values are based on manufacturer's certified data, where available. Where unavailable, values published by the EPA for the equivalent engine model were used.

At Tier 4, the HC limit is 10% of the combined HC+NOx limit. This ratio was used to estimate HC emissions for earlier tiers where no HC data was reported.

Quadratic fit curve coefficients are calculated above to estimate the load dependence of emissions factors. The general shape of these curves is based on a CAT 3516 Tier 3 engine for which complete emissions vs. load data was available.

The "Cycle Average" uses the BSEF predicted by the quadratic fit coefficients for specific load points with the weighting factors specified in the EPA rules for calculating emissions. See 40 CFR §1042 for additional details.

Changes to emissions for biodiesel are applied to total trip emissions below.

BSEF at Operating Profile Load Points

	Molinari	Barberi	Ollis	Austen	Midsize
		NOx			
Transit	5.9	9.0	1.0	5.5	1.0
Manv	7.9	13.1	1.5	7.7	1.4
Push	10.7	17.6	1.9	9.2	1.9
Gensets	20.2	18.2	5.1	17.8	5.3
		CO			
Transit	1.0	0.8	0.3	0.7	1.0
Manv	1.3	1.1	0.4	0.9	1.4
Push	1.8	1.5	0.5	1.1	1.9
Gensets	1.3	1.2	1.3	1.1	5.3
		HC			
Transit	0.63	0.15	0.01	0.66	0.26
Manv	0.85	0.22	0.01	0.92	0.37
Push	1.16	0.29	0.02	1.10	0.51
Gensets	1.28	1.15	0.61	1.12	1.33
		PM			
Transit	0.15	0.25	0.02	0.04	0.02
Manv	0.21	0.36	0.03	0.06	0.02
Push	0.28	0.48	0.04	0.07	0.03
Gensets	0.17	0.39	0.10	0.39	0.11

Note: calculated from quadratic coefficients on previous sheet and the engine's operating point (%MCR) at that phase of the operating profile

Total Energy, Fuel, Emissions Per Trip

Route profile (time per phase, minutes)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	19	18	19	15	15
Manv	3	4	3	7	7
Push	8	8	8	8	8
Gensets	30	30	30	30	30

Total Trip Energy (all engines) (kwh)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1201	1110	1393	491	578
Manv	101	104	93	97	114
Push	101	69	82	37	43
Gensets	92	109	109	71	82
Total	1496	1392	1678	696	817

Notes:
Route profile times were based on shipcheck notes.
Energy calculated from product of profile times and power

Total Trip Fuel (kg)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	256	264	286	100	96
Manv	26	39	22	21	24
Push	45	35	29	9	11
Gensets	25	26	31	17	24
Total	352	364	368	146	155

Total Trip Fuel (gal)

	Molinari	Barberi	Ollis	Austen	Midsize
Fuel	110	114	115	46	49

+1% for B20 lower energy density

CO2 and SO2 per Trip

	Molinari	Barberi	Ollis	Austen	Midsize
CO2 (kg)	1015	1050	1061	422	447
SO2 (kg)	0.008	0.009	0.009	0.004	0.004

CO2 Reduced by 10% (50% CO2 emissions for 20% B100)
SO2 Reduced by 20% (B100 component of fuel has zero sulfur)

Fuel calculated from each engine's SFC, power level, and time
kg CO2 = 3.206 · kg diesel (MEPC 67/INF.3: Third IMO GHG Study, MGO value)
SO2 from mass balance using 15 ppm S oxidized to SO2

Diesel density = 3.218 kg/gal

Criteria Emissions per Trip (kg)

kg = BSEF · power level · no. engines

NOx

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	7.0	9.9	1.4	2.7	0.6
Manv	0.8	1.4	0.1	0.7	0.2
Push	1.1	1.2	0.2	0.3	0.1
Gensets	1.9	2.0	0.6	1.3	0.4

CO

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1.2	0.9	0.4	0.3	0.6
Manv	0.1	0.1	0.0	0.1	0.2
Push	0.2	0.1	0.0	0.0	0.1
Gensets	0.1	0.1	0.1	0.1	0.4

HC

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.76	0.17	0.01	0.32	0.15
Manv	0.09	0.02	0.00	0.09	0.04
Push	0.12	0.02	0.00	0.04	0.02
Gensets	0.12	0.12	0.07	0.08	0.11

PM

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.18	0.27	0.03	0.02	0.010
Manv	0.02	0.04	0.00	0.01	0.003
Push	0.03	0.03	0.00	0.00	0.001
Gensets	0.02	0.04	0.01	0.03	0.009

Capital Cost Estimate

	Molinari			Barberi			Ollis			Austen			Midsize		
Equipment	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
Engineering	1	$ 5,000	$ 5,000	1	$ 5,000	$ 5,000	1	$ 5,000	$ 5,000	1	$ 5,000	$ 5,000		$ -	$ -
Fuel System Mods	3	$ 5,000	$ 15,000	1	$ 5,000	$ 5,000	3	$ 5,000	$ 15,000	2	$ 5,000	$ 10,000		$ -	$ -
Tank Cleaning	3	$ 9,281	$ 27,842	1	$ 11,202	$ 11,202	3	$ 11,022	$ 33,066	2	$ 5,280	$ 10,560		$ -	$ -
Barge Cleaning	1	$ 175,500	$ 175,500		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Subtotal			$ 223,342			$ 21,202			$ 53,066			$ 25,560			$ -
Total Installation Cost (@20%)			$ 44,668			$ 4,240			$ 10,613			$ 5,112			$ -
Total			$ 268,011			$ 25,442			$ 63,679			$ 30,672			$ -

Notes:

Cleaning cost based on $.30/gal of tank capacity. Ref MARAD biodiesel report for WSF's costs

Barge cleaning applies to whole fleet. Included in Molinari class for calculation purposes

Maintenance Cost Estimate

			Molinari		Barberi		Ollis		Austen		Midsize	
Item	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost
Main Propulsion Diesel Engine (engine hrs/yr)			15054		3796		27664		4940		4940	
Lube Oil Change	4000	hrs	$ 6,500	$ 24,462	$ 6,500	$ 6,169	$ 6,500	$ 44,954	$ 6,500	$ 8,028	$ 6,500	$ 8,028
Minor Overhaul	8000	hrs	$ 37,000	$ 69,623	$ 37,000	$ 17,558	$ 37,000	$ 127,947	$ 37,000	$ 22,848	$ 37,000	$ 22,848
Major Overhaul	30000	hrs	$ 242,000	$ 121,433	$ 242,000	$ 30,624	$ 242,000	$ 223,158	$ 242,000	$ 39,849	$ 242,000	$ 39,849
Alternator Overhaul	10	yrs	$ 50,000	$ 45,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Ship Service Diesel Generator (engine hrs/yr)			7527		949		6916		2470		2470	
Lube Oil Change	1000	hrs	$ 500	$ 3,763	$ 500	$ 475	$ 500	$ 3,458	$ 500	$ 1,235	$ 500	$ 1,235
Minor Overhaul	20000	hrs	$ 50,000	$ 18,817	$ 50,000	$ 2,373	$ 50,000	$ 17,290	$ 50,000	$ 6,175	$ 50,000	$ 6,175
Major Overhaul	20000	hrs	$ 100,000	$ 37,634	$ 100,000	$ 4,745	$ 100,000	$ 34,580	$ 100,000	$ 12,350	$ 100,000	$ 12,350
Alternator Overhaul	10	yrs	$ 25,000	$ 15,000	$ 25,000	$ 2,143	$ 25,000	$ 13,810	$ 25,000	$ 5,000	$ 25,000	$ 7,143
General												
Hull Coating	3	yrs	$ 10,000	$ 10,000	$ 10,000	$ 1,429	$ 10,000	$ 9,206	$ 6,000	$ 2,000	$ 7,500	$ 3,571
Average ($/yr)				$ 345,734		$ 65,515		$ 474,404		$ 97,484		$ 101,199

Notes

Hours/year are an average value from 2020-2040

Summary	Molinari	Barberi	Ollis	Austen	Midsize	
Fuel/trip (gal)	110	114	115	46	49	
		Emissions/trip (kg)				
CO2	1015	1050	1061	422	447	
SO2	0.008	0.009	0.009	0.004	0.004	
NOx	11.0	14.8	2.3	5.1	1.2	2% added to total
CO	1.4	1.0	0.5	0.5	1.0	-15% from total
HC	0.9	0.3	0.1	0.5	0.3	-15% from total
PM	0.2	0.3	0.0	0.0	0.0	-15% from total
		Cost Estimate				
Capital ($)	$ 268,011	$ 25,442	$ 63,679	$ 30,672	$ -	
Maintenance ($/yr)	$ 345,734	$ 65,515	$ 474,404	$ 97,484	$ 101,199	

Summary

	Barberi	Molinari	Ollis	Austen	Midsize
Fuel/trip (gal)	113	109	114	45	48
Emissions/trip (kg)					
CO2	788	761	796	317	336
SO2	0.005	0.005	0.006	0.002	0.002
NOx	14.1	10.5	2.2	4.9	1.2
CO	1.0	1.4	0.5	0.5	1.0
HC	0.3	0.9	0.1	0.5	0.3
PM	0.3	0.2	0.0	0.0	0.0
Cost Estimate					
Capital ($)	$ -	$ -	$ -	$ -	$ -
Maintenance ($/yr)	$ 65,515	$ 345,734	$ 474,404	$ 97,484	$ 101,199

Baseline input data is formatted in orange
Baseline formulas are formatted in gray
Format changed input data or formulas
Unconfirmed data is in yellow (baseline or option-specific)

Baseline Route Profile

	Total Shaft Power by Class (kw)				
Phase	Molinari	Barberi	Ollis	Austen	Midsize
Transit	3640	3700	4400	1965	2312
Manv	1943	1566	1862	832	979
Push	729	520	618	276	325
Gensets	170	200	200	130	150

Notes:
Power levels above are generator powers where applicable. Efficiency applied below
Molinari profile based on total generator loading reported at the HMI, documented in shipcheck notes
Barberi power based on HMI readings of % power, modified by notes from Ollis design discussions and Barberi tank test data
Austen power based on SIF reporting
Midsize power extrapolated from Barberi and Ollis using Holtrop estimate. Full details in writeup by TSL

Engines and Conversion Efficiencies

	Molinari		Barberi		Ollis		Austen		Midsize	
Engines	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG
# Running	2	1	4	1	4	1	2	1	2	1
MCR (kw)	2983	370	1305	340	1861	430	2350	175	1491	340
MCR (hp)	4000	496	1750	456	2496	577	3151	235	1999	456
Elec. Efficiency	0.96	0.92	1	0.92	1	0.92	1	0.92	1	0.92

Notes:
Molinari operates 2 of 3 installed propulsion generators. All other classes normally operate all propulsion engines.
Electrical efficiency applied to estimate engine load from switchboard readings. Efficiency based on similar generators

SFC Equations (ref fuel consumption/emissions workbook)

		a	b	c	Description (x=%MCR)	Reference for fit
Molinari	Propulsion	7800	-1.33	182	Power fit with constant offset: ax^b+c	Manufacturer data from 25%-100% MCR. Fit includes additional points <25% calculated from past study data provided by SIF
	SSDG	34600	-1.84	243	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Barberi	Propulsion	0.05	-8.36	581	Quadratic fit: ax^2+bx+c	Manufacturer data sheet. Sheet based on engine RPM and cubic propeller law. % of rated RPM used to estimate %MCR
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Ollis	Propulsion	2512	-1.30	193	Power fit with constant offset: ax^b+c	FAT for Ollis engines documented by SIF owner's representative
	SSDG	5130	-1.26	246	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 C18
Austen	Propulsion	104	-0.44	184	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 3516
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Midsize	Propulsion	0.02	-3.14	290	Quadratic fit: ax^2+bx+c	Simplified from manufacturer's data sheet
	SSDG	0.019	-3.31	406	Quadratic fit: ax^2+bx+c	Based on CAT Tier 3 C18

Engine Load Point, SFC

	Molinari	Barberi	Ollis	Austen	Midsize	Notes
	bkw per engine					Load per engine calculated from route profile, electrical efficiency, and number of engines operating
Transit	1896	925	1100	983	1156	
Manv	1012	392	466	416	489	
Push	380	130	155	138	162	
Gensets	185	217	217	141	163	
	% MCR					Based on engine ratings listed above
Transit	64	71	59	42	78	
Manv	34	30	25	18	33	
Push	13	10	8	6	11	
Gensets	50	64	51	81	48	
	SFC (g/kwh)					Calculated from %MCR using fit curve types and coefficients listed above
Transit	213	238	206	204	167	
Manv	254	375	231	214	208	
Push	447	503	354	232	258	
Gensets	269	241	283	236	290	

Brake-Specific Criteria Emissions Factors (BSEF) Load-Dependent Fit Equations

Enter cycle weighted emissions target in orange cells (EPA limit or other value)

Molinari		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	6.5	NOx	0.0013	-0.20	13.0	6.5	20.2	NOx	0.0040	-0.61	40.4	20.1
	1.1	CO	0.0002	-0.03	2.2	1.1	1.3	CO	0.0003	-0.04	2.6	1.3
	0.70	HC	0.0001	-0.02	1.4	0.70	1.27	HC	0.0003	-0.04	2.5	1.27
	0.17	PM	0.0000	-0.01	0.3	0.17	0.44	PM	0.0001	-0.01	0.9	0.44
Barberi		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	10.2	NOx	0.0020	-0.31	20.4	10.1	20.2	NOx	0.0040	-0.61	40.4	20.1
	0.9	CO	0.0002	-0.03	1.8	0.9	1.3	CO	0.0003	-0.04	2.6	1.3
	0.17	HC	0.0000	-0.01	0.3	0.17	1.27	HC	0.0003	-0.04	2.5	1.27
	0.28	PM	0.0001	-0.01	0.6	0.28	0.44	PM	0.0001	-0.01	0.9	0.44
Ollis		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
	0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
	0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
	0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10
Austen		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	5.0	NOx	0.0010	-0.15	10.0	5.0	20.2	NOx	0.0040	-0.61	40.4	20.1
	0.6	CO	0.0001	-0.02	1.2	0.6	1.3	CO	0.0003	-0.04	2.6	1.3
	0.60	HC	0.0001	-0.02	1.2	0.60	1.27	HC	0.0003	-0.04	2.5	1.27
	0.04	PM	0.0000	0.00	0.1	0.04	0.44	PM	0.0001	-0.01	0.9	0.44
Midsize		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
	0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
	0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
	0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10

Notes:

Orange target values are based on manufacturer's certified data, where available. Where unavailable, values published by the EPA for the equivalent engine model were used.

At Tier 4, the HC limit is 10% of the combined HC+NOx limit. This ratio was used to estimate HC emissions for earlier tiers where no HC data was reported.

Quadratic fit curve coefficients are calculated above to estimate the load dependence of emissions factors. The general shape of these curves is based on a CAT 3516 Tier 3 engine for which complete emissions vs. load data was available.

The "Cycle Average" uses the BSEF predicted by the quadratic fit coefficients for specific load points with the weighting factors specified in the EPA rules for calculating emissions. See 40 CFR §1042 for additional details.

Changes to emissions for renewable diesel are applied to total trip emissions below.

BSEF at Operating Profile Load Points

	Molinari	Barberi	Ollis	Austen	Midsize
		NOx			
Transit	5.9	9.0	1.0	5.5	1.0
Manv	7.9	13.1	1.5	7.7	1.4
Push	10.7	17.6	1.9	9.2	1.9
Gensets	20.2	18.2	5.1	17.8	5.3
		CO			
Transit	1.0	0.8	0.3	0.7	1.0
Manv	1.3	1.1	0.4	0.9	1.4
Push	1.8	1.5	0.5	1.1	1.9
Gensets	1.3	1.2	1.3	1.1	5.3
		HC			
Transit	0.63	0.15	0.01	0.66	0.26
Manv	0.85	0.22	0.01	0.92	0.37
Push	1.16	0.29	0.02	1.10	0.51
Gensets	1.28	1.15	0.61	1.12	1.33
		PM			
Transit	0.15	0.25	0.02	0.04	0.02
Manv	0.21	0.36	0.03	0.06	0.02
Push	0.28	0.48	0.04	0.07	0.03
Gensets	0.17	0.39	0.10	0.39	0.11

Note: calculated from quadratic coefficients on previous sheet and the engine's operating point (%MCR) at that phase of the operating profile

Total Energy, Fuel, Emissions Per Trip

Route profile (time per phase, minutes)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	19	18	19	15	15
Manv	3	4	3	7	7
Push	8	8	8	8	8
Gensets	30	30	30	30	30

Total Trip Energy (all engines) (kwh)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1201	1110	1393	491	578
Manv	101	104	93	97	114
Push	101	69	82	37	43
Gensets	92	109	109	71	82
Total	1496	1392	1678	696	817

Notes:

Route profile times were based on shipcheck notes.

Energy calculated from product of profile times and power

Total Trip Fuel (kg)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	256	264	286	100	96
Manv	26	39	22	21	24
Push	45	35	29	9	11
Gensets	25	26	31	17	24
Total	352	364	368	146	155

Total Trip Fuel (gal)

	Molinari	Barberi	Ollis	Austen	Midsize
Fuel	109	113	114	45	48

CO2 and SO2 per Trip

	Molinari	Barberi	Ollis	Austen	Midsize
CO2 (kg)	761	788	796	317	336
SO2 (kg)	0.011	0.011	0.011	0.004	0.005

Blend level	CI of R100	O2 Reduction
50	35	33%

Fuel calculated from each engine's SFC, power level, and time

kg CO2 = 3.206 · kg diesel (MEPC 67/INF.3: Third IMO GHG Study, MGO value)

SO2 from mass balance using 15 ppm S oxidized to SO2

Carbon intensity described in Sections 2.2.3 and 5.3.4

Diesel density = 3.218 kg/gal

Criteria Emissions per Trip (kg)

NOx

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	7.0	9.9	1.4	2.7	0.6
Manv	0.8	1.4	0.1	0.7	0.2
Push	1.1	1.2	0.2	0.3	0.1
Gensets	1.9	2.0	0.6	1.3	0.4

CO

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1.2	0.9	0.4	0.3	0.6
Manv	0.1	0.1	0.0	0.1	0.2
Push	0.2	0.1	0.0	0.0	0.1
Gensets	0.1	0.1	0.1	0.1	0.4

HC

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.76	0.17	0.01	0.32	0.15
Manv	0.09	0.02	0.00	0.09	0.04
Push	0.12	0.02	0.00	0.04	0.02
Gensets	0.12	0.12	0.07	0.08	0.11

PM

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.18	0.27	0.03	0.02	0.010
Manv	0.02	0.04	0.00	0.01	0.003
Push	0.03	0.03	0.00	0.00	0.001
Gensets	0.02	0.04	0.01	0.03	0.009

kg = BSEF · power level · no. engines

Capital Cost Estimate

	Molinari			Barberi			Ollis			Austen			Midsize		
Equipment	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Subtotal			$ -			$ -			$ -			$ -			$ -
Installation (@50%)			$ -			$ -			$ -			$ -			$ -
Total			$ -			$ -			$ -			$ -			$ -

Maintenance Cost Estimate

			Molinari		Barberi		Ollis		Austen		Midsize	
Item	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost
Main Propulsion Diesel Engine (engine hrs/yr)			15054		3796		27664		4940		4940	
Lube Oil Change	4000	hrs	$ 6,500	$ 24,462	$ 6,500	$ 6,169	$ 6,500	$ 44,954	$ 6,500	$ 8,028	$ 6,500	$ 8,028
Minor Overhaul	8000	hrs	$ 37,000	$ 69,623	$ 37,000	$ 17,558	$ 37,000	$ 127,947	$ 37,000	$ 22,848	$ 37,000	$ 22,848
Major Overhaul	30000	hrs	$ 242,000	$ 121,433	$ 242,000	$ 30,624	$ 242,000	$ 223,158	$ 242,000	$ 39,849	$ 242,000	$ 39,849
Alternator Overhaul	10	yrs	$ 50,000	$ 45,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Ship Service Diesel Generator (engine hrs/yr)			7527		949		6916		2470		2470	
Lube Oil Change	1000	hrs	$ 500	$ 3,763	$ 500	$ 475	$ 500	$ 3,458	$ 500	$ 1,235	$ 500	$ 1,235
Minor Overhaul	20000	hrs	$ 50,000	$ 18,817	$ 50,000	$ 2,373	$ 50,000	$ 17,290	$ 50,000	$ 6,175	$ 50,000	$ 6,175
Major Overhaul	20000	hrs	$ 100,000	$ 37,634	$ 100,000	$ 4,745	$ 100,000	$ 34,580	$ 100,000	$ 12,350	$ 100,000	$ 12,350
Alternator Overhaul	10	yrs	$ 25,000	$ 15,000	$ 25,000	$ 2,143	$ 25,000	$ 13,810	$ 25,000	$ 5,000	$ 25,000	$ 7,143
General												
Hull Coating	3	yrs	$ 10,000	$ 10,000	$ 10,000	$ 1,429	$ 10,000	$ 9,206	$ 6,000	$ 2,000	$ 7,500	$ 3,571
Average ($/yr)				$ 345,734		$ 65,515		$ 474,404		$ 97,484		$ 101,199

Notes

Hours/year are an average value from 2020-2040

SIF Renewable Diesel Analysis

Summary	Molinari	Barberi	Ollis	Austen	Midsize
Fuel/trip (gal)	109	113	114	45	48
Emissions/trip (kg)					
CO2	761	788	796	317	336
SO2	0.005	0.005	0.006	0.002	0.002
NOx	10.5	14.1	2.2	4.9	1.2
CO	1.4	1.0	0.5	0.5	1.0
HC	0.9	0.3	0.1	0.5	0.3
PM	0.2	0.3	0.0	0.0	0.0
Cost Estimate					
Capital ($)	$ -	$ -	$ -	$ -	$ -
Maintenance ($/yr)	$ 345,734	$ 65,515	$ 474,404	$ 97,484	$ 101,199

Blend level	R100[1]	Reduction
50	100%	**50%**
50	5%	**3%**
50	30%	**15%**
50	30%	**15%**
50	30%	**15%**

[1] Reduction in pollutant for pure R100 renewable diesel

Baseline input data is formatted in orange

Baseline formulas are formatted in gray

Format changed input data or formulas

Unconfirmed data is in yellow (baseline or option-specific)

Summary

	Barberi	Molinari	Ollis	Austen	Midsize
Fuel/trip (gal)	113	62	114	45	48
Emissions/trip (kg)					
CO2e	1167	1127	1179	469	497
SO2	0.011	0.006	0.011	0.004	0.005
NOx	14.5	10.8	2.3	5.0	1.2
CO	1.2	1.6	0.6	0.5	1.2
HC	0.3	1.1	0.1	0.5	0.3
PM	0.4	0.2	0.0	0.1	0.0
Cost Estimate					
Capital ($)	$ -	$30.0M	$ -	$ -	$ -
Maintenance ($/yr)	$ 65,515	$ 345,734	$ 474,404	$ 97,484	$ 101,199

Baseline Route Profile

	Total Shaft Power by Class (kw)				
Phase	Molinari	Barberi	Ollis	Austen	Midsize
Transit	3640	3700	4400	1965	2312
Manv	1943	1566	1862	832	979
Push	729	520	618	276	325
Gensets	170	200	200	130	150

Notes:

Power levels above are generator powers where applicable. Efficiency applied below

Molinari profile based on total generator loading reported at the HMI, documented in shipcheck notes

Barberi power based on HMI readings of % power, modified by notes from Ollis design discussions and Barberi tank test data

Austen power based on SIF reporting

Midsize power extrapolated from Barberi and Ollis using Holtrop estimate. Full details in writeup by TSL

Engines and Conversion Efficiencies

	Molinari		Barberi		Ollis		Austen		Midsize	
Engines	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG
# Running	2	1	4	1	4	1	2	1	2	1
MCR (kw)	2983	370	1305	340	1861	430	2350	175	1491	340
MCR (hp)	4000	496	1750	456	2496	577	3151	235	1999	456
Elec. Efficiency	0.96	0.92	1	0.92	1	0.92	1	0.92	1	0.92

Notes:

Molinari operates 2 of 3 installed propulsion generators. All other classes normally operate all propulsion engines.

Electrical efficiency applied to estimate engine load from switchboard readings. Efficiency based on similar generators

SFC Equations (ref fuel consumption/emissions workbook)

		a	b	c	Description (x=%MCR)	Reference for fit
Molinari	Propulsion	7800	-1.33	182	Power fit with constant offset: ax^b+c	Manufacturer data from 25%-100% MCR. Fit includes additional points <25% calculated from past study data provided by SIF
	SSDG	34600	-1.84	243	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Barberi	Propulsion	0.05	-8.36	581	Quadratic fit: ax^2+bx+c	Manufacturer data sheet. Sheet based on engine RPM and cubic propeller law. % of rated RPM used to estimate %MCR
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Ollis	Propulsion	2512	-1.30	193	Power fit with constant offset: ax^b+c	FAT for Ollis engines documented by SIF owner's representative
	SSDG	5130	-1.26	246	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 C18
Austen	Propulsion	104	-0.44	184	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 3516
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Midsize	Propulsion	0.02	-3.14	290	Quadratic fit: ax^2+bx+c	Simplified from manufacturer's data sheet
	SSDG	0.019	-3.31	406	Quadratic fit: ax^2+bx+c	Based on CAT Tier 3 C18

Engine Load Point, SFC

	Molinari	Barberi	Ollis	Austen	Midsize	Notes
	bkw per engine					Load per engine calculated from route profile, electrical efficiency, and number of engines operat
Transit	1896	925	1100	983	1156	
Manv	1012	392	466	416	489	
Push	380	130	155	138	162	
Gensets	185	217	217	141	163	
	% MCR					Based on engine ratings listed above
Transit	64	71	59	42	78	
Manv	34	30	25	18	33	
Push	13	10	8	6	11	
Gensets	50	64	51	81	48	
	SFC (g/kwh)					Calculated from %MCR using fit curve types and coefficients listed above
Transit	213	238	206	204	167	
Manv	254	375	231	214	208	
Push	447	503	354	232	258	
Gensets	269	241	283	236	290	

DGB Gas Engine Fuel Consumption

Gas Substitution[1] (cubic fit coeff).		Gas Consumption (MJ/kwh) (quad. fit coeff)	
a	-0.00012	a	0.00016
b	0.014	b	-0.031
c	0.6	c	8.99
d	-4.4		

[1] No sub. below 25% MCR

Diesel efficiency lost	7%

Phase	Gas Sub %	Gas Power kw	Diesel Power kw	SFGC MJ/kwh	SFOC g/kwh	FGC MJ/min	FOC kg/min	Base FOC for comp.
Transit	59	1128	768	7.7	226	144	2.9	404
Manv	27	277	735	8.1	267	38	3.3	257
Push	0	0	380	8.6	459	0	2.9	170

Brake-Specific Criteria Emissions Factors (BSEF) Load-Dependent Fit Equations

Enter cycle weighted emissions target in orange cells (EPA limit or other value)

Molinari		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	6.5	NOx	0.0013	-0.20	13.0	6.5	20.2	NOx	0.0040	-0.61	40.4	20.1
	1.1	CO	0.0002	-0.03	2.2	1.1	1.3	CO	0.0003	-0.04	2.6	1.3
	0.70	HC	0.0001	-0.02	1.4	0.70	1.27	HC	0.0003	-0.04	2.5	1.27
	0.17	PM	0.0000	-0.01	0.3	0.17	0.44	PM	0.0001	-0.01	0.9	0.44
Barberi		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	10.2	NOx	0.0020	-0.31	20.4	10.1	20.2	NOx	0.0040	-0.61	40.4	20.1
	0.9	CO	0.0002	-0.03	1.8	0.9	1.3	CO	0.0003	-0.04	2.6	1.3
	0.17	HC	0.0000	-0.01	0.3	0.17	1.27	HC	0.0003	-0.04	2.5	1.27
	0.28	PM	0.0001	-0.01	0.6	0.28	0.44	PM	0.0001	-0.01	0.9	0.44
Ollis		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
	0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
	0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
	0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10
Austen		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	5.0	NOx	0.0010	-0.15	10.0	5.0	20.2	NOx	0.0040	-0.61	40.4	20.1
	0.6	CO	0.0001	-0.02	1.2	0.6	1.3	CO	0.0003	-0.04	2.6	1.3
	0.60	HC	0.0001	-0.02	1.2	0.60	1.27	HC	0.0003	-0.04	2.5	1.27
	0.04	PM	0.0000	0.00	0.1	0.04	0.44	PM	0.0001	-0.01	0.9	0.44
Midsize		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
	0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
	0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
	0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10

Notes:

Orange target values are based on manufacturer's certified data, where available. Where unavailable, values published by the EPA for the equivalent engine model were used.

At Tier 4, the HC limit is 10% of the combined HC+NOx limit. This ratio was used to estimate HC emissions for earlier tiers where no HC data was reported.

Quadratic fit curve coefficients are calculated above to estimate the load dependence of emissions factors. The general shape of these curves is based on a CAT 3516 Tier 3 engine for which complete emissions vs. load data was available.

The "Cycle Average" uses the BSEF predicted by the quadratic fit coefficients for specific load points with the weighting factors specified in the EPA rules for calculating emissions. See 40 CFR §1042 for additional details.

BSEF at Operating Profile Load Points

	Molinari	Barberi	Ollis	Austen	Midsize
NOx					
Transit	5.9	9.0	1.0	5.5	1.0
Manv	7.9	13.1	1.5	7.7	1.4
Push	10.7	17.6	1.9	9.2	1.9
Gensets	20.2	18.2	5.1	17.8	5.3
CO					
Transit	1.0	0.8	0.3	0.7	1.0
Manv	1.3	1.1	0.4	0.9	1.4
Push	1.8	1.5	0.5	1.1	1.9
Gensets	1.3	1.2	1.3	1.1	5.3
HC					
Transit	0.63	0.15	0.01	0.66	0.26
Manv	0.85	0.22	0.01	0.92	0.37
Push	1.16	0.29	0.02	1.10	0.51
Gensets	1.28	1.15	0.61	1.12	1.33
PM					
Transit	0.15	0.25	0.02	0.04	0.02
Manv	0.21	0.36	0.03	0.06	0.02
Push	0.28	0.48	0.04	0.07	0.03
Gensets	0.17	0.39	0.10	0.39	0.11

Note: calculated from quadratic coefficients on previous sheet and the engine's operating point (%MCR) at that phase of the operating profile

Specific Methane Emissions Rates (g/kwh)

Transit	5
Manv	5
Push	5
Gensets	

Ref: SINTEF study "GHG and NOx emissions from gas fuelled engines", Table 1.1

Total Energy, Fuel, Emissions Per Trip

Route profile (time per phase, minutes)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	19	18	19	15	15
Manv	3	4	3	7	7
Push	8	8	8	8	8
Gensets	30	30	30	30	30

Total Trip Energy (all engines) (kwh)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1201	1110	1393	491	578
Manv	101	104	93	97	114
Push	101	69	82	37	43
Gensets	92	109	109	71	82
Total	1496	1392	1678	696	817

Notes:
Route profile times were based on shipcheck notes.
Energy calculated from product of profile times and power

Total Trip Diesel (kg)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	110	264	286	100	96
Manv	20	39	22	21	24
Push	47	35	29	9	11
Gensets	25	26	31	17	24
Total	201	364	368	146	155

Total Trip Fuel (gal)

	Molinari	Barberi	Ollis	Austen	Midsize
Fuel	62	113	114	45	48

CO2 and SO2 per Trip

	Molinari	Barberi	Ollis	Austen	Midsize
CO2e (kg)	1127	1167	1179	469	497
SO2 (kg)	0.006	0.011	0.011	0.004	0.005

CO2e calculated from total trip methane and 28x GWP multiplier

Diesel density = 3.218 kg/gal

Criteria Emissions per Trip (kg)

kg = BSEF · power level · no. engines

NOx

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	7.0	9.9	1.4	2.7	0.6
Manv	0.8	1.4	0.1	0.7	0.2
Push	1.1	1.2	0.2	0.3	0.1
Gensets	1.9	2.0	0.6	1.3	0.4

CO

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1.2	0.9	0.4	0.3	0.6
Manv	0.1	0.1	0.0	0.1	0.2
Push	0.2	0.1	0.0	0.0	0.1
Gensets	0.1	0.1	0.1	0.1	0.4

HC

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.76	0.17	0.01	0.32	0.15
Manv	0.09	0.02	0.00	0.09	0.04
Push	0.12	0.02	0.00	0.04	0.02
Gensets	0.12	0.12	0.07	0.08	0.11

PM

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.18	0.27	0.03	0.02	0.010
Manv	0.02	0.04	0.00	0.01	0.003
Push	0.03	0.03	0.00	0.00	0.001
Gensets	0.02	0.04	0.01	0.03	0.009

Total Trip Gas (MJ)

	Molinari
Transit	5477
Manv	225
Push	0
Gensets	
Total	5702

Total Trip Methane Emissions (kg)

	Molinari
Transit	6.0
Manv	0.5
Push	0.5
Gensets	
Total	7.0

kwh · slip rate

Note: Molinari DGB gas and diesel totals calculated from route profile time and fuel/minute rates calculated on SFC sheet

Capital Cost Estimate

Equipment	Molinari Qty	Molinari Cost (ea)	Molinari Cost	Barberi Qty	Barberi Cost (ea)	Barberi Cost	Ollis Qty	Ollis Cost (ea)	Ollis Cost	Austen Qty	Austen Cost (ea)	Austen Cost	Midsize Qty	Midsize Cost (ea)	Midsize Cost
Conversion	3	$10.0M	$30.0M		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		-	-		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		-	-		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		-	-		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		-	-		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Subtotal			$30.0M			$ -			$ -			$ -			$ -
Installation (@50%)						$ -			$ -			$ -			$ -
Total			$30.0M			$ -			$ -			$ -			$ -

Note: $10M to convert one Molinari class is a high level estimate based on other gas projects.

Maintenance Cost Estimate

Item	Interval	Units	Molinari Cost (ea)	Molinari Cost	Barberi Cost (ea)	Barberi Cost	Ollis Cost (ea)	Ollis Cost	Austen Cost (ea)	Austen Cost	Midsize Cost (ea)	Midsize Cost
Main Propulsion Diesel Engine (engine hrs/yr)			15054		3796		27664		4940		4940	
Lube Oil Change	4000	hrs	$ 6,500	$ 24,462	$ 6,500	$ 6,169	$ 6,500	$ 44,954	$ 6,500	$ 8,028	$ 6,500	$ 8,028
Minor Overhaul	8000	hrs	$ 37,000	$ 69,623	$ 37,000	$ 17,558	$ 37,000	$ 127,947	$ 37,000	$ 22,848	$ 37,000	$ 22,848
Major Overhaul	30000	hrs	$ 242,000	$ 121,433	$ 242,000	$ 30,624	$ 242,000	$ 223,158	$ 242,000	$ 39,849	$ 242,000	$ 39,849
Alternator Overhaul	10	yrs	$ 50,000	$ 45,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Ship Service Diesel Generator (engine hrs/yr)			7527		949		6916		2470		2470	
Lube Oil Change	1000	hrs	$ 500	$ 3,763	$ 500	$ 475	$ 500	$ 3,458	$ 500	$ 1,235	$ 500	$ 1,235
Minor Overhaul	20000	hrs	$ 50,000	$ 18,817	$ 50,000	$ 2,373	$ 50,000	$ 17,290	$ 50,000	$ 6,175	$ 50,000	$ 6,175
Major Overhaul	20000	hrs	$ 100,000	$ 37,634	$ 100,000	$ 4,745	$ 100,000	$ 34,580	$ 100,000	$ 12,350	$ 100,000	$ 12,350
Alternator Overhaul	10	yrs	$ 25,000	$ 15,000	$ 25,000	$ 2,143	$ 25,000	$ 13,810	$ 25,000	$ 5,000	$ 25,000	$ 7,143
General												
Hull Coating	3	yrs	$ 10,000	$ 10,000	$ 10,000	$ 1,429	$ 10,000	$ 9,206	$ 6,000	$ 2,000	$ 7,500	$ 3,571
Average ($/yr)				$ 345,734		$ 65,515		$ 474,404		$ 97,484		$ 101,199

Notes

Hours/year are an average value from 2020-2040

Baseline input data is formatted in orange

Baseline formulas are formatted in gray

Format changed input data or formulas

Unconfirmed data is in yellow (baseline or option-specific)

Summary

	Barberi	Molinari	Ollis	Austen	Midsize
Fuel/trip (gal)	113	109	15	45	8
Emissions/trip (kg)					
CO2e	1167	1128	957	469	460
SO2	0.011	0.011	0.001	0.004	0.001
NOx	14.5	10.8	2.3	5.0	1.2
CO	1.2	1.6	0.6	0.5	1.2
HC	0.3	1.1	0.1	0.5	0.3
PM	0.4	0.2	0.0	0.1	0.0
Cost Estimate					
Capital ($)	$ -	$ -	$ 36.0M	$ -	$ 12.0M
Maintenance ($/yr)	$ 65,515	$ 345,734	$ 474,404	$ 97,484	$ 101,199

Baseline Route Profile

Total Shaft Power by Class (kw)

Phase	Molinari	Barberi	Ollis	Austen	Midsize
Transit	3640	3700	4400	1965	2312
Manv	1943	1566	1862	832	979
Push	729	520	618	276	325
Gensets	170	200	200	130	150

Notes:

Power levels above are generator powers where applicable. Efficiency applied below

Molinari profile based on total generator loading reported at the HMI, documented in shipcheck notes

Barberi power based on HMI readings of % power, modified by notes from Ollis design discussions and Barberi tank test data

Austen power based on SIF reporting

Midsize power extrapolated from Barberi and Ollis using Holtrop estimate. Full details in writeup by TSL

Engines and Conversion Efficiencies

	Molinari		Barberi		Ollis		Austen		Midsize	
Engines	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG
# Running	2	1	4	1	4	1	2	1	2	1
MCR (kw)	2983	370	1305	340	1861	430	2350	175	1491	340
MCR (hp)	**4000**	**496**	**1750**	**456**	**2496**	**577**	**3151**	**235**	**1999**	**456**
Elec. Efficiency	0.96	0.92	1	0.92	1	0.92	1	0.92	1	0.92

Notes:

Molinari operates 2 of 3 installed propulsion generators. All other classes normally operate all propulsion engines.

Electrical efficiency applied to estimate engine load from switchboard readings. Efficiency based on similar generators

SFC Equations (ref fuel consumption/emissions workbook)

		a	b	c	Description (x=%MCR)	Reference for fit
Molinari	Propulsion	7800	-1.33	182	Power fit with constant offset: ax^b+c	Manufacturer data from 25%-100% MCR. Fit includes additional points <25% calculated from past study data provided by SIF
	SSDG	34600	-1.84	243	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Barberi	Propulsion	0.05	-8.36	581	Quadratic fit: ax^2+bx+c	Manufacturer data sheet. Sheet based on engine RPM and cubic propeller law. % of rated RPM used to estimate %MCR
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Ollis	Propulsion	2512	-1.30	193	Power fit with constant offset: ax^b+c	FAT for Ollis engines documented by SIF owner's representative
	SSDG	5130	-1.26	246	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 C18
Austen	Propulsion	104	-0.44	184	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 3516
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Midsize	Propulsion	0.02	-3.14	290	Quadratic fit: ax^2+bx+c	Simplified from manufacturer's data sheet
	SSDG	0.019	-3.31	406	Quadratic fit: ax^2+bx+c	Based on CAT Tier 3 C18

Engine Load Point, SFC

	Molinari	Barberi	Ollis	Austen	Midsize	Notes
		bkw per engine				Load per engine calculated from route profile, electrical efficiency, and number of engines operating
Transit	1896	925	1100	983	1156	
Manv	1012	392	466	416	489	
Push	380	130	155	138	162	
Gensets	185	217	217	141	163	
		% MCR				Based on engine ratings listed above
Transit	64	71	59	42	78	
Manv	34	30	25	18	33	
Push	13	10	8	6	11	
Gensets	50	64	51	81	48	
		SFC (g/kwh)				Calculated from %MCR using fit curve types and coefficients listed above
Transit	213	238	206	204	167	
Manv	254	375	231	214	208	
Push	447	503	354	232	258	
Gensets	269	241	283	236	290	

DIG Gas Engine Fuel Consumption

Ollis

Phase	Gas Sub %	Gas Power kw	Diesel Powe kw	SFGC MJ/kwh	SFOC g/kwh	FGC MJ/min	FOC kg/min
Transit	95	1045	55	7.7	206	134	0.2
Manv	95	442	23	8.3	231	61	0.1
Push	95	147	8	8.7	354	21	0.0

Midsize

Phase	Gas Sub %	Gas Power kw	Diesel Powe kw	SFGC MJ/kwh	SFOC g/kwh	FGC MJ/min	FOC kg/min
Transit	95	1098	58	7.6	167	138	0.2
Manv	95	465	24	8.1	208	63	0.1
Push	95	154	8	8.7	258	22	0.0

Gas Consumption (MJ/kwh)
(quad. fit coeff)

a	0.00016
b	-0.031
c	8.99

Brake-Specific Criteria Emissions Factors (BSEF) Load-Dependent Fit Equations

Enter cycle weighted emissions target in orange cells (EPA limit or other value)

Molinari	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
6.5	NOx	0.0013	-0.20	13.0	6.5	20.2	NOx	0.0040	-0.61	40.4	20.1
1.1	CO	0.0002	-0.03	2.2	1.1	1.3	CO	0.0003	-0.04	2.6	1.3
0.70	HC	0.0001	-0.02	1.4	0.70	1.27	HC	0.0003	-0.04	2.5	1.27
0.17	PM	0.0000	-0.01	0.3	0.17	0.44	PM	0.0001	-0.01	0.9	0.44
Barberi	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
10.2	NOx	0.0020	-0.31	20.4	10.1	20.2	NOx	0.0040	-0.61	40.4	20.1
0.9	CO	0.0002	-0.03	1.8	0.9	1.3	CO	0.0003	-0.04	2.6	1.3
0.17	HC	0.0000	-0.01	0.3	0.17	1.27	HC	0.0003	-0.04	2.5	1.27
0.28	PM	0.0001	-0.01	0.6	0.28	0.44	PM	0.0001	-0.01	0.9	0.44
Ollis	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10
Austen	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
5.0	NOx	0.0010	-0.15	10.0	5.0	20.2	NOx	0.0040	-0.61	40.4	20.1
0.6	CO	0.0001	-0.02	1.2	0.6	1.3	CO	0.0003	-0.04	2.6	1.3
0.60	HC	0.0001	-0.02	1.2	0.60	1.27	HC	0.0003	-0.04	2.5	1.27
0.04	PM	0.0000	0.00	0.1	0.04	0.44	PM	0.0001	-0.01	0.9	0.44
Midsize	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10

Notes:

Orange target values are based on manufacturer's certified data, where available. Where unavailable, values published by the EPA for the equivalent engine model were used.

At Tier 4, the HC limit is 10% of the combined HC+NOx limit. This ratio was used to estimate HC emissions for earlier tiers where no HC data was reported.

Quadratic fit curve coefficients are calculated above to estimate the load dependence of emissions factors. The general shape of these curves is based on a CAT 3516 Tier 3 engine for which complete emissions vs. load data was available.

The "Cycle Average" uses the BSEF predicted by the quadratic fit coefficients for specific load points with the weighting factors specified in the EPA rules for calculating emissions. See 40 CFR §1042 for additional details.

BSEF at Operating Profile Load Points

	Molinari	Barberi	Ollis	Austen	Midsize
		NOx			
Transit	5.9	9.0	1.0	5.5	1.0
Manv	7.9	13.1	1.5	7.7	1.4
Push	10.7	17.6	1.9	9.2	1.9
Gensets	20.2	18.2	5.1	17.8	5.3
		CO			
Transit	1.0	0.8	0.3	0.7	1.0
Manv	1.3	1.1	0.4	0.9	1.4
Push	1.8	1.5	0.5	1.1	1.9
Gensets	1.3	1.2	1.3	1.1	5.3
		HC			
Transit	0.63	0.15	0.01	0.66	0.26
Manv	0.85	0.22	0.01	0.92	0.37
Push	1.16	0.29	0.02	1.10	0.51
Gensets	1.28	1.15	0.61	1.12	1.33
		PM			
Transit	0.15	0.25	0.02	0.04	0.02
Manv	0.21	0.36	0.03	0.06	0.02
Push	0.28	0.48	0.04	0.07	0.03
Gensets	0.17	0.39	0.10	0.39	0.11

Note: calculated from quadratic coefficients on previous sheet and the engine's operating point (%MCR) at that phase of the operating profile

Specific Methane Emissions Rates (g/kwh)

Transit			5		5
Manv			5		5
Push			5		5
Gensets					

Total Energy, Fuel, Emissions Per Trip

Route profile (time per phase, minutes)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	19	18	19	15	15
Manv	3	4	3	7	7
Push	8	8	8	8	8
Gensets	30	30	30	30	30

Total Trip Energy (all engines) (kwh)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1201	1110	1393	491	578
Manv	101	104	93	97	114
Push	101	69	82	37	43
Gensets	92	109	109	71	82
Total	1496	1392	1678	696	817

Notes:
Route profile times were based on shipcheck notes.
Energy calculated from product of profile times and power

Total Trip Diesel (kg)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	256	264	14	100	2
Manv	26	39	1	21	1
Push	45	35	1	9	0
Gensets	25	26	31	17	24
Total	352	364	48	146	27

Total Trip Fuel (gal)

	Molinari	Barberi	Ollis	Austen	Midsize
Fuel	109	113	15	45	8

CO2 and SO2 per Trip

	Molinari	Barberi	Ollis	Austen	Midsize
CO2e (kg)	1128	1167	957	469	460
SO2 (kg)	0.011	0.011	0.001	0.004	0.001

CO2e calculated from total trip methane and 28x GWP multiplier

Diesel density = 3.218 kg/gal

Criteria Emissions per Trip (kg)

kg = BSEF · power level · no. engines

NOx

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	7.0	9.9	1.4	2.7	0.6
Manv	0.8	1.4	0.1	0.7	0.2
Push	1.1	1.2	0.2	0.3	0.1
Gensets	1.9	2.0	0.6	1.3	0.4

CO

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1.2	0.9	0.4	0.3	0.6
Manv	0.1	0.1	0.0	0.1	0.2
Push	0.2	0.1	0.0	0.0	0.1
Gensets	0.1	0.1	0.1	0.1	0.4

HC

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.76	0.17	0.01	0.32	0.15
Manv	0.09	0.02	0.00	0.09	0.04
Push	0.12	0.02	0.00	0.04	0.02
Gensets	0.12	0.12	0.07	0.08	0.11

PM

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.18	0.27	0.03	0.02	0.010
Manv	0.02	0.04	0.00	0.01	0.003
Push	0.03	0.03	0.00	0.00	0.001
Gensets	0.02	0.04	0.01	0.03	0.009

Total Trip Gas (MJ)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit			10218		4146
Manv			736		884
Push			685		357
Gensets					
Total			11639		5387

Total Trip Methane Emissions (kg)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit			7.0		2.9
Manv			0.5		0.6
Push			0.4		0.2
Gensets					
Total			7.8		3.7

Note: Ollis/Midsize Gas and diesel totals calculated from route profile time and fuel/minute rates calculated on SFC sheet

SIF DIG Analysis (Ollis/Midsize)

Capital Cost Estimate

	Molinari			Barberi			Ollis			Austen			Midsize		
Equipment	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
Conversion		$ -	$ -		$ -	$ -	3	$ 12.0M	$ 36.0M		$ -	$ -	3	$ 4.0M	$ 12.0M
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Subtotal			$ -			$ -			$ 36.0M			$ -			$ 12.0M
(Installation cost included in above estimates)			$ -			$ -			$ -			$ -			$ -
Total			$ -			$ -			$ 36.0M			$ -			$ 12.0M

Note: $12M to convert one Ollis class is a high level estimate based on other gas projects. Midsize vessels are assumed to have a higher initial construction cost due to the LNG system

Maintenance Cost Estimate

			Molinari		Barberi		Ollis		Austen		Midsize	
Item	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost
Main Propulsion Diesel Engine (engine hrs/yr)			15054		3796		27664		4940		4940	
Lube Oil Change	4000	hrs	$ 6,500	$ 24,462	$ 6,500	$ 6,169	$ 6,500	$ 44,954	$ 6,500	$ 8,028	$ 6,500	$ 8,028
Minor Overhaul	8000	hrs	$ 37,000	$ 69,623	$ 37,000	$ 17,558	$ 37,000	$ 127,947	$ 37,000	$ 22,848	$ 37,000	$ 22,848
Major Overhaul	30000	hrs	$ 242,000	$ 121,433	$ 242,000	$ 30,624	$ 242,000	$ 223,158	$ 242,000	$ 39,849	$ 242,000	$ 39,849
Alternator Overhaul	10	yrs	$ 50,000	$ 45,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Ship Service Diesel Generator (engine hrs/yr)			7527		949		6916		2470		2470	
Lube Oil Change	1000	hrs	$ 500	$ 3,763	$ 500	$ 475	$ 500	$ 3,458	$ 500	$ 1,235	$ 500	$ 1,235
Minor Overhaul	20000	hrs	$ 50,000	$ 18,817	$ 50,000	$ 2,373	$ 50,000	$ 17,290	$ 50,000	$ 6,175	$ 50,000	$ 6,175
Major Overhaul	20000	hrs	$ 100,000	$ 37,634	$ 100,000	$ 4,745	$ 100,000	$ 34,580	$ 100,000	$ 12,350	$ 100,000	$ 12,350
Alternator Overhaul	10	yrs	$ 25,000	$ 15,000	$ 25,000	$ 2,143	$ 25,000	$ 13,810	$ 25,000	$ 5,000	$ 25,000	$ 7,143
General												
Hull Coating	3	yrs	$ 10,000	$ 10,000	$ 10,000	$ 1,429	$ 10,000	$ 9,206	$ 6,000	$ 2,000	$ 7,500	$ 3,571
Average ($/yr)				$ 345,734		$ 65,515		$ 474,404		$ 97,484		$ 101,199

Notes

Hours/year are an average value from 2020-2040

SIF Integrated Plant Analysis (Molinari)

Summary

	Barberi	Molinari	Ollis	Austen	Midsize
Fuel/trip (gal)	113	106	114	45	48
Emissions/trip (kg)					
CO2	1167	1093	1179	469	497
SO2	0.011	0.010	0.011	0.004	0.005
NOx	14.5	9.4	2.3	5.0	1.2
CO	1.2	1.6	0.6	0.5	1.2
HC	0.3	1.0	0.1	0.5	0.3
PM	0.4	0.2	0.0	0.1	0.0
Cost Estimate					
Capital ($)	$ -	$ 6.8M	$ -	$ -	$ -
Maintenance ($/yr)	$ 65,515	$ 270,519	$ 474,404	$ 97,484	$ 101,199

Baseline input data is formatted in orange

Baseline formulas are formatted in gray

Format changed input data or formulas

Unconfirmed data is in yellow (baseline or option-specific)

Baseline Route Profile

Total Shaft Power by Class (kw)

Phase	Molinari	Barberi	Ollis	Austen	Midsize
Transit	3640	3700	4400	1965	2312
Manv	1943	1566	1862	832	979
Push	729	520	618	276	325
Gensets	170	200	200	130	150

Notes:
Power levels above are generator powers where applicable. Efficiency applied below
Molinari profile based on total generator loading reported at the HMI, documented in shipcheck notes
Barberi power based on HMI readings of % power, modified by notes from Ollis design discussions and Barberi tank test data
Austen power based on SIF reporting
Midsize power extrapolated from Barberi and Ollis using Holtrop estimate. Full details in writeup by TSL

Assumptions:

1. Applicable to only Molinari class
2. Assume SSDG is not operating, all load is on propulsion generators
3. Assume 97% efficiency on Ship Service load due to added transformer and filtering equipment

97%

Engines and Conversion Efficiencies

	Molinari		Barberi		Ollis		Austen		Midsize	
Engines	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG
# Running	2	0	4	1	4	1	2	1	2	1
MCR (kw)	2983	370	1305	340	1861	430	2350	175	1491	340
MCR (hp)	**4000**	**496**	**1750**	**456**	**2496**	**577**	**3151**	**235**	**1999**	**456**
Elec. Efficiency	0.96	0.92	1	0.92	1	0.92	1	0.92	1	0.92

Notes:
Molinari operates 2 of 3 installed propulsion generators. All other classes normally operate all propulsion engines.
Electrical efficiency applied to estimate engine load from switchboard readings. Efficiency based on similar generators
Austen propulsion engines are derated based on VSP limits. Full rating used here to accurately calculate SFC

Molinari with an Integrated Plant would operate only propulsion generators, no ship's service generators

SFC Equations (ref fuel consumption/emissions workbook)

		a	b	c	Description (x=%MCR)	Reference for fit
Molinari	Propulsion	7800	-1.33	182	Power fit with constant offset: ax^b+c	Manufacturer data from 25%-100% MCR. Fit includes additional points <25% calculated from past study data provided by SIF
	SSDG	34600	-1.84	243	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Barberi	Propulsion	0.05	-8.36	581	Quadratic fit: ax^2+bx+c	Manufacturer data sheet. Sheet based on engine RPM and cubic propeller law. % of rated RPM used to estimate %MCR
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Ollis	Propulsion	2512	-1.30	193	Power fit with constant offset: ax^b+c	FAT for Ollis engines documented by SIF owner's representative
	SSDG	5130	-1.26	246	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 C18
Austen	Propulsion	104	-0.44	184	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 3516
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Midsize	Propulsion	0.02	-3.14	290	Quadratic fit: ax^2+bx+c	Simplified from manufacturer's data sheet
	SSDG	0.019	-3.31	406	Quadratic fit: ax^2+bx+c	Based on CAT Tier 3 C18

Engine Load Point, SFC

	Molinari	Barberi	Ollis	Austen	Midsize	Notes
bkw per engine						Load per engine calculated from route profile, electrical efficiency, and number of engines operating
Transit	1987	925	1100	983	1156	Molinari ship's service load with 97% efficiency factor are combined with propulsion loads
Manv	1103	392	466	416	489	
Push	471	130	155	138	162	
Gensets	0	217	217	141	163	Genset load is 0 for an Integrated Plant
% MCR						Based on engine ratings listed above
Transit	67	71	59	42	78	
Manv	37	30	25	18	33	
Push	16	10	8	6	11	
Gensets	0	64	51	81	48	
SFC (g/kwh)						Calculated from %MCR using fit curve types and coefficients listed above
Transit	211	238	206	204	167	
Manv	246	375	231	214	208	
Push	381	503	354	232	258	
Gensets	0	241	283	236	290	Genset SFC is 0 for an Integrated Plant

Brake-Specific Criteria Emissions Factors (BSEF) Load-Dependent Fit Equations

Enter cycle weighted emissions target in orange cells (EPA limit or other value)

Molinari		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	6.5	NOx	0.0013	-0.20	13.0	6.5	20.2	NOx	0.0040	-0.61	40.4	20.1
	1.1	CO	0.0002	-0.03	2.2	1.1	1.3	CO	0.0003	-0.04	2.6	1.3
	0.70	HC	0.0001	-0.02	1.4	0.70	1.27	HC	0.0003	-0.04	2.5	1.27
	0.17	PM	0.0000	-0.01	0.3	0.17	0.44	PM	0.0001	-0.01	0.9	0.44
Barberi		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	10.2	NOx	0.0020	-0.31	20.4	10.1	20.2	NOx	0.0040	-0.61	40.4	20.1
	0.9	CO	0.0002	-0.03	1.8	0.9	1.3	CO	0.0003	-0.04	2.6	1.3
	0.17	HC	0.0000	-0.01	0.3	0.17	1.27	HC	0.0003	-0.04	2.5	1.27
	0.28	PM	0.0001	-0.01	0.6	0.28	0.44	PM	0.0001	-0.01	0.9	0.44
Ollis		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
	0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
	0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
	0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10
Austen		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	5.0	NOx	0.0010	-0.15	10.0	5.0	20.2	NOx	0.0040	-0.61	40.4	20.1
	0.6	CO	0.0001	-0.02	1.2	0.6	1.3	CO	0.0003	-0.04	2.6	1.3
	0.60	HC	0.0001	-0.02	1.2	0.60	1.27	HC	0.0003	-0.04	2.5	1.27
	0.04	PM	0.0000	0.00	0.1	0.04	0.44	PM	0.0001	-0.01	0.9	0.44
Midsize		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
	0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
	0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
	0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10

Notes:

Orange target values are based on manufacturer's certified data, where available. Where unavailable, the Tier limit for the certified or equivalent Tier claimed by the engine.

At Tier 4, the HC limit is 10% of the combined HC+NOx limit. This ratio was used to estimate HC emissions for earlier tiers where no HC data was reported.

Quadratic fit curve coefficients are calculated above to estimate the load dependence of emissions factors. The general shape of these curves is based on a CAT 3516 Tier 3 engine for which complete emissions vs. load data was available.

The "Cycle Average" uses the BSEF predicted by the quadratic fit coefficients for specific load points with the weighting factors specified in the EPA rules for calculating emissions. See 40 CFR §1042 for additional details.

BSEF at Operating Profile Load Points

	Molinari	Barberi	Ollis	Austen	Midsize
		NOx			
Transit	5.8	9.0	1.0	5.5	1.0
Manv	7.6	13.1	1.5	7.7	1.4
Push	10.2	17.6	1.9	9.2	1.9
Gensets	40.4	18.2	5.1	17.8	5.3
		CO			
Transit	1.0	0.8	0.3	0.7	1.0
Manv	1.3	1.1	0.4	0.9	1.4
Push	1.7	1.5	0.5	1.1	1.9
Gensets	2.6	1.2	1.3	1.1	5.3
		HC			
Transit	0.62	0.15	0.01	0.66	0.26
Manv	0.81	0.22	0.01	0.92	0.37
Push	1.10	0.29	0.02	1.10	0.51
Gensets	2.55	1.15	0.61	1.12	1.33
		PM			
Transit	0.15	0.25	0.02	0.04	0.02
Manv	0.20	0.36	0.03	0.06	0.02
Push	0.27	0.48	0.04	0.07	0.03
Gensets	0.34	0.39	0.10	0.39	0.11

Note: calculated from quadratic coefficients on previous sheet and the engine's operating point (%MCR) at that phase of the operating profile

Total Energy, Fuel, Emissions Per Trip

Route profile (time per phase, minutes)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	19	18	19	15	15
Manv	3	4	3	7	7
Push	8	8	8	8	8
Gensets	30	30	30	30	30

Total Trip Energy (all engines) (kwh)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1259	1110	1393	491	578
Manv	110	104	93	97	114
Push	126	69	82	37	43
Gensets	0	109	109	71	82
Total	1494	1392	1678	696	817

Notes:

Route profile times were based on shipcheck notes.

Energy calculated from product of profile times and power

Total Trip Fuel (kg)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	266	264	286	100	96
Manv	27	39	22	21	24
Push	48	35	29	9	11
Gensets	0	26	31	17	24
Total	341	364	368	146	155

Total Trip Fuel (gal)

	Molinari	Barberi	Ollis	Austen	Midsize
Fuel	106	113	114	45	48

CO2 and SO2 per Trip

	Molinari	Barberi	Ollis	Austen	Midsize
CO2 (kg)	1093	1167	1179	469	497
SO2 (kg)	0.010	0.011	0.011	0.004	0.005

Fuel calculated from each engine's SFC, power level, and time

kg CO2 = 3.206 · kg diesel (MEPC 67/INF.3: Third IMO GHG Study, MGO value)

SO2 from mass balance using 15 ppm S oxidized to SO2

Diesel density = 3.218 kg/gal

Criteria Emissions per Trip (kg)

kg = BSEF · power level · no. engines

NOx

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	7.3	9.9	1.4	2.7	0.6
Manv	0.8	1.4	0.1	0.7	0.2
Push	1.3	1.2	0.2	0.3	0.1
Gensets	0.0	2.0	0.6	1.3	0.4

CO

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1.2	0.9	0.4	0.3	0.6
Manv	0.1	0.1	0.0	0.1	0.2
Push	0.2	0.1	0.0	0.0	0.1
Gensets	0.0	0.1	0.1	0.1	0.4

HC

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.78	0.17	0.01	0.32	0.15
Manv	0.09	0.02	0.00	0.09	0.04
Push	0.14	0.02	0.00	0.04	0.02
Gensets	0.00	0.12	0.07	0.08	0.11

PM

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.19	0.27	0.03	0.02	0.010
Manv	0.02	0.04	0.00	0.01	0.003
Push	0.03	0.03	0.00	0.00	0.001
Gensets	0.00	0.04	0.01	0.03	0.009

Capital Cost Estimate

	Molinari			Barberi			Ollis			Austen			Midsize		
Equipment	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
Int Bus Swbd	3	$ 900,000	$ 2.7M		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Active Filters	3	$ 100,000	$ .3M		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Upgrade SS Swbd	3	$ 500,000	$ 1.5M		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Subtotal			$ 4.5M			$ -			$ -			$ -			$ -
Installation (@50%)			$ 2.3M			$ -			$ -			$ -			$ -
Total			$ 6.8M			$ -			$ -			$ -			$ -

Maintenance Cost Estimate

			Molinari		Barberi		Ollis		Austen		Midsize	
Item	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost
Main Propulsion Diesel Engine (engine hrs/yr)			15054		3796		27664		4940		4940	
Lube Oil Change	4000	hrs	$ 6,500	$ 24,462	$ 6,500	$ 6,169	$ 6,500	$ 44,954	$ 6,500	$ 8,028	$ 6,500	$ 8,028
Minor Overhaul	8000	hrs	$ 37,000	$ 69,623	$ 37,000	$ 17,558	$ 37,000	$ 127,947	$ 37,000	$ 22,848	$ 37,000	$ 22,848
Major Overhaul	30000	hrs	$ 242,000	$ 121,433	$ 242,000	$ 30,624	$ 242,000	$ 223,158	$ 242,000	$ 39,849	$ 242,000	$ 39,849
Alternator Overhaul	10	yrs	$ 50,000	$ 45,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Ship Service Diesel Generator (engine hrs/yr)			0		949		6916		2470		2470	
Lube Oil Change	1000	hrs	$ 500	$ -	$ 500	$ 475	$ 500	$ 3,458	$ 500	$ 1,235	$ 500	$ 1,235
Minor Overhaul	20000	hrs	$ 50,000	$ -	$ 50,000	$ 2,373	$ 50,000	$ 17,290	$ 50,000	$ 6,175	$ 50,000	$ 6,175
Major Overhaul	20000	hrs	$ 100,000	$ -	$ 100,000	$ 4,745	$ 100,000	$ 34,580	$ 100,000	$ 12,350	$ 100,000	$ 12,350
Alternator Overhaul	10	yrs	$ -	$ -	$ 25,000	$ 2,143	$ 25,000	$ 13,810	$ 25,000	$ 5,000	$ 25,000	$ 7,143
General												
Hull Coating	3	yrs	$ 10,000	$ 10,000	$ 10,000	$ 1,429	$ 10,000	$ 9,206	$ 6,000	$ 2,000	$ 7,500	$ 3,571
Average ($/yr)				$ 270,519		$ 65,515		$ 474,404		$ 97,484		$ 101,199

Notes

Hours/year are an average value from 2020-2040

SIF Integrated Plant + Variable Speed Analysis (Molinari)

Summary

	Barberi	Molinari	Ollis	Austen	Midsize
Fuel/trip (gal)	113	96	114	45	48
Emissions/trip (kg)					
CO2	1167	995	1179	469	497
SO2	0.011	0.009	0.011	0.004	0.005
NOx	14.5	9.9	2.3	5.0	1.2
CO	1.2	1.6	0.6	0.5	1.2
HC	0.3	1.1	0.1	0.5	0.3
PM	0.4	0.2	0.0	0.1	0.0
Cost Estimate					
Capital ($)	$ -	$ 32.6M	$ -	$ -	$ -
Maintenance ($/yr)	$ 65,515	$ 270,519	$ 474,404	$ 97,484	$ 101,199

Baseline input data is formatted in orange

Baseline formulas are formatted in gray

Format changed input data or formulas

Unconfirmed data is in yellow (baseline or option-specific)

Baseline Route Profile

Total Shaft Power by Class (kw)

Phase	Molinari	Barberi	Ollis	Austen	Midsize
Transit	3640	3700	4400	1965	2312
Manv	1943	1566	1862	832	979
Push	729	520	618	276	325
Gensets	170	200	200	130	150

Notes:
Power levels above are generator powers where applicable. Efficiency applied below
Molinari profile based on total generator loading reported at the HMI, documented in shipcheck notes
Barberi power based on HMI readings of % power, modified by notes from Ollis design discussions and Barberi tank test data
Austen power based on SIF reporting
Midsize power extrapolated from Barberi and Ollis using Holtrop estimate. Full details in writeup by TSL

Assumptions:

1. Applicable to only Molinari class
2. Assume SSDG is not operating, all load is on propulsion generators
3. Assume 97% efficiency on Ship Service load due to added transformer
4. SFC for variable speed operation is based on the EMD engine propulsion curve

97%

Engines and Conversion Efficiencies

	Molinari		Barberi		Ollis		Austen		Midsize	
Engines	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG
# Running	2	0	4	1	4	1	2	1	2	1
MCR (kw)	2983	370	1305	340	1861	430	2350	175	1491	340
MCR (hp)	**4000**	**496**	**1750**	**456**	**2496**	**577**	**3151**	**235**	**1999**	**456**
Elec. Efficiency	0.96	0.92	1	0.92	1	0.92	1	0.92	1	0.92

Notes:
Molinari operates 2 of 3 installed propulsion generators. All other classes normally operate all propulsion engines.
Electrical efficiency applied to estimate engine load from switchboard readings. Efficiency based on similar generators
Austen propulsion engines are derated based on VSP limits. Full rating used here to accurately calculate SFC

Molinari with an Integrated Plant would operate only propulsion generators, no ship's service generators

SIF Integrated Plant + Variable Speed Analysis (Molinari)

SFC Equations (ref fuel consumption/emissions workbook)

		a	b	c	d	Description (x=%MCR)	Reference for fit
Molinari	Propulsion	-0.00006	0.014	-1.17	241	Cubic fit: ax^3+bx^2+cx+d	SFC curve estimate based on variable speed propeller curve for equivalent engines
	SSDG	34600	-1.84	243		Power fit with constant offset: ax^b+c	Manufacturer data sheet
Barberi	Propulsion	0.05	-8.36	581		Quadratic fit: ax^2+bx+c	Manufacturer data sheet. Sheet based on engine RPM and cubic propeller law. % of rated RPM used to estimate %MCR
	SSDG	17654	-1.67	224		Power fit with constant offset: ax^b+c	Manufacturer data sheet
Ollis	Propulsion	2512	-1.30	193		Power fit with constant offset: ax^b+c	FAT for Ollis engines documented by SIF owner's representative
	SSDG	5130	-1.26	246		Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 C18
Austen	Propulsion	104	-0.44	184		Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 3516
	SSDG	17654	-1.67	224		Power fit with constant offset: ax^b+c	Manufacturer data sheet
Midsize	Propulsion	0.02	-3.14	290		Quadratic fit: ax^2+bx+c	Simplified from manufacturer's data sheet
	SSDG	0.019	-3.31	406		Quadratic fit: ax^2+bx+c	Based on CAT Tier 3 C18

Engine Load Point, SFC

	Molinari	Barberi	Ollis	Austen	Midsize	Notes
		bkw per engine				Load per engine calculated from route profile, electrical efficiency, and number of engines operating
Transit	1987	925	1100	983	1156	Molinari ship's service load with 97% efficiency factor are combined with propulsion loads
Manv	1103	392	466	416	489	
Push	471	130	155	138	162	
Gensets	0	217	217	141	163	Genset load is 0 for an Integrated Plant
		% MCR				Based on engine ratings listed above
Transit	67	71	59	42	78	
Manv	37	30	25	18	33	
Push	16	10	8	6	11	
Gensets	0	64	51	81	48	
		SFC (g/kwh)				Calculated from %MCR using fit curve types and coefficients listed above
Transit	205	238	206	204	167	
Manv	213	375	231	214	208	
Push	226	503	354	232	258	
Gensets	0	241	283	236	290	Genset SFC is 0 for an Integrated Plant

Brake-Specific Criteria Emissions Factors (BSEF) Load-Dependent Fit Equations

Enter cycle weighted emissions target in orange cells (EPA limit or other value)

Molinari	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
6.8	NOx	0.0014	-0.21	13.7	6.8	20.2	NOx	0.0040	-0.61	40.4	20.1
1.1	CO	0.0002	-0.03	2.2	1.1	1.3	CO	0.0003	-0.04	2.6	1.3
0.76	HC	0.0002	-0.02	1.5	0.76	1.27	HC	0.0003	-0.04	2.5	1.27
0.14	PM	0.0000	0.00	0.3	0.14	0.44	PM	0.0001	-0.01	0.9	0.44
Barberi	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
10.2	NOx	0.0020	-0.31	20.4	10.1	20.2	NOx	0.0040	-0.61	40.4	20.1
0.9	CO	0.0002	-0.03	1.8	0.9	1.3	CO	0.0003	-0.04	2.6	1.3
0.17	HC	0.0000	-0.01	0.3	0.17	1.27	HC	0.0003	-0.04	2.5	1.27
0.28	PM	0.0001	-0.01	0.6	0.28	0.44	PM	0.0001	-0.01	0.9	0.44
Ollis	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10
Austen	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
5.0	NOx	0.0010	-0.15	10.0	5.0	20.2	NOx	0.0040	-0.61	40.4	20.1
0.6	CO	0.0001	-0.02	1.2	0.6	1.3	CO	0.0003	-0.04	2.6	1.3
0.60	HC	0.0001	-0.02	1.2	0.60	1.27	HC	0.0003	-0.04	2.5	1.27
0.04	PM	0.0000	0.00	0.1	0.04	0.44	PM	0.0001	-0.01	0.9	0.44
Midsize	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10

Notes:

Orange target values are based on manufacturer's certified data, where available. Where unavailable, values published by the EPA for the equivalent engine model were used.

At Tier 4, the HC limit is 10% of the combined HC+NOx limit. This ratio was used to estimate HC emissions for earlier tiers where no HC data was reported.

Quadratic fit curve coefficients are calculated above to estimate the load dependence of emissions factors. The general shape of these curves is based on a CAT 3516 Tier 3 engine for which complete emissions vs. load data was available.

The "Cycle Average" uses the BSEF predicted by the quadratic fit coefficients for specific load points with the weighting factors specified in the EPA rules for calculating emissions. See 40 CFR §1042 for additional details.

BSEF at Operating Profile Load Points

	Molinari	Barberi	Ollis	Austen	Midsize
		NOx			
Transit	6.1	9.0	1.0	5.5	1.0
Manv	8.0	13.1	1.5	7.7	1.4
Push	10.8	17.6	1.9	9.2	1.9
Gensets	40.4	18.2	5.1	17.8	5.3
		CO			
Transit	1.0	0.8	0.3	0.7	1.0
Manv	1.3	1.1	0.4	0.9	1.4
Push	1.7	1.5	0.5	1.1	1.9
Gensets	2.6	1.2	1.3	1.1	5.3
		HC			
Transit	0.68	0.15	0.01	0.66	0.26
Manv	0.88	0.22	0.01	0.92	0.37
Push	1.20	0.29	0.02	1.10	0.51
Gensets	2.55	1.15	0.61	1.12	1.33
		PM			
Transit	0.12	0.25	0.02	0.04	0.02
Manv	0.16	0.36	0.03	0.06	0.02
Push	0.22	0.48	0.04	0.07	0.03
Gensets	0.28	0.39	0.10	0.39	0.11

Note: calculated from quadratic coefficients on previous sheet and the engine's operating point (%MCR) at that phase of the operating profile

Total Energy, Fuel, Emissions Per Trip

Route profile (time per phase, minutes)	Molinari	Barberi	Ollis	Austen	Midsize
Transit	19	18	19	15	15
Manv	3	4	3	7	7
Push	8	8	8	8	8
Gensets	30	30	30	30	30

Total Trip Energy (all engines) (kwh)	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1259	1110	1393	491	578
Manv	110	104	93	97	114
Push	126	69	82	37	43
Gensets	0	109	109	71	82
Total	1494	1392	1678	696	817

Notes:

Route profile times were based on shipcheck notes.

Energy calculated from product of profile times and power

Total Trip Fuel (kg)	Molinari	Barberi	Ollis	Austen	Midsize
Transit	259	264	286	100	96
Manv	24	39	22	21	24
Push	28	35	29	9	11
Gensets	0	26	31	17	24
Total	310	364	368	146	155
Total Trip Fuel (gal)					
Fuel	96	113	114	45	48

CO2 and SO2 per Trip	Molinari	Barberi	Ollis	Austen	Midsize
CO2 (kg)	995	1167	1179	469	497
SO2 (kg)	0.009	0.011	0.011	0.004	0.005

Fuel calculated from each engine's SFC, power level, and time

kg CO2 = 3.206 · kg diesel (Source: MEPC 67/INF.3: Third IMO GHG

SO2 from mass balance using 15 ppm S oxidized to SO2

Diesel density = 3.218 kg/gal

Criteria Emissions per Trip (kg)

kg = BSEF · power level · no. engines

NOx	Molinari	Barberi	Ollis	Austen	Midsize
Transit	7.7	9.9	1.4	2.7	0.6
Manv	0.9	1.4	0.1	0.7	0.2
Push	1.4	1.2	0.2	0.3	0.1
Gensets	0.0	2.0	0.6	1.3	0.4

CO	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1.2	0.9	0.4	0.3	0.6
Manv	0.1	0.1	0.0	0.1	0.2
Push	0.2	0.1	0.0	0.0	0.1
Gensets	0.0	0.1	0.1	0.1	0.4

HC	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.85	0.17	0.01	0.32	0.15
Manv	0.10	0.02	0.00	0.09	0.04
Push	0.15	0.02	0.00	0.04	0.02
Gensets	0.00	0.12	0.07	0.08	0.11

PM	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.16	0.27	0.03	0.02	0.010
Manv	0.02	0.04	0.00	0.01	0.003
Push	0.03	0.03	0.00	0.00	0.001
Gensets	0.00	0.04	0.01	0.03	0.009

SIF Integrated Plant + Variable Speed Analysis (Molinari)

Capital Cost Estimate

	Molinari			Barberi			Ollis			Austen			Midsize		
Equipment	Qty	Cost (ea)	Cost (fleet)	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
VS PDG Alternator	3	$ 7,238,000	$ 21.7M		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Subtotal			$ 21.7M			$ -			$ -			$ -			$ -
Installation (@50%)			$ 10.9M			$ -			$ -			$ -			$ -
Total			$ 32.6M			$ -			$ -			$ -			$ -

Maintenance Cost Estimate

			Molinari		Barberi		Ollis		Austen		Midsize	
Item	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost
Main Propulsion Diesel Engine (engine hrs/yr)			15054		3796		27664		4940		4940	
Lube Oil Change	4000	hrs	$ 6,500	$ 24,462	$ 6,500	$ 6,169	$ 6,500	$ 44,954	$ 6,500	$ 8,028	$ 6,500	$ 8,028
Minor Overhaul	8000	hrs	$ 37,000	$ 69,623	$ 37,000	$ 17,558	$ 37,000	$ 127,947	$ 37,000	$ 22,848	$ 37,000	$ 22,848
Major Overhaul	30000	hrs	$ 242,000	$ 121,433	$ 242,000	$ 30,624	$ 242,000	$ 223,158	$ 242,000	$ 39,849	$ 242,000	$ 39,849
Alternator Overhaul	10	yrs	$ 50,000	$ 45,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Ship Service Diesel Generator (engine hrs/yr)			0		949		6916		2470		2470	
Lube Oil Change	1000	hrs	$ 500	$ -	$ 500	$ 475	$ 500	$ 3,458	$ 500	$ 1,235	$ 500	$ 1,235
Minor Overhaul	20000	hrs	$ 50,000	$ -	$ 50,000	$ 2,373	$ 50,000	$ 17,290	$ 50,000	$ 6,175	$ 50,000	$ 6,175
Major Overhaul	20000	hrs	$ 100,000	$ -	$ 100,000	$ 4,745	$ 100,000	$ 34,580	$ 100,000	$ 12,350	$ 100,000	$ 12,350
Alternator Overhaul	10	yrs	$ -	$ -	$ 25,000	$ 2,143	$ 25,000	$ 13,810	$ 25,000	$ 5,000	$ 25,000	$ 7,143
General												
Hull Coating	3	yrs	$ 10,000	$ 10,000	$ 10,000	$ 1,429	$ 10,000	$ 9,206	$ 6,000	$ 2,000	$ 7,500	$ 3,571
Average ($/yr)				$ 270,519		$ 65,515		$ 474,404		$ 97,484		$ 101,199

Notes

Hours/year are an average value from 2020-2040

Appendix A.9

SIF Molinari Class Hybrid Analysis

Summary

	Barberi	Molinari	Ollis	Austen	Midsize
Fuel/trip (gal)	113	98	114	45	48
Emissions/trip (kg)					
CO2	1167	1008	1179	469	497
SO2	0.011	0.009	0.011	0.004	0.005
NOx	14.5	11.7	2.3	5.0	1.2
CO	1.2	1.6	0.6	0.5	1.2
HC	0.3	1.2	0.1	0.5	0.3
PM	0.4	0.2	0.0	0.1	0.0
Cost Estimate					
Capital ($)	$ -	$ 36.7M	$ -	$ -	$ -
Maintenance ($/yr)	$ 65,515	$ 387,974	$ 474,404	$ 97,484	$ 101,199

Baseline input data is formatted in orange

Baseline formulas are formatted in gray

Format changed input data or formulas

Unconfirmed data is in yellow (baseline or option-specific)

Baseline Route Profile

Total Shaft Power by Class (kw)

Phase	Molinari	Barberi	Ollis	Austen	Midsize
Transit	3640	3700	4400	1965	2312
Manv	1943	1566	1862	832	979
Push	729	520	618	276	325
Gensets	170	200	200	130	150

Notes:
Power levels above are generator powers where applicable. Efficiency applied below
Molinari profile based on total generator loading reported at the HMI, documented in shipcheck notes
Barberi power based on HMI readings of % power, modified by notes from Ollis design discussions and Barberi tank test data
Austen power based on SIF reporting
Midsize power extrapolated from Barberi and Ollis using Holtrop estimate. Full details in writeup by TSL

Assumptions:
1. Applicable to only Molinari class
2. Includes integrated plant where PDG's, SSDG's, and batteries can supply power to entire vessel

Engines and Conversion Efficiencies

	Molinari		Barberi		Ollis		Austen		Midsize	
Engines	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG
# Running	1	1	4	1	4	1	2	1	2	1
MCR (kw)	2983	370	1305	340	1861	430	2350	175	1491	340
MCR (hp)	4000	496	1750	456	2496	577	3151	235	1999	456
Elec. Efficiency	0.96	0.92	1	0.92	1	0.92	1	0.92	1	0.92

Notes:
Molinari operates 2 of 3 installed propulsion generators. All other classes normally operate all propulsion engines.
Electrical efficiency applied to estimate engine load from switchboard readings. Efficiency based on similar generators
Austen propulsion engines are derated based on VSP limits. Full rating used here to accurately calculate SFC

For hybrid operation only 1 propulsion and 1 ship's service generator are assumed to be in operation

	bkw required	Engine (kW)	Battery (kW)	Battery kWh	w/ Efficiency	Feasible?
Transit	3810	2916	894	283	292	Yes
Maneuvering	2113	2916	-803	-40	-39	
Pushing Dock	899	2916	-2017	-269	-261	

Positive battery energy indicates battery discharging, negative battery energy indicates battery is charging
The "feasible" check determines if the selected engine combination produces enough total energy
Hybrid system efficiency is assumed to be 97% during both charging and discharging

97%

SFC Equations (ref fuel consumption/emissions workbook)

		a	b	c	Description (x=%MCR)		Reference for fit
Molinari	Propulsion	-0.00006	0.014	-1.17	241	Cubic fit: ax^3+bx^2+cx+c	SFC curve estimate based on variable speed propeller curve for equivalent engines
	SSDG	34600	-1.84	243	Power fit with constant offset: ax^b+c		Manufacturer data sheet
Barberi	Propulsion	0.05	-8.36	581	Quadratic fit: ax^2+bx+c		Manufacturer data sheet. Sheet based on engine RPM and cubic propeller law. % of rated RPM used to estimate %MCR
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c		Manufacturer data sheet
Ollis	Propulsion	2512	-1.30	193	Power fit with constant offset: ax^b+c		FAT for Ollis engines documented by SIF owner's representative
	SSDG	5130	-1.26	246	Power fit with constant offset: ax^b+c		Manufacturer's data sheet for Tier 3 C18
Austen	Propulsion	104	-0.44	184	Power fit with constant offset: ax^b+c		Manufacturer's data sheet for Tier 3 3516
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c		Manufacturer data sheet
Midsize	Propulsion	0.02	-3.14	290	Quadratic fit: ax^2+bx+c		Simplified from manufacturer's data sheet
	SSDG	0.019	-3.31	406	Quadratic fit: ax^2+bx+c		Based on CAT Tier 3 C18

Engine Load Point, SFC

	Molinari	Barberi	Ollis	Austen	Midsize	Notes
		bkw per engine				Load per engine calculated from route profile, electrical efficiency, and number of engines operating
Transit	2714	925	1100	983	1156	Load per engine is based on "% MCR" engine operating point, not operating load.
Manv	2714	392	466	416	489	
Push	2714	130	155	138	162	
Gensets	337	217	217	141	163	
		% MCR				Based on engine ratings listed above
Transit	91	71	59	42	78	"% MCR" is an input - engines will run at this level and excess energy will go to batteries
Manv	91	30	25	18	33	
Push	91	10	8	6	11	
Gensets	91	64	51	81	48	
		SFC (g/kwh)				Calculated from %MCR using fit curve types and coefficients listed above
Transit	200	238	206	204	167	
Manv	200	375	231	214	208	
Push	200	503	354	232	258	
Gensets	252	241	283	236	290	

Brake-Specific Criteria Emissions Factors (BSEF) Load-Dependent Fit Equations

Enter cycle weighted emissions target in orange cells (EPA limit or other value)

Molinari	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
6.8	NOx	0.0014	-0.21	13.7	6.8	20.2	NOx	0.0040	-0.61	40.4	20.1
1.1	CO	0.0002	-0.03	2.2	1.1	1.3	CO	0.0003	-0.04	2.6	1.3
0.76	HC	0.0002	-0.02	1.5	0.76	1.27	HC	0.0003	-0.04	2.5	1.27
0.14	PM	0.0000	0.00	0.3	0.14	0.44	PM	0.0001	-0.01	0.9	0.44
Barberi	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
10.2	NOx	0.0020	-0.31	20.4	10.1	20.2	NOx	0.0040	-0.61	40.4	20.1
0.9	CO	0.0002	-0.03	1.8	0.9	1.3	CO	0.0003	-0.04	2.6	1.3
0.17	HC	0.0000	-0.01	0.3	0.17	1.27	HC	0.0003	-0.04	2.5	1.27
0.28	PM	0.0001	-0.01	0.6	0.28	0.44	PM	0.0001	-0.01	0.9	0.44
Ollis	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10
Austen	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
5.0	NOx	0.0010	-0.15	10.0	5.0	20.2	NOx	0.0040	-0.61	40.4	20.1
0.6	CO	0.0001	-0.02	1.2	0.6	1.3	CO	0.0003	-0.04	2.6	1.3
0.60	HC	0.0001	-0.02	1.2	0.60	1.27	HC	0.0003	-0.04	2.5	1.27
0.04	PM	0.0000	0.00	0.1	0.04	0.44	PM	0.0001	-0.01	0.9	0.44
Midsize	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10

Notes:

Orange target values are based on manufacturer's certified data, where available. Where unavailable, values published by the EPA for the equivalent engine model were used.

At Tier 4, the HC limit is 10% of the combined HC+NOx limit. This ratio was used to estimate HC emissions for earlier tiers where no HC data was reported.

Quadratic fit curve coefficients are calculated above to estimate the load dependence of emissions factors. The general shape of these curves is based on a CAT 3516 Tier 3 engine for which complete emissions vs. load data was available.

The "Cycle Average" uses the BSEF predicted by the quadratic fit coefficients for specific load points with the weighting factors specified in the EPA rules for calculating emissions. See 40 CFR §1042 for additional details.

BSEF at Operating Profile Load Points

	Molinari	Barberi	Ollis	Austen	Midsize
			NOx		
Transit	6.3	9.0	1.0	5.5	1.0
Manv	6.3	13.1	1.5	7.7	1.4
Push	6.3	17.6	1.9	9.2	1.9
Gensets	18.7	18.2	5.1	17.8	5.3
			CO		
Transit	1.0	0.8	0.3	0.7	1.0
Manv	1.0	1.1	0.4	0.9	1.4
Push	1.0	1.5	0.5	1.1	1.9
Gensets	1.2	1.2	1.3	1.1	5.3
			HC		
Transit	0.70	0.15	0.01	0.66	0.26
Manv	0.70	0.22	0.01	0.92	0.37
Push	0.70	0.29	0.02	1.10	0.51
Gensets	1.18	1.15	0.61	1.12	1.33
			PM		
Transit	0.13	0.25	0.02	0.04	0.02
Manv	0.13	0.36	0.03	0.06	0.02
Push	0.13	0.48	0.04	0.07	0.03
Gensets	0.13	0.39	0.10	0.39	0.11

Note: calculated from quadratic coefficients on previous sheet and the engine's operating point (%MCR) at that phase of the operating profile

Total Energy, Fuel, Emissions Per Trip

Route profile (time per phase, minutes)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	19	18	19	15	15
Manv	3	4	3	7	7
Push	8	8	8	8	8
Gensets	30	30	30	30	30

Total Trip Energy (all engines) (kwh)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	860	1110	1393	491	578
Manv	136	104	93	97	114
Push	362	69	82	37	43
Gensets	168	109	109	71	82
Total	1526	1392	1678	696	817

Notes:

Route profile times were based on shipcheck notes.

Energy calculated from product of profile times and power

Total Trip Fuel (kg)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	172	264	286	100	96
Manv	27	39	22	21	24
Push	73	35	29	9	11
Gensets	42	26	31	17	24
Total	314	364	368	146	155

Total Trip Fuel (gal)

	Molinari	Barberi	Ollis	Austen	Midsize
Fuel	98	113	114	45	48

CO2 and SO2 per Trip

	Molinari	Barberi	Ollis	Austen	Midsize
CO2 (kg)	1008	1167	1179	469	497
SO2 (kg)	0.009	0.011	0.011	0.004	0.005

Fuel calculated from each engine's SFC, power level, and time

kg CO2 = 3.206 · kg diesel (MEPC 67/INF.3: Third IMO GHG Study, MGO value)

SO2 from mass balance using 15 ppm S oxidized to SO2

Diesel density = 3.218 kg/gal

Criteria Emissions per Trip (kg)

kg = BSEF · power level · no. engines

NOx

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	5.4	9.9	1.4	2.7	0.6
Manv	0.9	1.4	0.1	0.7	0.2
Push	2.3	1.2	0.2	0.3	0.1
Gensets	3.1	2.0	0.6	1.3	0.4

CO

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.9	0.9	0.4	0.3	0.6
Manv	0.1	0.1	0.0	0.1	0.2
Push	0.4	0.1	0.0	0.0	0.1
Gensets	0.2	0.1	0.1	0.1	0.4

HC

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.61	0.17	0.01	0.32	0.15
Manv	0.10	0.02	0.00	0.09	0.04
Push	0.25	0.02	0.00	0.04	0.02
Gensets	0.20	0.12	0.07	0.08	0.11

PM

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.11	0.27	0.03	0.02	0.010
Manv	0.02	0.04	0.00	0.01	0.003
Push	0.05	0.03	0.00	0.00	0.001
Gensets	0.02	0.04	0.01	0.03	0.009

Capital Cost Estimate

	Molinari			Barberi			Ollis			Austen			Midsize		
Equipment	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
Hybrid Equipment	3	$ 8,148,000	$ 24.4M		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Subtotal			$ 24.4M			$ -			$ -			$ -			$ -
Installation (@50%)			$ 12.2M			$ -			$ -			$ -			$ -
Total			$ 36.7M			$ -			$ -			$ -			$ -

Maintenance Cost Estimate

			Molinari		Barberi		Ollis		Austen		Midsize		
Item	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	
Main Propulsion Diesel Engine (engine hrs/yr)			7527		3796		27664		4940		4940		
Lube Oil Change	4000	hrs	$ 6,500	$ 12,231	$ 6,500	$ 6,169	$ 6,500	$ 44,954	$ 6,500	$ 8,028	$ 6,500	$ 8,028	
Minor Overhaul	8000	hrs	$ 37,000	$ 34,812	$ 37,000	$ 17,558	$ 37,000	$ 127,947	$ 37,000	$ 22,848	$ 37,000	$ 22,848	
Major Overhaul	30000	hrs	$ 242,000	$ 60,717	$ 242,000	$ 30,624	$ 242,000	$ 223,158	$ 242,000	$ 39,849	$ 242,000	$ 39,849	
Alternator Overhaul	10	yrs	$ 50,000	$ 45,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
Ship Service Diesel Generator (engine hrs/yr)			7527		949		6916		2470		2470		
Lube Oil Change	1000	hrs	$ 500	$ 3,763	$ 500	$ 475	$ 500	$ 3,458	$ 500	$ 1,235	$ 500	$ 1,235	
Minor Overhaul	20000	hrs	$ 50,000	$ 18,817	$ 50,000	$ 2,373	$ 50,000	$ 17,290	$ 50,000	$ 6,175	$ 50,000	$ 6,175	
Major Overhaul	20000	hrs	$ 100,000	$ 37,634	$ 100,000	$ 4,745	$ 100,000	$ 34,580	$ 100,000	$ 12,350	$ 100,000	$ 12,350	
Alternator Overhaul	10	yrs	$ 25,000	$ 15,000	$ 25,000	$ 2,143	$ 25,000	$ 13,810	$ 25,000	$ 5,000	$ 25,000	$ 7,143	
General													
Hull Coating	3	yrs	$ 10,000	$ 10,000	$ 10,000	$ 1,429	$ 10,000	$ 9,206	$ 6,000	$ 2,000	$ 7,500	$ 3,571	
Battery Replacement	6	yrs	$ 300,000	$ 150,000									Assumes $300/kwh for future replacements
Average ($/yr)				$ 387,974		$ 65,515		$ 474,404		$ 97,484		$ 101,199	

Notes

Hours/year are an average value from 2020-2040

SIF Plugin Electric Analysis

Baseline input data is formatted in orange

Baseline formulas are formatted in gray

Format changed input data or formulas

Unconfirmed data is in yellow (baseline or option-specific)

Summary

	Barberi	Molinari	Ollis	Austen	Midsize
Fuel/trip (gal)	113	0	0	45	0
Elec/trip (kwh)		1516	1687		858
Emissions/trip (kg)					
CO2	1167	302	353	469	171
SO2	0.011	0.179	0.209	0.004	0.101
NOx	14.5	0.3	0.4	5.0	0.2
CO	1.2	0.2	0.3	0.5	0.1
HC	0.3	0.0	0.0	0.5	0.0
PM	0.4	0.0	0.0	0.1	0.0
Cost Estimate					
Capital ($)	$ -	$ 75.0M	$ 75.0M	$ -	$ 12.0M
Maintenance ($/yr)	$ 65,515	$ .7M	$ 764,127	$ 97,484	$ 191,667

Highest Electric Deman 17.7 MW

Baseline Route Profile

Total Shaft Power by Class (kw)

Phase	Molinari	Barberi	Ollis	Austen	Midsize
Transit	3810	3700	4600	1965	2462
Manv	2113	1566	2062	832	1129
Push	899	520	818	276	475
Gensets	0	200	0	130	0

Notes:

Power levels above are generator powers where applicable. Efficiency applied below

Molinari profile based on total generator loading reported at the HMI, documented in shipcheck notes

Barberi power based on HMI readings of % power, modified by notes from Ollis design discussions and Barberi tank test data

Austen power based on SIF reporting

Midsize power extrapolated from Barberi and Ollis using Holtrop estimate. Full details in writeup by TSL

For integrated plants propulsion and ship service loads are combined

Assumptions:

1. Applicable to Molinari, Ollis and Midsize class
2. Would need integrated plant where PDG's, SSDG's, and batteries can supply power to entire vessel
3. Battery system efficiency is assumed to be 97% during both charging and discharging
4. Assume that required charging power is available shoreside
5. Assume 2 minutes for connect/disconnect and ramp up/down
6. Molinari, Midsize, and Ollis would be operated with fully electric propulsion

Engines and Conversion Efficiencies

	Molinari		Barberi		Ollis		Austen		Midsize	
Engines	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG
# Running	0	0	4	1	0	0	2	1	0	0
MCR (kw)	2983	370	1305	340	1861	340	2350	175	1491	340
MCR (hp)	4000	496	1750	456	2496	456	3151	235	1999	456
Elec. Efficiency	0.97		1	0.92	0.97		1	0.92	0.97	

Notes:

Molinari operates 2 of 3 installed propulsion generators. All other classes normally operate all propulsion engines.

Electrical efficiency applied to estimate engine load from switchboard readings. Efficiency based on similar generators

Austen propulsion engines are derated based on VSP limits. Full rating used here to accurately calculate SFC

Electrical efficiencies listed in green above represent the efficiency of the switchgear, either discharging the batteries to the propulsion motors, or charging the batteries from shore power.

Assume Molinari, Midsize, and Ollis operate with no engines

SFC Equations (ref fuel consumption/emissions workbook)

		a	b	c	Description (x=%MCR)	Reference for fit
Molinari	Propulsion	7800	-1.33	182	Power fit with constant offset: ax^b+c	Manufacturer data from 25%-100% MCR. Fit includes additional points <25% calculated from past study data provided by SIF
	SSDG	34600	-1.84	243	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Barberi	Propulsion	0.05	-8.36	581	Quadratic fit: ax^2+bx+c	Manufacturer data sheet. Sheet based on engine RPM and cubic propeller law. % of rated RPM used to estimate %MCR
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Ollis	Propulsion	2512	-1.30	193	Power fit with constant offset: ax^b+c	FAT for Ollis engines documented by SIF owner's representative
	SSDG	5130	-1.26	246	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 C18
Austen	Propulsion	104	-0.44	184	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 3516
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Midsize	Propulsion	0.02	-3.14	290	Quadratic fit: ax^2+bx+c	Simplified from manufacturer's data sheet
	SSDG	0.019	-3.31	406	Quadratic fit: ax^2+bx+c	Based on CAT Tier 3 C18

Engine Load Point, SFC

	Molinari	Barberi	Ollis	Austen	Midsize	Notes
		bkw per engine				Load per engine calculated from route profile, electrical efficiency, and number of engines operating
Transit	0	925	0	983	0	
Manv	0	392	0	416	0	
Push	0	130	0	138	0	
Gensets	0	217	0	141	0	
		% MCR				Based on engine ratings listed above
Transit	0	71	0	42	0	
Manv	0	30	0	18	0	
Push	0	10	0	6	0	
Gensets	0	64	0	81	0	
		SFC (g/kwh)				Calculated from %MCR using fit curve types and coefficients listed above
Transit	0	238	0	204	0	
Manv	0	375	0	214	0	
Push	0	503	0	232	0	
Gensets	0	241	0	236	0	

Brake-Specific Criteria Emissions Factors (BSEF) Load-Dependent Fit Equations

Enter cycle weighted emissions target in orange cells (EPA limit or other value)

~~**Molinari**~~		~~*Prop.*~~	~~a~~	~~b~~	~~c~~	~~**Cycle avg**~~	~~*SSDG*~~		~~a~~	~~b~~	~~c~~	~~**Cycle avg**~~
	~~6.5~~	~~NOx~~	~~0.0013~~	~~0.20~~	~~13.0~~	~~6.5~~	~~20.2~~	~~NOx~~	~~0.0040~~	~~0.61~~	~~40.4~~	~~20.1~~
	~~1.1~~	~~CO~~	~~0.0002~~	~~0.03~~	~~2.2~~	~~1.1~~	~~1.3~~	~~CO~~	~~0.0003~~	~~0.04~~	~~2.6~~	~~1.3~~
	~~0.70~~	~~HC~~	~~0.0001~~	~~0.02~~	~~1.4~~	~~0.70~~	~~1.27~~	~~HC~~	~~0.0003~~	~~0.04~~	~~2.5~~	~~1.27~~
	~~0.17~~	~~PM~~	~~0.0000~~	~~0.01~~	~~0.3~~	~~0.17~~	~~0.44~~	~~PM~~	~~0.0001~~	~~0.01~~	~~0.9~~	~~0.44~~
Barberi		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	10.2	NOx	0.0020	-0.31	20.4	10.1	20.2	NOx	0.0040	-0.61	40.4	20.1
	0.9	CO	0.0002	-0.03	1.8	0.9	1.3	CO	0.0003	-0.04	2.6	1.3
	0.17	HC	0.0000	-0.01	0.3	0.17	1.27	HC	0.0003	-0.04	2.5	1.27
	0.28	PM	0.0001	-0.01	0.6	0.28	0.44	PM	0.0001	-0.01	0.9	0.44
~~**Ollis**~~		~~*Prop.*~~	~~a~~	~~b~~	~~c~~	~~**Cycle avg**~~	~~*SSDG*~~		~~a~~	~~b~~	~~c~~	~~**Cycle avg**~~
	~~1.1~~	~~NOx~~	~~0.0002~~	~~-0.03~~	~~2.2~~	~~1.1~~	~~5.2~~	~~NOx~~	~~0.0010~~	~~-0.16~~	~~10.3~~	~~5.1~~
	~~0.3~~	~~CO~~	~~0.0001~~	~~-0.01~~	~~0.6~~	~~0.3~~	~~1.3~~	~~CO~~	~~0.0003~~	~~-0.04~~	~~2.6~~	~~1.3~~
	~~0.01~~	~~HC~~	~~0.0000~~	~~0.00~~	~~0.0~~	~~0.01~~	~~0.61~~	~~HC~~	~~0.0001~~	~~-0.02~~	~~1.2~~	~~0.61~~
	~~0.02~~	~~PM~~	~~0.0000~~	~~0.00~~	~~0.0~~	~~0.02~~	~~0.10~~	~~PM~~	~~0.0000~~	~~0.00~~	~~0.2~~	~~0.10~~
Austen		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	5.0	NOx	0.0010	-0.15	10.0	5.0	20.2	NOx	0.0040	-0.61	40.4	20.1
	0.6	CO	0.0001	-0.02	1.2	0.6	1.3	CO	0.0003	-0.04	2.6	1.3
	0.60	HC	0.0001	-0.02	1.2	0.60	1.27	HC	0.0003	-0.04	2.5	1.27
	0.04	PM	0.0000	0.00	0.1	0.04	0.44	PM	0.0001	-0.01	0.9	0.44
~~**Midsize**~~		~~*Prop.*~~	~~a~~	~~b~~	~~c~~	~~**Cycle avg**~~	~~*SSDG*~~		~~a~~	~~b~~	~~c~~	~~**Cycle avg**~~
	~~1.1~~	~~NOx~~	~~0.0002~~	~~0.03~~	~~2.2~~	~~1.1~~	~~5.2~~	~~NOx~~	~~0.0010~~	~~0.16~~	~~10.3~~	~~5.1~~
	~~0.3~~	~~CO~~	~~0.0001~~	~~0.01~~	~~0.6~~	~~0.3~~	~~1.3~~	~~CO~~	~~0.0003~~	~~0.04~~	~~2.6~~	~~1.3~~
	~~0.01~~	~~HC~~	~~0.0000~~	~~0.00~~	~~0.0~~	~~0.01~~	~~0.61~~	~~HC~~	~~0.0001~~	~~0.02~~	~~1.2~~	~~0.61~~
	~~0.02~~	~~PM~~	~~0.0000~~	~~0.00~~	~~0.0~~	~~0.02~~	~~0.10~~	~~PM~~	~~0.0000~~	~~0.00~~	~~0.2~~	~~0.10~~

Notes:

Orange target values are based on manufacturer's certified data, where available. Where unavailable, values published by the EPA for the equivalent engine model were used.

At Tier 4, the HC limit is 10% of the combined HC+NOx limit. This ratio was used to estimate HC emissions for earlier tiers where no HC data was reported.

Quadratic fit curve coefficients are calculated above to estimate the load dependence of emissions factors. The general shape of these curves is based on a CAT 3516 Tier 3 engine for which complete emissions vs. load data was available.

The "Cycle Average" uses the BSEF predicted by the quadratic fit coefficients for specific load points with the weighting factors specified in the EPA rules for calculating emissions. See 40 CFR §1042 for additional details.

Emissions for energy from shore is based on NY State average emissions data from EIA and EPA, directly entered in profile point calculations below.

BSEF at Operating Profile Load Points

	Molinari	Barberi	Ollis	Austen	Midsize
NOx					
Transit	0.222	9.0	0.222	5.5	0.222
Manv		13.1		7.7	
Push		17.6		9.2	
Gensets		18.2		17.8	
CO					
Transit	0.146	0.8	0.146	0.7	0.146
Manv		1.1		0.9	
Push		1.5		1.1	
Gensets		1.2		1.1	
HC					
Transit	0.007	0.15	0.007	0.66	0.007
Manv		0.22		0.92	
Push		0.29		1.10	
Gensets		1.15		1.12	
PM					
Transit	0.011	0.25	0.011	0.04	0.011
Manv		0.36		0.06	
Push		0.48		0.07	
Gensets		0.39		0.39	

Note: calculated from quadratic coefficients on previous sheet and the engine's operating point (%MCR) at that phase of the operating profile

Battery Sizing and Shore Energy Calculations

	Molinari	Mid-Size	Ollis		
Ramp Up/Down Time		2		min	
Energy per Trip	1342	763	1587	kWh/trip	
Battery Energy Required	1384	787	1636	kWh/trip	Incorporate discharging efficiency
Battery Size for D.O.D. 30%	4612	2622	5454	kWh	Incorporate 30% depth of discharge
Shore Energy to Charge Battery	1426	811	1687	kWh/trip	Incorporate charging efficiency
Power to Push Dock	899	475	818	kW	
Charging Time Available		6		min	
Charging Power Required	14264	8109	16867	kW	Necessary to charge battery in 6 minutes
Shore Power Required	15.2	8.6	17.7	MW	Power for charging and pushing the dock
Shore Energy Used	1516	858	1769	kWh/trip	Total shore energy used per trip
Carbon Dioxide Rate		199		g/kWh	
Sulfur Oxides Rate		0.118		g/kWh	

Notes

Carbon and Sulfur rates above are applicable to all shore energy used

Total Energy, Fuel, Emissions Per Trip

Route profile (time per phase, minutes)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	19	18	19	15	15
Manv	3	4	3	7	7
Push	8	8	8	8	8
Gensets	30	30	30	30	30

Total Trip Energy (all engines) (kwh)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0	1110	0	491	0
Manv	0	104	0	97	0
Push	0	69	0	37	0
Gensets	0	109	0	71	0
Total	0	1392	0	696	0

Notes:
Route profile times were based on shipcheck notes.
Energy calculated from product of profile times and power

Total Trip Fuel (kg)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0	264	0	100	0
Manv	0	39	0	21	0
Push	0	35	0	9	0
Gensets	0	26	0	17	0
Total	0	364	0	146	0

Total Trip Fuel (gal)

	Molinari	Barberi	Ollis	Austen	Midsize
Fuel	0	113	0	45	0

CO2 and SO2 per Trip

	Molinari	Barberi	Ollis	Austen	Midsize
CO2 (kg)	302	1167	353	469	171
SO2 (kg)	0.179	0.011	0.209	0.004	0.101

Fuel calculated from each engine's SFC, power level, and time
kg CO2 = 3.206 · kg diesel (MEPC 67/INF.3: Third IMO GHG Study, MGO value)
SO2 from mass balance using 15 ppm S oxidized to SO2
Diesel density = 3.218 kg/gal

Criteria Emissions per Trip (kg)

kg = BSEF · power level · no. engines

NOx

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.34	9.95	0.39	2.69	0.19
Manv		1.36		0.74	
Push		1.22		0.34	
Gensets		1.97		1.26	

CO

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.22	0.86	0.26	0.32	0.13
Manv		0.12		0.09	
Push		0.11		0.04	
Gensets		0.13		0.08	

HC

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.01	0.17	0.01	0.32	0.01
Manv		0.02		0.09	
Push		0.02		0.04	
Gensets		0.12		0.08	

PM

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.02	0.27	0.02	0.02	0.01
Manv		0.04		0.01	
Push		0.03		0.00	
Gensets		0.04		0.03	

SIF Plugin Electric Analysis

Capital Cost Estimate

Equipment	Molinari Qty	Molinari Cost (ea)	Molinari Cost	Barberi Qty	Barberi Cost (ea)	Barberi Cost	Ollis Qty	Ollis Cost (ea)	Ollis Cost	Austen Qty	Austen Cost (ea)	Austen Cost	Midsize Qty	Midsize Cost (ea)	Midsize Cost
Vessel Conversion	3	$ 25.0M	$ 75.0M		$ -	$ -	3	$ 25.0M	$ 75.0M		$ -	$ -	3	$ 4.0M	$ 12.0M
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Subtotal			$ 75.0M			$ -			$ 75.0M			$ -			$ 12.0M
Total Installation Cost (Included)			$ -			$ -			$ -			$ -			$ -
Total			$ 75.0M			$ -			$ 75.0M			$ -			$ 12.0M

Maintenance Cost Estimate

Item	Interval	Units	Molinari Cost (ea)	Molinari Cost	Barberi Cost (ea)	Barberi Cost	Ollis Cost (ea)	Ollis Cost	Austen Cost (ea)	Austen Cost	Midsize Cost (ea)	Midsize Cost	
Main Propulsion Diesel Engine (engine hrs/yr)			0		3796		0		4940		0		
Lube Oil Change	4000	hrs	$ 6,500	$ -	$ 6,500	$ 6,169	$ 6,500	$ -	$ 6,500	$ 8,028	$ 6,500	$ -	
Minor Overhaul	8000	hrs	$ 37,000	$ -	$ 37,000	$ 17,558	$ 37,000	$ -	$ 37,000	$ 22,848	$ 37,000	$ -	
Major Overhaul	30000	hrs	$ 242,000	$ -	$ 242,000	$ 30,624	$ 242,000	$ -	$ 242,000	$ 39,849	$ 242,000	$ -	
Alternator Overhaul	10	yrs	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	Assumes no alternator overhaul for plugin vessels
Ship Service Diesel Generator (engine hrs/yr)			0		949		0		2470		0		
Lube Oil Change	1000	hrs	$ 500	$ -	$ 500	$ 475	$ 500	$ -	$ 500	$ 1,235	$ 500	$ -	
Minor Overhaul	20000	hrs	$ 50,000	$ -	$ 50,000	$ 2,373	$ 50,000	$ -	$ 50,000	$ 6,175	$ 50,000	$ -	
Major Overhaul	20000	hrs	$ 100,000	$ -	$ 100,000	$ 4,745	$ 100,000	$ -	$ 100,000	$ 12,350	$ 100,000	$ -	
Alternator Overhaul	10	yrs	$ -	$ -	$ 25,000	$ 2,143	$ -	$ -	$ 25,000	$ 5,000	$ -	$ -	Assumes no alternator overhaul for plugin vessels
General													
Hull Coating	3	yrs	$ 10,000	$ 10,000	$ 10,000	$ 1,429	$ 10,000	$ 9,206	$ 6,000	$ 2,000	$ 7,500	$ 3,571	
Battery Replacement	6		$ 1.4M	$ 690,000			$ 1.6M	$ 754,921			$ 790,000	$ 188,095	Assumes $300/kwh for future replacements
Average ($/yr)				$ .7M		$ 65,515		$ 764,127		$ 97,484		$ 191,667	$300

Notes

Hours/year are an average value from 2020-2040

Appendix A.11 SIF LF Coatings Analysis

Summary

	Barberi	Molinari	Ollis	Austen	Midsize
Fuel/trip (gal)	112	107	112	45	47
Emissions/trip (kg)					
CO2	1152	1108	1154	460	488
SO2	0.011	0.010	0.011	0.004	0.005
NOx	14.2	10.6	2.3	5.0	1.2
CO	1.2	1.6	0.6	0.5	1.2
HC	0.3	1.1	0.1	0.5	0.3
PM	0.4	0.2	0.0	0.1	0.0
Cost Estimate					
Capital ($)	$ -	$ -	$ -	$ -	$ -
Maintenance ($/yr)	$ 66,015	$ 349,234	$ 477,627	$ 98,184	$ 102,449

Baseline input data is formatted in orange

Baseline formulas are formatted in gray

Format changed input data or formulas

Unconfirmed data is in yellow (baseline or option-specific)

Baseline Route Profile

	Total Shaft Power by Class (kw)				
Phase	Molinari	Barberi	Ollis	Austen	Midsize
Transit	3531	3589	4268	1906	2243
Manv	1943	1566	1862	832	979
Push	729	520	618	276	325
Gensets	170	200	200	130	150

Notes:
Power levels above are generator powers where applicable. Efficiency applied below
Molinari profile based on total generator loading reported at the HMI, documented in shipcheck notes
Barberi power based on HMI readings of % power, modified by notes from Ollis design discussions and Barberi tank test data
Austen power based on SIF reporting
Midsize power extrapolated from Barberi and Ollis using Holtrop estimate. Full details in writeup by TSL

Effect of Low Friction Hull Coating incorporated by reducing Total Shaft Power by 3% from baseline during "Transit" only

Assumptions:
1. Based on calculations the power reductions are assumed to be 3% overall during transit phase (see Appendix A.13)
2. Applicable to all classes of SIF vessels

Engines and Conversion Efficiencies

	Molinari		Barberi		Ollis		Austen		Midsize	
Engines	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG
# Running	2	1	4	1	4	1	2	1	2	1
MCR (kw)	2983	370	1305	340	1861	430	2350	175	1491	340
MCR (hp)	4000	496	1750	456	2496	577	3151	235	1999	456
Elec. Efficiency	0.96	0.92	1	0.92	1	0.92	1	0.92	1	0.92

Notes:
Molinari operates 2 of 3 installed propulsion generators. All other classes normally operate all propulsion engines.
Electrical efficiency applied to estimate engine load from switchboard readings. Efficiency based on similar generators
Austen propulsion engines are derated based on VSP limits. Full rating used here to accurately calculate SFC

SFC Equations (ref fuel consumption/emissions workbook)

		a	b	c	Description (x=%MCR)	Reference for fit
Molinari	Propulsion	7800	-1.33	182	Power fit with constant offset: ax^b+c	Manufacturer data from 25%-100% MCR. Fit includes additional points <25% calculated from past study data provided by SIF
	SSDG	34600	-1.84	243	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Barberi	Propulsion	0.05	-8.36	581	Quadratic fit: ax^2+bx+c	Manufacturer data sheet. Sheet based on engine RPM and cubic propeller law. % of rated RPM used to estimate %MCR
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Ollis	Propulsion	2512	-1.30	193	Power fit with constant offset: ax^b+c	FAT for Ollis engines documented by SIF owner's representative
	SSDG	5130	-1.26	246	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 C18
Austen	Propulsion	104	-0.44	184	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 3516
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Midsize	Propulsion	0.02	-3.14	290	Quadratic fit: ax^2+bx+c	Simplified from manufacturer's data sheet
	SSDG	0.019	-3.31	406	Quadratic fit: ax^2+bx+c	Based on CAT Tier 3 C18

Engine Load Point, SFC

	Molinari	Barberi	Ollis	Austen	Midsize	Notes
	bkw per engine					Load per engine calculated from route profile, electrical efficiency, and number of engines operating
Transit	1839	897	1067	953	1121	
Manv	1012	392	466	416	489	
Push	380	130	155	138	162	
Gensets	185	217	217	141	163	
	% MCR					Based on engine ratings listed above
Transit	62	69	57	41	75	
Manv	34	30	25	18	33	
Push	13	10	8	6	11	
Gensets	50	64	51	81	48	
	SFC (g/kwh)					Calculated from %MCR using fit curve types and coefficients listed above
Transit	214	241	206	205	167	
Manv	254	375	231	214	208	
Push	447	503	354	232	258	
Gensets	269	241	283	236	290	

Brake-Specific Criteria Emissions Factors (BSEF) Load-Dependent Fit Equations

Enter cycle weighted emissions target in orange cells (EPA limit or other value)

Molinari		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	6.5	NOx	0.0013	-0.20	13.0	6.5	20.2	NOx	0.0040	-0.61	40.4	20.1
	1.1	CO	0.0002	-0.03	2.2	1.1	1.3	CO	0.0003	-0.04	2.6	1.3
	0.70	HC	0.0001	-0.02	1.4	0.70	1.27	HC	0.0003	-0.04	2.5	1.27
	0.17	PM	0.0000	-0.01	0.3	0.17	0.44	PM	0.0001	-0.01	0.9	0.44
Barberi		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	10.2	NOx	0.0020	-0.31	20.4	10.1	20.2	NOx	0.0040	-0.61	40.4	20.1
	0.9	CO	0.0002	-0.03	1.8	0.9	1.3	CO	0.0003	-0.04	2.6	1.3
	0.17	HC	0.0000	-0.01	0.3	0.17	1.27	HC	0.0003	-0.04	2.5	1.27
	0.28	PM	0.0001	-0.01	0.6	0.28	0.44	PM	0.0001	-0.01	0.9	0.44
Ollis		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
	0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
	0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
	0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10
Austen		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	5.0	NOx	0.0010	-0.15	10.0	5.0	20.2	NOx	0.0040	-0.61	40.4	20.1
	0.6	CO	0.0001	-0.02	1.2	0.6	1.3	CO	0.0003	-0.04	2.6	1.3
	0.60	HC	0.0001	-0.02	1.2	0.60	1.27	HC	0.0003	-0.04	2.5	1.27
	0.04	PM	0.0000	0.00	0.1	0.04	0.44	PM	0.0001	-0.01	0.9	0.44
Midsize		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
	0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
	0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
	0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10

Notes:

Orange target values are based on manufacturer's certified data, where available. Where unavailable, the Tier limit for the certified or equivalent Tier claimed by the engine.

At Tier 4, the HC limit is 10% of the combined HC+NOx limit. This ratio was used to estimate HC emissions for earlier tiers where no HC data was reported.

Quadratic fit curve coefficients are calculated above to estimate the load dependence of emissions factors. The general shape of these curves is based on a CAT 3516 Tier 3 engine for which complete emissions vs. load data was available.

The "Cycle Average" uses the BSEF predicted by the quadratic fit coefficients for specific load points with the weighting factors specified in the EPA rules for calculating emissions. See 40 CFR §1042 for additional details.

BSEF at Operating Profile Load Points

	Molinari	Barberi	Ollis	Austen	Midsize
		NOx			
Transit	5.9	9.0	1.0	5.6	1.0
Manv	7.9	13.1	1.5	7.7	1.4
Push	10.7	17.6	1.9	9.2	1.9
Gensets	20.2	18.2	5.1	17.8	5.3
		CO			
Transit	1.0	0.8	0.3	0.7	1.0
Manv	1.3	1.1	0.4	0.9	1.4
Push	1.8	1.5	0.5	1.1	1.9
Gensets	1.3	1.2	1.3	1.1	5.3
		HC			
Transit	0.64	0.15	0.01	0.67	0.26
Manv	0.85	0.22	0.01	0.92	0.37
Push	1.16	0.29	0.02	1.10	0.51
Gensets	1.28	1.15	0.61	1.12	1.33
		PM			
Transit	0.15	0.25	0.02	0.04	0.02
Manv	0.21	0.36	0.03	0.06	0.02
Push	0.28	0.48	0.04	0.07	0.03
Gensets	0.17	0.39	0.10	0.39	0.11

Note: calculated from quadratic coefficients on previous sheet and the engine's operating point (%MCR) at that phase of the operating profile

Total Energy, Fuel, Emissions Per Trip

Route profile (time per phase, minutes)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	19	18	19	15	15
Manv	3	4	3	7	7
Push	8	8	8	8	8
Gensets	30	30	30	30	30

Total Trip Energy (all engines) (kwh)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1165	1077	1352	477	561
Manv	101	104	93	97	114
Push	101	69	82	37	43
Gensets	92	109	109	71	82
Total	1460	1359	1636	681	800

Notes:

Route profile times were based on shipcheck notes.

Energy calculated from product of profile times and power

Total Trip Fuel (kg)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	250	259	278	98	94
Manv	26	39	22	21	24
Push	45	35	29	9	11
Gensets	25	26	31	17	24
Total	346	359	360	143	152

Total Trip Fuel (gal)

	Molinari	Barberi	Ollis	Austen	Midsize
Fuel	107	112	112	45	47

CO2 and SO2 per Trip

	Molinari	Barberi	Ollis	Austen	Midsize
CO2 (kg)	1108	1152	1154	460	488
SO2 (kg)	0.010	0.011	0.011	0.004	0.005

Fuel calculated from each engine's SFC, power level, and time

kg CO2 = 3.206 · kg diesel (MEPC 67/INF.3: Third IMO GHG Study, MGO value)

SO2 from mass balance using 15 ppm S oxidized to SO2

Diesel density = 3.218 kg/gal

Criteria Emissions per Trip (kg)

kg = BSEF · power level · no. engines

NOx

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	6.9	9.7	1.4	2.7	0.5
Manv	0.8	1.4	0.1	0.7	0.2
Push	1.1	1.2	0.2	0.3	0.1
Gensets	1.9	2.0	0.6	1.3	0.4

CO

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1.2	0.8	0.4	0.3	0.5
Manv	0.1	0.1	0.0	0.1	0.2
Push	0.2	0.1	0.0	0.0	0.1
Gensets	0.1	0.1	0.1	0.1	0.4

HC

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.74	0.16	0.01	0.32	0.15
Manv	0.09	0.02	0.00	0.09	0.04
Push	0.12	0.02	0.00	0.04	0.02
Gensets	0.12	0.12	0.07	0.08	0.11

PM

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.18	0.27	0.03	0.02	0.010
Manv	0.02	0.04	0.00	0.01	0.003
Push	0.03	0.03	0.00	0.00	0.001
Gensets	0.02	0.04	0.01	0.03	0.009

Capital Cost Estimate

	Molinari			Barberi			Ollis			Austen			Midsize		
Equipment	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Subtotal			$ -			$ -			$ -			$ -			$ -
Installation (@50%)			$ -			$ -			$ -			$ -			$ -
Total			$ -			$ -			$ -			$ -			$ -

Maintenance Cost Estimate

			Molinari		Barberi		Ollis		Austen		Midsize		
Item	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	
Main Propulsion Diesel Engine (engine hrs/yr)			15054		3796		27664		4940		4940		
Lube Oil Change	4000	hrs	$ 6,500	$ 24,462	$ 6,500	$ 6,169	$ 6,500	$ 44,954	$ 6,500	$ 8,028	$ 6,500	$ 8,028	
Minor Overhaul	8000	hrs	$ 37,000	$ 69,623	$ 37,000	$ 17,558	$ 37,000	$ 127,947	$ 37,000	$ 22,848	$ 37,000	$ 22,848	
Major Overhaul	30000	hrs	$ 242,000	$ 121,433	$ 242,000	$ 30,624	$ 242,000	$ 223,158	$ 242,000	$ 39,849	$ 242,000	$ 39,849	
Alternator Overhaul	10	yrs	$ 50,000	$ 45,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
Ship Service Diesel Generator (engine hrs/yr)			7527		949		6916		2470		2470		
Lube Oil Change	1000	hrs	$ 500	$ 3,763	$ 500	$ 475	$ 500	$ 3,458	$ 500	$ 1,235	$ 500	$ 1,235	
Minor Overhaul	20000	hrs	$ 50,000	$ 18,817	$ 50,000	$ 2,373	$ 50,000	$ 17,290	$ 50,000	$ 6,175	$ 50,000	$ 6,175	
Major Overhaul	20000	hrs	$ 100,000	$ 37,634	$ 100,000	$ 4,745	$ 100,000	$ 34,580	$ 100,000	$ 12,350	$ 100,000	$ 12,350	
Alternator Overhaul	10	yrs	$ 25,000	$ 15,000	$ 25,000	$ 2,143	$ 25,000	$ 13,810	$ 25,000	$ 5,000	$ 25,000	$ 7,143	
General													
Hull Coating	10	yrs	$ 45,000	$ 13,500	$ 45,000	$ 1,929	$ 45,000	$ 12,429	$ 27,000	$ 2,700	$ 33,750	$ 4,821	Based on vendor information
Average ($/yr)				$ 349,234		$ 66,015		$ 477,627		$ 98,184		$ 102,449	

Notes

Hours/year are an average value from 2020-2040

Summary

	Barberi	Molinari	Ollis	Austen	Midsize
Fuel/trip (gal)	119	109	114	45	48
Emissions/trip (kg)					
CO2	1229	1128	1179	469	497
SO2	0.011	0.011	0.011	0.004	0.005
NOx	10.1	10.8	2.3	5.0	1.2
CO	1.1	1.6	0.6	0.5	1.2
HC	0.4	1.1	0.1	0.5	0.3
PM	0.4	0.1	0.0	0.1	0.0
Cost Estimate					
Capital ($)	$ 100,000	$2.1M	$ -	$ -	$ -
Maintenance ($/yr)	$ 65,515	$ 345,734	$ 474,404	$ 97,484	$ 101,199

Baseline input data is formatted in orange

Baseline formulas are formatted in gray

Format changed input data or formulas

Unconfirmed data is in yellow (baseline or option-specific)

Baseline Route Profile

	Total Shaft Power by Class (kw)				
Phase	Molinari	Barberi	Ollis	Austen	Midsize
Transit	3640	3700	4400	1965	2312
Manv	1943	1566	1862	832	979
Push	729	520	618	276	325
Gensets	170	200	200	130	150

Notes:

Power levels above are generator powers where applicable. Efficiency applied below

Molinari profile based on total generator loading reported at the HMI, documented in shipcheck notes

Barberi power based on HMI readings of % power, modified by notes from Ollis design discussions and Barberi tank test data

Austen power based on SIF reporting

Midsize power extrapolated from Barberi and Ollis using Holtrop estimate. Full details in writeup by TSL

Engines and Conversion Efficiencies

	Molinari		Barberi		Ollis		Austen		Midsize	
Engines	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG
# Running	2	1	4	1	4	1	2	1	2	1
MCR (kw)	2983	370	1305	340	1861	430	2350	175	1491	340
MCR (hp)	**4000**	**496**	**1750**	**456**	**2496**	**577**	**3151**	**235**	**1999**	**456**
Elec. Efficiency	0.96	0.92	1	0.92	1	0.92	1	0.92	1	0.92

Notes:

Molinari operates 2 of 3 installed propulsion generators. All other classes normally operate all propulsion engines.

Electrical efficiency applied to estimate engine load from switchboard readings. Efficiency based on similar generators

Austen propulsion engines are derated based on VSP limits. Full rating used here to accurately calculate SFC

SFC Equations (ref fuel consumption/emissions workbook)

		a	b	c	Description (x=%MCR)	Reference for fit
Molinari	Propulsion	7800	-1.33	182	Power fit with constant offset: ax^b	Manufacturer data from 25%-100% MCR. Fit includes additional points <25% calculated from past study data provided by SIF
	SSDG	34600	-1.84	243	Power fit with constant offset: ax^b	Manufacturer data sheet
Barberi	Propulsion	0.05	-8.36	596	Quadratic fit: ax^2+bx+c	15 g/kwh increase added based on change in 100% MCR SFC reported to EPA
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b	Manufacturer data sheet
Ollis	Propulsion	2512	-1.30	193	Power fit with constant offset: ax^b	FAT for Ollis engines documented by SIF owner's representative
	SSDG	5130	-1.26	246	Power fit with constant offset: ax^b	Manufacturer's data sheet for Tier 3 C18
Austen	Propulsion	104	-0.44	184	Power fit with constant offset: ax^b	Manufacturer's data sheet for Tier 3 3516
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b	Manufacturer data sheet
Midsize	Propulsion	0.02	-3.14	290	Quadratic fit: ax^2+bx+c	Simplified from manufacturer's data sheet
	SSDG	0.019	-3.31	406	Quadratic fit: ax^2+bx+c	Based on CAT Tier 3 C18

Engine Load Point, SFC

	Molinari	Barberi	Ollis	Austen	Midsize	Notes
		bkw per engine				Load per engine calculated from route profile, electrical efficiency, and number of en
Transit	1896	925	1100	983	1156	
Manv	1012	392	466	416	489	
Push	380	130	155	138	162	
Gensets	185	217	217	141	163	
		% MCR				Based on engine ratings listed above
Transit	64	71	59	42	78	
Manv	34	30	25	18	33	
Push	13	10	8	6	11	
Gensets	50	64	51	81	48	
		SFC (g/kwh)				Calculated from %MCR using fit curve types and coefficients listed above
Transit	213	253	206	204	167	
Manv	254	390	231	214	208	
Push	447	518	354	232	258	
Gensets	269	241	283	236	290	

Brake-Specific Criteria Emissions Factors (BSEF) Load-Dependent Fit Equations

Enter cycle weighted emissions target in orange cells (EPA limit or other value)

Molinari	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
6.5	NOx	0.0013	-0.20	13.0	6.5	20.2	NOx	0.0040	-0.61	40.4	20.1
1.1	CO	0.0002	-0.03	2.2	1.1	1.3	CO	0.0003	-0.04	2.6	1.3
0.70	HC	0.0001	-0.02	1.4	0.70	1.27	HC	0.0003	-0.04	2.5	1.27
0.07	PM	0.0000	0.00	0.1	0.07	0.44	PM	0.0001	-0.01	0.9	0.44
Barberi	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
6.7	NOx	0.0013	-0.20	13.3	6.6	20.2	NOx	0.0040	-0.61	40.4	20.1
0.8	CO	0.0002	-0.02	1.6	0.8	1.3	CO	0.0003	-0.04	2.6	1.3
0.22	HC	0.0000	-0.01	0.4	0.22	1.27	HC	0.0003	-0.04	2.5	1.27
0.28	PM	0.0001	-0.01	0.6	0.28	0.44	PM	0.0001	-0.01	0.9	0.44
Ollis	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10
Austen	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
5.0	NOx	0.0010	-0.15	10.0	5.0	20.2	NOx	0.0040	-0.61	40.4	20.1
0.6	CO	0.0001	-0.02	1.2	0.6	1.3	CO	0.0003	-0.04	2.6	1.3
0.60	HC	0.0001	-0.02	1.2	0.60	1.27	HC	0.0003	-0.04	2.5	1.27
0.04	PM	0.0000	0.00	0.1	0.04	0.44	PM	0.0001	-0.01	0.9	0.44
Midsize	*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10

Notes:

Orange target values are based on manufacturer's certified data, where available. Where unavailable, the Tier limit for the certified or equivalent Tier claimed by the engine.

At Tier 4, the HC limit is 10% of the combined HC+NOx limit. This ratio was used to estimate HC emissions for earlier tiers where no HC data was reported.

Quadratic fit curve coefficients are calculated above to estimate the load dependence of emissions factors. The general shape of these curves is based on a CAT 3516 Tier 3 engine for which complete emissions vs. load data was available.

The "Cycle Average" uses the BSEF predicted by the quadratic fit coefficients for specific load points with the weighting factors specified in the EPA rules for calculating emissions. See 40 CFR §1042 for additional details.

BSEF at Operating Profile Load Points

	Molinari	Barberi	Ollis	Austen	Midsize
		NOx			
Transit	5.9	5.8	1.0	5.5	1.0
Manv	7.9	8.5	1.5	7.7	1.4
Push	10.7	11.4	1.9	9.2	1.9
Gensets	20.2	18.2	5.1	17.8	5.3
		CO			
Transit	1.0	0.7	0.3	0.7	1.0
Manv	1.3	1.0	0.4	0.9	1.4
Push	1.8	1.4	0.5	1.1	1.9
Gensets	1.3	1.2	1.3	1.1	5.3
		HC			
Transit	0.63	0.19	0.01	0.66	0.26
Manv	0.85	0.28	0.01	0.92	0.37
Push	1.16	0.37	0.02	1.10	0.51
Gensets	1.28	1.15	0.61	1.12	1.33
		PM			
Transit	0.06	0.25	0.02	0.04	0.02
Manv	0.08	0.36	0.03	0.06	0.02
Push	0.12	0.48	0.04	0.07	0.03
Gensets	0.07	0.39	0.10	0.39	0.11

Note: calculated from quadratic coefficients on previous sheet and the engine's operating point (%MCR) at that phase of the operating profile

Total Energy, Fuel, Emissions Per Trip

Route profile (time per phase, minutes)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	19	18	19	15	15
Manv	3	4	3	7	7
Push	8	8	8	8	8
Gensets	30	30	30	30	30

Total Trip Energy (all engines) (kwh)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1201	1110	1393	491	578
Manv	101	104	93	97	114
Push	101	69	82	37	43
Gensets	92	109	109	71	82
Total	1496	1392	1678	696	817

Total Trip Fuel (kg)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	256	280	286	100	96
Manv	26	41	22	21	24
Push	45	36	29	9	11
Gensets	25	26	31	17	24
Total	352	383	368	146	155

Total Trip Fuel (gal)

	Molinari	Barberi	Ollis	Austen	Midsize
Fuel	109	119	114	45	48

CO2 and SO2 per Trip

	Molinari	Barberi	Ollis	Austen	Midsize
CO2 (kg)	1128	1229	1179	469	497
SO2 (kg)	0.011	0.011	0.011	0.004	0.005

Notes:

Route profile times were based on shipcheck notes.

Energy calculated from product of profile times and power

Fuel calculated from each engine's SFC, power level, and time

kg CO2 = 3.206 · kg diesel (MEPC 67/INF.3: Third IMO GHG Study, MGO value)

SO2 from mass balance using 15 ppm S oxidized to SO2

Carbon intensity described in Sections 2.2.3 and 5.3.4

Diesel density = 3.218 kg/gal

Criteria Emissions per Trip (kg)

kg = BSEF · power level · no. engines

NOx

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	7.0	6.5	1.4	2.7	0.6
Manv	0.8	0.9	0.1	0.7	0.2
Push	1.1	0.8	0.2	0.3	0.1
Gensets	1.9	2.0	0.6	1.3	0.4

CO

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	1.2	0.8	0.4	0.3	0.6
Manv	0.1	0.1	0.0	0.1	0.2
Push	0.2	0.1	0.0	0.0	0.1
Gensets	0.1	0.1	0.1	0.1	0.4

HC

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.76	0.21	0.01	0.32	0.15
Manv	0.09	0.03	0.00	0.09	0.04
Push	0.12	0.03	0.00	0.04	0.02
Gensets	0.12	0.12	0.07	0.08	0.11

PM

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.08	0.27	0.03	0.02	0.010
Manv	0.01	0.04	0.00	0.01	0.003
Push	0.01	0.03	0.00	0.00	0.001
Gensets	0.01	0.04	0.01	0.03	0.009

Capital Cost Estimate

	Molinari			Barberi			Ollis			Austen			Midsize		
Equipment	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
PDE Upgrades	3	$ 230,000	$2.1M	4	$ 25,000	$ 100,000		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Subtotal			$2.1M			$ 100,000			$ -			$ -			$ -
Installation (Included)			$ -						$ -			$ -			$ -
Total			$2.1M			$ 100,000			$ -			$ -			$ -

Upgrade cost excludes maintenance costs from below table, since upgrades accomplish overhauls and reset maintenance intervals

Maintenance Cost Estimate

			Molinari		Barberi		Ollis		Austen		Midsize	
Item	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost
Main Propulsion Diesel Engine (engine hrs/yr)			15054		3796		27664		4940		4940	
Lube Oil Change	4000	hrs	$ 6,500	$ 24,462	$ 6,500	$ 6,169	$ 6,500	$ 44,954	$ 6,500	$ 8,028	$ 6,500	$ 8,028
Minor Overhaul	8000	hrs	$ 37,000	$ 69,623	$ 37,000	$ 17,558	$ 37,000	$ 127,947	$ 37,000	$ 22,848	$ 37,000	$ 22,848
Major Overhaul	30000	hrs	$ 242,000	$ 121,433	$ 242,000	$ 30,624	$ 242,000	$ 223,158	$ 242,000	$ 39,849	$ 242,000	$ 39,849
Alternator Overhaul	10	yrs	$ 50,000	$ 45,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Ship Service Diesel Generator (engine hrs/yr)			7527		949		6916		2470		2470	
Lube Oil Change	1000	hrs	$ 500	$ 3,763	$ 500	$ 475	$ 500	$ 3,458	$ 500	$ 1,235	$ 500	$ 1,235
Minor Overhaul	20000	hrs	$ 50,000	$ 18,817	$ 50,000	$ 2,373	$ 50,000	$ 17,290	$ 50,000	$ 6,175	$ 50,000	$ 6,175
Major Overhaul	20000	hrs	$ 100,000	$ 37,634	$ 100,000	$ 4,745	$ 100,000	$ 34,580	$ 100,000	$ 12,350	$ 100,000	$ 12,350
Alternator Overhaul	10	yrs	$ 25,000	$ 15,000	$ 25,000	$ 2,143	$ 25,000	$ 13,810	$ 25,000	$ 5,000	$ 25,000	$ 7,143
General												
Hull Coating	3	yrs	$ 10,000	$ 10,000	$ 10,000	$ 1,429	$ 10,000	$ 9,206	$ 6,000	$ 2,000	$ 7,500	$ 3,571
Average ($/yr)				$ 345,734		$ 65,515		$ 474,404		$ 97,484		$ 101,199

Notes

Hours/year are an average value from 2020-2040

SIF Molinari Class Tier 3 Hybrid II Analysis

Summary

	Barberi	Molinari	Ollis	Austen	Midsize
Fuel/trip (gal)	113	100	114	45	48
Emissions/trip (kg)					
CO2	1167	1029	1179	469	497
SO2	0.011	0.010	0.011	0.004	0.005
NOx	14.5	8.0	2.3	5.0	1.2
CO	1.2	0.7	0.6	0.5	1.2
HC	0.3	0.2	0.1	0.5	0.3
PM	0.4	0.1	0.0	0.1	0.0
Cost Estimate					
Capital ($)	$ -	$ 15.2M	$ -	$ -	$ -
Maintenance ($/yr)	$ 65,515	$ 684,374	$ 474,404	$ 97,484	$ 101,199

Baseline input data is formatted in orange

Baseline formulas are formatted in gray

Format changed input data or formulas

Unconfirmed data is in yellow (baseline or option-specific)

Baseline Route Profile

Total Shaft Power by Class (kw)

Phase	Molinari	Barberi	Ollis	Austen	Midsize
Transit	3640	3700	4400	1965	2312
Manv	1943	1566	1862	832	979
Push	729	520	618	276	325
Genset	170	200	200	130	150

Notes:
Power levels above are generator powers where applicable. Efficiency applied below
Molinari profile based on total generator loading reported at the HMI, documented in shipcheck notes
Barberi power based on HMI readings of % power, modified by notes from Ollis design discussions and Barberi tank test data
Austen power based on SIF reporting
Midsize power extrapolated from Barberi and Ollis using Holtrop estimate. Full details in writeup by TSL

Assumptions:
1. Applicable to only Molinari class
2. New ship service diesel generators - CAT C18 at highest available rating
3. Upgrade to existing propulsion generators - EPA Tier 3 equivalent
4. Integration of ship service and propulsion electrical distribution, SSDGs can provide supplemental propulsion power
5. Additon of energy storage

Engines and Conversion Efficiencies

	Molinari		Barberi		Ollis		Austen		Midsize	
Engines	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG	Prop	SSDG
# Running	1	1	4	1	4	1	2	1	2	1
MCR (kw)	2983	600	1305	340	1861	430	2350	175	1491	340
MCR (hp)	4000	805	1750	456	2496	577	3151	235	1999	456
Elec. Efficiency	0.96	0.92	1	0.92	1	0.92	1	0.92	1	0.92

Notes:
Molinari operates 2 of 3 installed propulsion generators. All other classes normally operate all propulsion engines.
Electrical efficiency applied to estimate engine load from switchboard readings. Efficiency based on similar generators
Austen propulsion engines are derated based on VSP limits. Full rating used here to accurately calculate SFC
For hybrid Molinari operation only 1 propulsion and 1 ship's service generator are assumed to be in operation. This case is provided as an average of the vessel's load profile. Practically, a second ship service generator and/or shore power charging will be needed on some percentage of the trips. This option assumes 2520ekW are provided by the online propulsion generator.

	bkw required	Engine (kW)	Battery (kW)	Battery kWh	w/ Efficiency
Transit	3810	3006	804	255	280
Maneuvering	2113	3006	-893	-45	-41
Pushing Dock	899	3006	-2107	-281	-256

			Power Ratios	
MCR (%)	*Hybrid Eff.*	*kWh/trip*	*PDGs*	*SSDGs*
88	91%	-16	84%	16%

Positive battery energy indicates battery discharging, negative battery energy indicates battery is charging

SFC Equations (ref fuel consumption/emissions workbook)

		a	b	c	Description (x=%MCR)	Reference for fit
Molinari	Propulsion	7800	-1.33	182	Power fit with constant offset: ax^b+c	Manufacturer data from 25%-100% MCR. Fit includes additional points <25% calculated from past study data provided by SIF
	SSDG	503.22	-0.20	0	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Barberi	Propulsion	0.05	-8.36	581	Quadratic fit: ax^2+bx+c	Manufacturer data sheet. Sheet based on engine RPM and cubic propeller law. % of rated RPM used to estimate %MCR
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Ollis	Propulsion	2512	-1.30	193	Power fit with constant offset: ax^b+c	FAT for Ollis engines documented by SIF owner's representative
	SSDG	5130	-1.26	246	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 C18
Austen	Propulsion	104	-0.44	184	Power fit with constant offset: ax^b+c	Manufacturer's data sheet for Tier 3 3516
	SSDG	17654	-1.67	224	Power fit with constant offset: ax^b+c	Manufacturer data sheet
Midsize	Propulsion	0.02	-3.14	290	Quadratic fit: ax^2+bx+c	Simplified from manufacturer's data sheet
	SSDG	0.019	-3.31	406	Quadratic fit: ax^2+bx+c	Based on CAT Tier 3 C18

Engine Load Point, SFC

	Molinari	Barberi	Ollis	Austen	Midsize
	bkw all engines		bkw per engine		
Transit	2625	925	1100	983	1156
Manv	2625	392	466	416	489
Push	2625	130	155	138	162
Genset	528	217	217	141	163
		% MCR			
Transit	88	71	59	42	78
Manv	88	30	25	18	33
Push	88	10	8	6	11
Genset	88	64	51	81	48
		SFC (g/kwh)			
Transit	202	238	206	204	167
Manv	202	375	231	214	208
Push	202	503	354	232	258
Genset	210	241	283	236	290

Notes

Load per engine calculated from route profile, electrical efficiency, and number of engines operating

Load per engine is based on "% MCR" engine operating point. This is defined above.

bkW for Molinari class is given for all engines online, as defined above.

Based on engine ratings listed above

"% MCR" is an input - engines will run at this level and excess energy will go to batteries

Calculated from %MCR using fit curve types and coefficients listed above

Brake-Specific Criteria Emissions Factors (BSEF) Load-Dependent Fit Equations

Enter cycle weighted emissions target in orange cells (EPA limit or other value)

			a	b	c	Cycle avg			a	b	c	Cycle avg
Molinari		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	6.70	NOx	0.0013	-0.20	13.4	6.7	4.50	NOx	0.0009	-0.14	9.0	4.5
	0.61	CO	0.0001	-0.02	1.2	0.6	0.80	CO	0.0002	-0.02	1.6	0.8
	0.19	HC	0.0000	-0.01	0.4	0.19	0.14	HC	0.0000	0.00	0.3	0.14
	0.07	PM	0.0000	0.00	0.1	0.07	0.08	PM	0.0000	0.00	0.2	0.08
Barberi		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	10.2	NOx	0.0020	-0.31	20.4	10.1	20.2	NOx	0.0040	-0.61	40.4	20.1
	0.9	CO	0.0002	-0.03	1.8	0.9	1.3	CO	0.0003	-0.04	2.6	1.3
	0.17	HC	0.0000	-0.01	0.3	0.17	1.27	HC	0.0003	-0.04	2.5	1.27
	0.28	PM	0.0001	-0.01	0.6	0.28	0.44	PM	0.0001	-0.01	0.9	0.44
Ollis		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
	0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
	0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
	0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10
Austen		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	5.0	NOx	0.0010	-0.15	10.0	5.0	20.2	NOx	0.0040	-0.61	40.4	20.1
	0.6	CO	0.0001	-0.02	1.2	0.6	1.3	CO	0.0003	-0.04	2.6	1.3
	0.60	HC	0.0001	-0.02	1.2	0.60	1.27	HC	0.0003	-0.04	2.5	1.27
	0.04	PM	0.0000	0.00	0.1	0.04	0.44	PM	0.0001	-0.01	0.9	0.44
Midsize		*Prop.*	a	b	c	**Cycle avg**	*SSDG*		a	b	c	**Cycle avg**
	1.1	NOx	0.0002	-0.03	2.2	1.1	5.2	NOx	0.0010	-0.16	10.3	5.1
	0.3	CO	0.0001	-0.01	0.6	0.3	1.3	CO	0.0003	-0.04	2.6	1.3
	0.01	HC	0.0000	0.00	0.0	0.01	0.61	HC	0.0001	-0.02	1.2	0.61
	0.02	PM	0.0000	0.00	0.0	0.02	0.10	PM	0.0000	0.00	0.2	0.10

Molinari propulsion diesel generators are assumed upgraded to Tier 3,
Molinari ship service diesel generators are replaced with new Tier 3 engines.

Notes:

Orange target values are based on manufacturer's certified data, where available. Where unavailable, values published by the EPA for the equivalent engine model were used.

At Tier 4, the HC limit is 10% of the combined HC+NOx limit. This ratio was used to estimate HC emissions for earlier tiers where no HC data was reported.

Quadratic fit curve coefficients are calculated above to estimate the load dependence of emissions factors. The general shape of these curves is based on a CAT 3516 Tier 3 engine for which complete emissions vs. load data was available.

The "Cycle Average" uses the BSEF predicted by the quadratic fit coefficients for specific load points with the weighting factors specified in the EPA rules for calculating emissions. See 40 CFR §1042 for additional details.

BSEF at Operating Profile Load Points

	Molinari	Barberi	Ollis	Austen	Midsize
			NOx		
Transit	6.1	9.0	1.0	5.5	1.0
Manv	6.1	13.1	1.5	7.7	1.4
Push	6.1	17.6	1.9	9.2	1.9
Gensets	4.1	18.2	5.1	17.8	5.3
			CO		
Transit	0.5	0.8	0.3	0.7	1.0
Manv	0.5	1.1	0.4	0.9	1.4
Push	0.5	1.5	0.5	1.1	1.9
Gensets	0.7	1.2	1.3	1.1	5.3
			HC		
Transit	0.17	0.15	0.01	0.66	0.26
Manv	0.17	0.22	0.01	0.92	0.37
Push	0.17	0.29	0.02	1.10	0.51
Gensets	0.13	1.15	0.61	1.12	1.33
			PM		
Transit	0.06	0.25	0.02	0.04	0.02
Manv	0.06	0.36	0.03	0.06	0.02
Push	0.06	0.48	0.04	0.07	0.03
Gensets	0.07	0.39	0.10	0.39	0.11

Note: calculated from quadratic coefficients on previous sheet and the engine's operating point (%MCR) at that phase of the operating profile

Total Energy, Fuel, Emissions Per Trip

Route profile (time per phase, minutes)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	19	18	19	15	15
Manv	3	4	3	7	7
Push	8	8	8	8	8
Gensets	30	30	30	30	30

Total Trip Energy (all engines) (kwh)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	831	1110	1393	491	578
Manv	131	104	93	97	114
Push	350	69	82	37	43
Gensets	264	109	109	71	82
Total	1576	1392	1678	696	817

Notes:

Route profile times were based on shipcheck notes.

Energy calculated from product of profile times and power

Total Trip Fuel (kg)

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	168	264	286	100	96
Manv	27	39	22	21	24
Push	71	35	29	9	11
Gensets	55	26	31	17	24
Total	321	364	368	146	155

Total Trip Fuel (gal)

	Molinari	Barberi	Ollis	Austen	Midsize
Fuel	100	113	114	45	48

CO2 and SO2 per Trip

	Molinari	Barberi	Ollis	Austen	Midsize
CO2 (kg)	1029	1167	1179	469	497
SO2 (kg)	0.010	0.011	0.011	0.004	0.005

Fuel calculated from each engine's SFC, power level, and time

kg CO2 = 3.206 · kg diesel (MEPC 67/INF.3: Third IMO GHG Study, MGO value)

SO2 from mass balance using 15 ppm S oxidized to SO2

Diesel density = 3.218 kg/gal

Criteria Emissions per Trip (kg)

kg = BSEF · power level · no. engines

NOx

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	5.1	9.9	1.4	2.7	0.6
Manv	0.8	1.4	0.1	0.7	0.2
Push	2.1	1.2	0.2	0.3	0.1
Gensets	1.1	2.0	0.6	1.3	0.4

CO

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.5	0.9	0.4	0.3	0.6
Manv	0.1	0.1	0.0	0.1	0.2
Push	0.2	0.1	0.0	0.0	0.1
Gensets	0.2	0.1	0.1	0.1	0.4

HC

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.1	0.17	0.01	0.32	0.15
Manv	0.0	0.02	0.00	0.09	0.04
Push	0.1	0.02	0.00	0.04	0.02
Gensets	0.0	0.12	0.07	0.08	0.11

PM

	Molinari	Barberi	Ollis	Austen	Midsize
Transit	0.05	0.27	0.03	0.02	0.010
Manv	0.01	0.04	0.00	0.01	0.003
Push	0.02	0.03	0.00	0.00	0.001
Gensets	0.02	0.04	0.01	0.03	0.009

SIF Molinari Class Tier 3 Hybrid II Analysis

Capital Cost Estimate

	Molinari			Barberi			Ollis			Austen			Midsize		
Equipment	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
New CAT C18s	3	$ 400,000	$ 1.2M		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Upgrade Auxilliaries	3	$ 100,000	$ .3M		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
EMD T3 Updgrade	3	$ 460,000	$ 1.4M												
Hybrid Equipment	3	$ 2,410,000	$ 7.2M												
		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -		$ -	$ -
Subtotal			$ 10.1M			$ -			$ -			$ -			$ -
Installation (@50%)			$ 5.1M			$ -			$ -			$ -			$ -
Total			$ 15.2M			$ -			$ -			$ -			$ -

Maintenance Cost Estimate

			Molinari		Barberi		Ollis		Austen		Midsize		
Item	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	Cost (ea)	Cost	
Main Propulsion Diesel Engine (engine hrs/yr)			7527		3796		27664		4940		4940		
Lube Oil Change	4000	hrs	$ 6,500	$ 12,231	$ 6,500	$ 6,169	$ 6,500	$ 44,954	$ 6,500	$ 8,028	$ 6,500	$ 8,028	
Minor Overhaul	8000	hrs	$ 37,000	$ 34,812	$ 37,000	$ 17,558	$ 37,000	$ 127,947	$ 37,000	$ 22,848	$ 37,000	$ 22,848	
Major Overhaul	30000	hrs	$ 242,000	$ 60,717	$ 242,000	$ 30,624	$ 242,000	$ 223,158	$ 242,000	$ 39,849	$ 242,000	$ 39,849	
Alternator Overhaul	10	yrs	$ 50,000	$ 45,000	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	
Ship Service Diesel Generator (engine hrs/yr)			7527		949		6916		2470		2470		
Lube Oil Change	1000	hrs	$ 500	$ 3,763	$ 500	$ 475	$ 500	$ 3,458	$ 500	$ 1,235	$ 500	$ 1,235	
Minor Overhaul	20000	hrs	$ 50,000	$ 18,817	$ 50,000	$ 2,373	$ 50,000	$ 17,290	$ 50,000	$ 6,175	$ 50,000	$ 6,175	
Major Overhaul	20000	hrs	$ 100,000	$ 37,634	$ 100,000	$ 4,745	$ 100,000	$ 34,580	$ 100,000	$ 12,350	$ 100,000	$ 12,350	
Alternator Overhaul	10	yrs	$ 25,000	$ 15,000	$ 25,000	$ 2,143	$ 25,000	$ 13,810	$ 25,000	$ 5,000	$ 25,000	$ 7,143	
General													
Hull Coating	3	yrs	$ 10,000	$ 10,000	$ 10,000	$ 1,429	$ 10,000	$ 9,206	$ 6,000	$ 2,000	$ 7,500	$ 3,571	
Battery Replacement	10	yrs	$ 1,488,000	$ 446,400									Assumes $300/kwh for future replacements
Average ($/yr)				$ 684,374		$ 65,515		$ 474,404		$ 97,484		$ 101,199	

Notes

Hours/year are an average value from 2020-2040

Appendix B NYCF Data

Sample Calculation - NYCF Baseline

Orange Font	Indicates Calculation Result
Input Data	Indicates input data

Ferry Installed Power

		No. Boats on Route/Day	Engine Model	Installed HP
1	East River - Weekday	5	6M26.3	1606
2	East River - Weekend	3	6M26.3	1606
3	Rockaway - Weekday	3	12M26.3	2760
4	South Brooklyn - Weekday	3	6M26.3	1606
5	South Brooklyn Weekend - Gove	4	6M26.3	1606
6	Astoria - Weekday	4	6M26.3	1606
7	Astoria - Weekend	4	6M26.3	1606
8	Soundview - Weekday	3	6M26.3	1606
9	Soundview - Weekend	2	6M26.3	1606
10	Lower East Side - Weekday	3	6M26.3	1606
11	Lower East Side - Weekend	2	6M26.3	1606
12	Soundview - Throgs Neck 150, al	3	6M26.3	1606
13	Soundview - Throgs Neck 350, al	1	12M26.3	2760
14	St Georges - All Days	3	12M26.3	2760
15	Coney Island - All Days	3	6M26.3	1606

	Route Assumptions			**Specific Fuel Consumption - Curves provided by Baudouin [g/kwhr]**				**Specific Emissions Data - Tier 3 standards**						**Tier 4 Standards** *Update Required for final report, current CO values assume Tier 3 (Tier 4 unavail)					
	Assumed operational profile	**Assumed % Installed HP**	**Assumed time [in seconds]**	**BSFC 6M26.3 Tier 3**	**BSFC 12M26.3 Tier 3**	**BSFC 6M26.3 Tier 4**	**BSFC 12M26.3 Tier 4**	**CO [g/kwhr]**	**PM [g/kwhr]**	**NOx [g/kwhr]**	**HC [g/kwhr]**	**CO2 [lb/gal]**	**SO2 [lb/gal]**	**CO [g/kwhr]**	**PM [g/kwhr]**	**NOx [g/kwhr]**	**HC [g/kwhr]**	**CO2 [lb/gal]**	**SO2 [lb/gal]**
				6M26.3	**12M26.3**	**6M26.3**	**12M26.3**												
1	Dwell (Pushing the Dock)	20%		196.01	209.47	199.57	220.27	1.0	0.2	6.7	0.2	22.21	0.0002078	1.0	0.1	1.4	0.2	22.21	0.0002078
2	Dept Manoeuv + Hand + Accel to Full Speed	60%	30	205.50	214.01	190.47	188.94	0.6	0.1	4.2	0.1	22.21	0.0002078	0.6	0.0	0.9	0.1	22.21	0.0002078
3	Full Speed/Cruising*	42%		198.88	204.04	187.55	192.66	0.8	0.1	4.9	0.1	22.21	0.0002078	0.8	0.0	1.0	0.1	22.21	0.0002078
4	Deceleration for docking + arrival maneuv/hand	40%	30	199.14	202.74	187.74	192.87	0.8	0.1	5.1	0.1	22.21	0.0002078	0.8	0.0	1.1	0.1	22.21	0.0002078
7	Layover	20%		196.01	209.47	199.57	220.27	1.0	0.2	6.7	0.2	22.21	0.0002078	1.0	0.1	1.4	0.2	22.21	0.0002078
8	Deadheading	40%		199.14	202.74	187.74	192.87	0.8	0.1	5.1	0.1	22.21	0.0002078	0.8	0.0	1.1	0.1	22.21	0.0002078

*Full Speed/Cruising effort level calculated based on schedule and vessel resistance approximations

Geared Diesel - Baseline											**Tier 3 Standards**							**Tier 4 Standards**						
		Lookup Value	**Time [min per leg trip]**	**Distance [miles]**	**Approx Speed [knots]**	**Approx BHP [actual]**	**Approx mkW [actual]**	**Approx in transit [per engine]**	**Total Energy [kWhr]**	**Total Energy [MJ]**	**Gal**	**CO [MT]**	**PM [MT]**	**NOx [MT]**	**HC [MT]**	**CO2 [MT]**	**SO2 [MT]**	**Gal**	**CO [MT]**	**PM [MT]**	**NOx [MT]**	**HC [MT]**	**CO2 [MT]**	**SO2 [MT]**
Vessel Route No:	Pushing the Dock	1	5	- -		321	239.52	119.76	19.96	71.86	1.25	0.00002	0.00000	0.00013	0.00000	0.0125	0.0000	1.27	0.00002	0.00000	0.00003	0.00000	0.0128	0.0000
1	Departure Manoeuvering and Handling	2	0.5	- -		964	718.56	359.28	5.99	21.56	0.39	0.00000	0.00000	0.00002	0.00000	0.0039	0.0000	0.36	0.00000	0.00000	0.00001	0.00000	0.0037	0.0000
	Full Speed/Cruising (total - sum)	3	3	1	17.38	675.57	504.16	252.08	25.21	90.75	1.60	0.00002	0.00000	0.00012	0.00000	0.0161	0.0000	1.50	0.00002	0.00000	0.00003	0.00000	0.0152	0.0000
Leg No.	Deceleration for docking	4	0.5	- -		642	479.04	239.52	3.99	14.37	0.25	0.00000	0.00000	0.00002	0.00000	0.0025	0.0000	0.24	0.00000	0.00000	0.00000	0.00000	0.0024	0.0000
10																								
	Leg Totals							252.08	55.15	198.53	3.49	0.0000	0.0000	0.0003	0.0000	0.04	0.0000	3.37	0.0000	0.0000	0.0001	0.0000	0.03	0.0000

	50.19	30.97	111.48	1.95	0.0000	0.0000	0.0002	0.0000	0.02	0.0000	1.82	0.0000	0.0000	0.0000	0.0000	0.02	0.0000
	24.31	32.43	116.75	2.07	0.0000	0.0000	0.0002	0.0000	0.02	0.0000	1.70	0.0000	0.0000	0.0000	0.0000	0.02	0.0000
	252.08	47.16	169.79	2.99	0.0000	0.0000	0.0003	0.0000	0.03	0.0000	2.87	0.0000	0.0000	0.0001	0.0000	0.03	0.0000
	491.68	58.73	211.41	3.95	0.0000	0.0000	0.0003	0.0000	0.04	0.0000	3.68	0.0000	0.0000	0.0001	0.0000	0.04	0.0000
	491.68	54.73	197.04	3.70	0.0000	0.0000	0.0003	0.0000	0.04	0.0000	3.42	0.0000	0.0000	0.0001	0.0000	0.03	0.0000
	109.68	29.27	105.37	1.85	0.0000	0.0000	0.0002	0.0000	0.02	0.0000	1.82	0.0000	0.0000	0.0000	0.0000	0.02	0.0000
	514.77	52.81	190.10	3.46	0.0000	0.0000	0.0003	0.0000	0.03	0.0000	3.34	0.0000	0.0000	0.0001	0.0000	0.03	0.0000
	491.68	58.73	211.41	3.95	0.0000	0.0000	0.0003	0.0000	0.04	0.0000	3.68	0.0000	0.0000	0.0001	0.0000	0.04	0.0000
	491.68	54.73	197.04	3.70	0.0000	0.0000	0.0003	0.0000	0.04	0.0000	3.42	0.0000	0.0000	0.0001	0.0000	0.03	0.0000
	252.08	55.15	198.53	3.49	0.0000	0.0000	0.0003	0.0000	0.04	0.0000	3.37	0.0000	0.0000	0.0001	0.0000	0.03	0.0000
	50.19	33.67	121.20	2.12	0.0000	0.0000	0.0002	0.0000	0.02	0.0000	1.84	0.0000	0.0000	0.0000	0.0000	0.02	0.0000
	50.19	30.97	111.48	1.95	0.0000	0.0000	0.0002	0.0000	0.02	0.0000	1.82	0.0000	0.0000	0.0000	0.0000	0.02	0.0000
Generator	22.50	37.16	133.79	2.89	0.0000	0.0000	0.0002	0.0000	0.03	0.00	2.89	0.0000	0.0000	0.0001	0.0000	0.03	0.0000003
Round Trip Totals		576.50	2,075.40	38.06	0.0005	0.0001	0.0032	0.0001	0.38	0.00	35.68	0.00	0.00	0.00	0.00	0.36	0.0000034
Boat Totals																	
Boat 1		6,433.17	23,159.40	420.17	0.0055	0.0009	0.0354	0.0008	4.23	0.00	396.82	0.0055	0.0002	0.0074	0.0008	4.00	0.0000374
Boat 2		2,869.69	10,330.90	188.64	0.0024	0.0004	0.0157	0.0003	1.90	0.00	177.37	0.0024	0.0001	0.0033	0.0003	1.79	0.0000167
Boat 3		4,825.91	17,373.27	316.26	0.0041	0.0007	0.0265	0.0006	3.19	0.00	298.00	0.0041	0.0002	0.0056	0.0006	3.00	0.0000281
Boat 4		5,954.13	21,434.86	389.97	0.0051	0.0008	0.0327	0.0007	3.93	0.00	367.59	0.0051	0.0002	0.0069	0.0007	3.70	0.0000346
Boat 5		5,534.14	19,922.92	362.63	0.0047	0.0008	0.0304	0.0007	3.65	0.00	341.72	0.0047	0.0002	0.0064	0.0007	3.44	0.0000322
		[kWhr]	[MJ]	[gal]	[tons]	[tons]	[tons]	[tons]	[lbs]	[lbs]	[gal]	[tons]	[tons]	[tons]	[tons]	[lbs]	[lbs]

										Tier 3 Emissions							**Tier 4 Emissions**						
	Lookup Value	**Time [hour per day]**	**Purposely Blank**	**Purposely Blank**	**Approx BHP [installed]**	**Approx mkW [installed]**	**Approx mkW [per engine]**	**Energy [kWhr]**	**Energy [MJ]**	**Gal**	**CO [MT]**	**PM [MT]**	**NOx [MT]**	**HC [MT]**	**CO2 [MT]**	**SO2 [MT]**	**Gal**	**CO [MT]**	**PM [MT]**	**NOx [MT]**	**HC [MT]**	**CO2 [MT]**	**SO2 [MT]**
1 - Layover	7	2.13			321	239.52	119.76	510.97	1839.50	31.88	0.00053	0.00011	0.00343	0.00008	0.32	0.000003	32.46	0.00053	0.00003	0.00072	0.00008	0.33	0.000003
2 - Layover	7	0.38			321	239.52	119.76	91.82	330.54	5.73	0.00010	0.00002	0.00062	0.00001	0.06	0.000001	5.83	0.00010	0.00000	0.00013	0.00001	0.06	0.000001
3 - Layover	7	1.10			321	239.52	119.76	263.47	948.49	16.44	0.00027	0.00005	0.00177	0.00004	0.17	0.000002	16.74	0.00027	0.00001	0.00037	0.00004	0.17	0.000002
4 - Layover	7	1.47			321	239.52	119.76	351.29	1264.66	21.92	0.00036	0.00007	0.00236	0.00006	0.22	0.000002	22.31	0.00036	0.00002	0.00049	0.00006	0.22	0.000002
5 - Layover	7	1.28			321	239.52	119.76	307.38	1106.58	19.18	0.00032	0.00006	0.00206	0.00005	0.19	0.000002	19.52	0.00032	0.00002	0.00043	0.00005	0.20	0.000002
1 - Deadheading	8	2.13			642	479.04	239.52	1021.95	3679.01	64.78	0.00080	0.00013	0.00518	0.00012	0.65	0.000006	61.07	0.00080	0.00003	0.00109	0.00012	0.62	0.000006
2 - Deadheading	8	0.38			642	479.04	239.52	183.63	661.07	11.64	0.00014	0.00002	0.00093	0.00002	0.12	0.000001	10.97	0.00014	0.00001	0.00020	0.00002	0.11	0.000001
3 - Deadheading	8	1.10			642	479.04	239.52	526.94	1896.99	33.40	0.00041	0.00006	0.00267	0.00006	0.34	0.000003	31.49	0.00041	0.00002	0.00056	0.00006	0.32	0.000003
4 - Deadheading	8	1.47			642	479.04	239.52	702.59	2529.32	44.53	0.00055	0.00009	0.00356	0.00008	0.45	0.000004	41.98	0.00055	0.00002	0.00075	0.00008	0.42	0.000004
5 - Deadheading	8	1.28			642	479.04	239.52	614.77	2213.15	38.97	0.00048	0.00008	0.00312	0.00007	0.39	0.000004	36.74	0.00048	0.00002	0.00065	0.00007	0.37	0.000003

NYCF Baseline Results - All Vessels

Tier 3 Results									One Round Trip						Daily Route Summary						
	One Round Trip Energy Consumption [kWhr]	One Round Trip Energy Consumption [MJ]	Daily Energy Consumption (average/vessel) [MJ]	One Round Trip Fuel Consumption [gal]	Daily Max Vessel Fuel Consumption [gal]	Daily Average Vessel Fuel Consumption [gal]	Daily Median Vessel Fuel Consumption [gal]	Fuel Consumption Total/Route/Day [gal]	**CO [MT]**	**PM [MT]**	**NOx [MT]**	**HC [MT]**	**CO2 [MT]**	**SO2 [MT]**	**CO [MT]**	**PM [MT]**	**NOx [MT]**	**HC [MT]**	**CO2 [MT]**	**SO2 [MT]**	**kWhr (all vessels)**
East River - Weekday	576.50	2,075.40	18,444.27	38.06	420.17	336	362.63	1,678	0.0005	0.0001	0.0032	0.0001	0.38	0.0000	0.0218	0.0035	0.1408	0.0031	16.90	0.00016	25617.0
East River - Weekend	827.89	2,980.41	21,715.18	54.88	438.50	398	402.75	1,193	0.0007	0.0001	0.0043	0.0002	0.55	0.0000	0.0148	0.0023	0.0956	0.0020	12.02	0.00011	18096.0
Rockaway	1,854.77	6,677.16	40,062.97	124.39	995.11	964	932.91	2,239	0.0014	0.0002	0.0088	0.0002	1.25	0.0000	0.0243	0.0034	0.1575	0.0034	22.55	0.00021	33385.8
South Brooklyn - Weekday	595.66	2,144.38	19,305.09	39.08	413.49	351	354.86	1,053	0.0005	0.0001	0.0032	0.0001	0.39	0.0000	0.0133	0.0021	0.0858	0.0019	10.61	0.00010	23582.1
South Brooklyn Weekend - Governor's Is	764.11	2,750.81	21,223.85	50.13	433.65	386	387.30	1,545	0.0006	0.0001	0.0039	0.0001	0.50	0.0000	0.0188	0.0029	0.1214	0.0026	15.57	0.00015	23582.1
Astoria - Weekday	643.63	2,317.07	22,808.67	44.79	537.54	436	495.64	1,743	0.0005	0.0001	0.0033	0.0001	0.45	0.0000	0.0206	0.0028	0.1331	0.0025	17.56	0.00016	25343.0
Astoria - Weekend	643.63	2,317.07	20,498.23	44.79	476.13	393	389.69	1,571	0.0005	0.0001	0.0033	0.0001	0.45	0.0000	0.0184	0.0025	0.1194	0.0022	15.82	0.00015	22775.8
Soundview - Weekday	1,027.18	3,697.83	27,622.07	68.73	596.64	512	522.26	1,537	0.0007	0.0001	0.0047	0.0001	0.69	0.0000	0.0163	0.0020	0.1053	0.0021	15.48	0.00014	23018.4
Soundview - Weekend	1,027.18	3,697.83	34,204.93	68.73	652.92	636	635.74	1,271	0.0007	0.0001	0.0047	0.0001	0.69	0.0000	0.0133	0.0016	0.0861	0.0017	12.81	0.00012	19002.7
Lower East Side	493.45	1,776.40	18,051.36	33.04	406.34	334	297.51	1,001	0.0004	0.0001	0.0026	0.0001	0.33	0.0000	0.0124	0.0019	0.0801	0.0017	10.09	0.00009	15042.8
Lower East Side - Weekend	515.28	1,855.01	24,167.61	34.43	454.66	446	446.05	892	0.0004	0.0001	0.0028	0.0001	0.35	0.0000	0.0112	0.0017	0.0722	0.0015	8.99	0.00008	13426.4
Soundview - Throgs Neck (150)	1,194.54	4,300.35	31,940.13	80.14	687.93	593.97	607.84	1,781.90	0.0008	0.0001	0.0054	0.0002	0.81	0.0000	0.0188	0.0023	0.1216	0.0024	17.95	0.00017	26616.8
Soundview - Throgs Neck (350)	1,519.81	5,471.33	48,364.42	100.60	888.09	888.09	888.09	888.09	0.0012	0.0002	0.0078	0.0002	1.01	0.0000	0.0107	0.0017	0.0693	0.0015	8.95	0.00008	13434.6
St Georges - All Days	559.75	2,015.09	10,075.43	38.02	190.09	190.09	190.09	570.26	0.0006	0.0001	0.0038	0.0001	0.38	0.0000	0.0088	0.0018	0.0572	0.0013	5.74	0.00005	8396.2
Coney Island - All Days	586.25	2,110.49	10,552.46	37.52	187.59	187.59	187.59	562.76	0.0005	0.0001	0.0031	0.0001	0.38	0.0000	0.0073	0.0012	0.0472	0.0011	5.67	0.00005	8793.7

Tier 4 Results						One Round Trip						Daily Route Summary					
	One Round Trip Fuel Consumption [gal]	Daily Max Vessel Fuel Consumption [gal]	Intentionally Blank	Intentionally Blank	Fuel Consumption Total/Route/Day [gal]	**CO [MT]**	**PM [MT]**	**NOx [MT]**	**HC [MT]**	**CO2 [MT]**	**SO2 [MT]**	**CO [MT]**	**PM [MT]**	**NOx [MT]**	**HC [MT]**	**CO2 [MT]**	**SO2 [MT]**
East River - Weekday	35.68	396.82			1581.50	0.0005	0.0000	0.0007	0.0001	0.36	0.000003	0.0218	0.0009	0.0295	0.0031	15.93	0.0001
East River - Weekend	51.78	415.05			1128.77	0.0007	0.0000	0.0009	0.0001	0.52	0.000005	0.0148	0.0006	0.0200	0.0020	11.37	0.0001
Rockaway	114.66	917.25			2063.80	0.0014	0.0000	0.0018	0.0002	1.15	0.000011	0.0243	0.0008	0.0330	0.0034	20.79	0.0002
South Brooklyn - Weekday	36.98	391.75			997.86	0.0005	0.0000	0.0007	0.0001	0.37	0.000003	0.0133	0.0005	0.0180	0.0019	10.05	0.0001
South Brooklyn Weekend - Governor's Island	47.47	410.78			1464.21	0.0006	0.0000	0.0008	0.0001	0.48	0.000004	0.0188	0.0007	0.0255	0.0026	14.75	0.0001
Astoria - Weekday	37.89	462.88			1498.67	0.0005	0.0000	0.0007	0.0001	0.38	0.000004	0.0206	0.0007	0.0279	0.0025	15.10	0.0001
Astoria - Weekend	37.89	408.92			1345.49	0.0005	0.0000	0.0007	0.0001	0.38	0.000004	0.0184	0.0006	0.0250	0.0022	13.55	0.0001
Soundview - Weekday	63.08	549.98			1413.32	0.0007	0.0000	0.0010	0.0001	0.64	0.000006	0.0163	0.0005	0.0221	0.0021	14.24	0.0001
Soundview - Weekend	63.08	599.31			1167.07	0.0007	0.0000	0.0010	0.0001	0.64	0.000006	0.0133	0.0004	0.0181	0.0017	11.76	0.0001
Lower East Side	29.22	361.62			893.47	0.0004	0.0000	0.0005	0.0001	0.29	0.000003	0.0124	0.0005	0.0168	0.0017	9.00	0.0001
Lower East Side - Weekend	30.64	407.81			800.30	0.0004	0.0000	0.0006	0.0001	0.31	0.000003	0.0112	0.0004	0.0151	0.0015	8.06	0.0001
Soundview - Throgs Neck (150)	73.43	632.71			1635.65	0.0008	0.0000	0.0011	0.0001	0.74	0.000007	0.0188	0.0006	0.0255	0.0024	16.48	0.0002
Soundview - Throgs Neck (350)	95.31	844.50			844.50	0.0012	0.0000	0.0016	0.0002	0.96	0.000009	0.0107	0.0004	0.0145	0.0015	8.51	0.0001
St Georges - All Days	44.26	221.32			663.96	0.0006	0.0000	0.0008	0.0001	0.45	0.000004	0.0088	0.0004	0.0120	0.0013	6.69	0.0001
Coney Island - All Days	36.42	182.11			546.34	0.0005	0.0000	0.0007	0.0001	0.37	0.000003	0.0073	0.0003	0.0099	0.0011	5.50	0.0001

Baseline Weekly Totals (Tier 3)			
	Energy [kWhr]	**Energy [MJ]**	**Gal**
Total Weekday	138,494.58	498,580.47	9251.08
Total Weekend	96,883.04	348,778.93	6472.97
Total (Week)	886,238.95	3,190,460.24	59,201.36
Total (Week)			2,369,830.48

NYCF Validation Model
Ref: NYCF August Fuel Consumption

Vessels	**Daily Consumption**								
	Calc Average Average	**NYC Average**	**% Difference**	**Calc Median Avg**	**NYC Median**	**% Difference**	**Calc Median Median**	**NYC Median**	**% Difference**
River 150s									
Weekday	393.68	429.78	-8%	351.09	421	-17%	362.63	421	-14%
All									
Weekend	451.71	441.65	2%	397.72	384	4%	402.75	384	5%
Rockaway 150s & 350s									
Weekday	964.01	997.13	-3%	964.01	1003	-4%	964.01	1003	-4%

**use route averages for extrapolation. Model overpredicts weekly totals.*

NYCF Electric Calculations

Battery Metrics

DoD/margin factor	4	*Compiled from previous projects*
Batt Specific volume	200	*MJ/m3*
Battery Weight-Density	0.4	*MJ/kg*
Contants	3.6	*kWhr/MJ*
	2.2	*lbs/kg*
	2000	*lbs/ton*
	3.28	*ft/m*

Vessel Weights [from stability letters]

	Lightship Displacement [LT]	Lightship Displacement [tons]	VCG [ft above baseline]	LCG [ft fwd fr 0]	Max Deadweight (kg)	Max Deadweight (tons)	Total Weight (LT)
Riverclass 150	51.62	57.81	10.27	32.74	18997	9.50	74.25
Rockaway 150	56.83	63.65	10.66	28.89	20552	10.28	73.93
Rockaway 350	65.22	73.05	12.02	36.00	37453	18.73	91.77

		One Round Trip						One Daily Operation				
		Energy/Round Trip [MJ]	Battery Size [kWhr]	Installed Capacity [kWhr]	Weight [tons]	Volume [ft3]	% Weight Estimate	Average Energy/Day [MJ]	Battery Size [kWhr]	Installed Capacity [kWhr]	Weight [tons]	Volume [ft3]
1	East River - Weekday	2,075	576.50	2,306.00	23	1,465	31%	18,444	5,123.41	20,493.63	203	13,017
2	East River - Weekend	2,980	827.89	3,311.57	33	2,103	44%	21,715	6,032.00	24,127.98	239	15,326
3	Rockaway - Weekday	6,677	1,854.77	7,419.07	73	4,712	80%	40,063	11,128.60	44,514.41	441	28,274
4	South Brooklyn - Weekday	2,144	595.66	2,382.65	24	1,513	32%	19,305	5,362.52	21,450.10	212	13,625
5	South Brooklyn Weekend	2,751	764.11	3,056.45	30	1,941	41%	21,224	5,895.51	23,582.05	233	14,979
6	Astoria - Weekday	2,317	643.63	2,574.52	25	1,635	34%	22,809	6,335.74	25,342.96	251	16,097
7	Astoria - Weekend	2,317	643.63	2,574.52	25	1,635	34%	20,498	5,693.95	22,775.81	225	14,467
8	Soundview - Weekday	3,698	1,027.18	4,108.70	41	2,610	55%	27,622	7,672.80	30,691.19	304	19,494
9	Soundview - Weekend	3,698	1,027.18	4,108.70	41	2,610	55%	34,205	9,501.37	38,005.48	376	24,140
10	Lower East Side - Weekday	1,776	493.45	1,973.78	20	1,254	26%	18,051	5,014.27	20,057.06	199	12,740
11	Lower East Side - Weekend	1,855	515.28	2,061.12	20	1,309	27%	24,168	6,713.22	26,852.90	266	17,056
12	Soundview - Throgs Neck 350	4,300	1,194.54	4,778.17	47	3,035	52%	31,940	8,872.26	35,489.03	351	22,542
13	Soundview - Throgs Neck 150	5,471	1,519.81	6,079.26	60	3,861	81%	48,364	13,434.56	53,738.24	532	34,133
14	St Georges - All Days	2,015	559.75	2,238.98	22	1,422	24%	10,075	2,798.73	11,194.92	111	7,111
15	Coney Island - All Days	2,110	586.25	2,344.99	23	1,489	25%	10,552	2,931.24	11,724.95	116	7,447

Average Required Battery Density

	MJ	Weight Margin (tons)	Required Energy Density (MJ/kg)
One Round Trip	3000	12.03	1.10
Average daily operati	21000	12.03	7.68

NYCF Plug-In Hybrid Calculations

Key Assumptions:
1. No change in schedule.
2. Only plug in overnight, no charging throughout day
3. Batteries are stored in the forward void, assume they fill 50% of available space.

Plug in Options - Volume limit

	Energy [MJ]	Useful Battery Energy [kWhr]	Installed Capacity [kWhr]	Weight [tons]	Volume [ft3]	Volume Limit [ft3]	Diesel Energy Eqv [gal]
River 150	1,300.00	361	1,444	14.30	917	932.4	9.66
Rockaway 150	1,300.00	361	1,444	14.30	917	932.4	9.66
Rockaway 350	2,000.00	556	2,222	22.00	1,412	1413.9	14.87

Key Conclusion:
1. Useful battery energy can only provide 1-3 legs worth of energy.
2. Vessel is weight limited, filling the forward void with batteries adds too much weight for the vessel to handle.

Key Assumptions:
1. No change in schedule.
2. Only plug in overnight, no charging throughout day
3. Additional battery weight of 10% above max deadweight is acceptable.

Plug in Options - Weight limit

	Energy [MJ]	Useful Battery Energy [kWhr]	Installed Capacity [kWhr]	Weight [tons]	Volume [ft3]	Max Weight [tons]	Weight Limit 10% Max Weight [ft3]	Diesel Energy Eqv [gal]
River 150	600.00	167	667	6.60	423	74.25	7.4	4.46
Rockaway 150	670.00	186	744	7.37	473	73.93	7.4	4.98
Rockaway 350	825.00	229	917	9.08	582	91.77	9.2	6.13

Key Conclusion:
1. Useful battery energy can only provide 1-2 legs worth of energy.
2. Vessel is weight limited, cannot handle enough batteries to provide useful propulsion.

NYCF All-Electric Plug-in Calculations

Assumptions:
Remove both engines
Keep one emergency generator
Keep one 500 gal tank of fuel

Additional Equipment
Propulsion motors
Batteries
Switchboard
Aux electrical equip

Sample Calculations - NYCF Hybrid Sizing - East River Route

Hybrid Calcs

Round Trip Values		**Required Energy**				**Time**				**Excess Energy**			
	Predicted Speed During Transit	Pushing the Dock	Departure Maneuvering and Handling + Acceleration to Full Speed	Full Speed/Cruising	Deceleration + Arrival Maneuvering and Handling	Pushing the Dock	Departure Maneuvering and Handling + Acceleration to Full Speed	Full Speed/Cruising	Deceleration + Arrival Maneuvering and Handling	Pushing the Dock	Departure Maneuvering and Handling + Acceleration to Full Speed	Full Speed/Cruising	Deceleration + Arrival Maneuvering and Handling
	Speed [knots]	Required Energy [mkWhr]	Req Energy [mkWhr]	Req Energy [mkWhr]	Req Energy [mkWhr]	Time [min]	Time [min]	Time [min]	Time [min]	Excess Energy [mkWhr]	Excess Energy [mkWhr]	Excess Energy [mkWhr]	Excess Energy [mkWhr]
Leg 1	10.43	15.97	5.99	5.02	3.99	4	0.5	3	0.5	6.48	-3.18	11.82	-1.19
Leg 2	9.78	15.97	5.99	6.48	3.99	4	0.5	8	0.5	6.48	-3.18	38.42	-1.19
Leg 3	17.38	11.98	5.99	25.21	3.99	3	0.5	3	0.5	4.86	-3.18	-8.37	-1.19
Leg 4	23.46	15.97	5.99	32.78	3.99	4	0.5	2	0.5	6.48	-3.18	-21.55	-1.19
Leg 5	23.46	11.98	5.99	32.78	3.99	3	0.5	2	0.5	4.86	-3.18	-21.55	-1.19
Leg 6	13.04	11.98	5.99	7.31	3.99	3	0.5	2	0.5	4.86	-3.18	3.91	-1.19
Leg 7	23.70	23.95	5.99	18.87	3.99	6	0.5	1.1	0.5	9.72	-3.18	-12.70	-1.19
Leg 8	23.46	15.97	5.99	32.78	3.99	4	0.5	2	0.5	6.48	-3.18	-21.55	-1.19
Leg 9	23.46	11.98	5.99	32.78	3.99	3	0.5	2	0.5	4.86	-3.18	-21.55	-1.19
Leg 10	17.38	19.96	5.99	25.21	3.99	5	0.5	3	0.5	8.10	-3.18	-8.37	-1.19
Leg 11	11.17	11.98	5.99	11.71	3.99	3	0.5	7	0.5	4.86	-3.18	27.58	-1.19
Leg 12	10.43	15.97	5.99	5.02	3.99	4	0.5	3	0.5	6.48	-3.18	11.82	-1.19
Leg 13										0.00	0.00	0.00	0.00
Leg 14										0.00	0.00	0.00	0.00
Total										74.53	-38.18	-22.12	-14.23

Round Trip Reporting

Total Charging	168.07	*[kWhr] *only pushing dock and low transit loads*
Total Discharging	-168.07	*[kWhr]*
Difference	0.00	*[kWhr] Want to get to zero*
Battery Size	38.42	*[kWhr]*
Installed Propulsion Power	336.73	*mkW [MIN_TP] Toggle this value*
Electrical Plant Size	464.15	*[ekW] - two SSDG generators*
PropulsionGenerator Size (2)	232.07	*[ekW]*
	0	
Installed propulsion elec	374.15	*[mkW]*
Electrical efficiency	0.9	*Should be refined with actual equipment when necessary*

Battery Constants

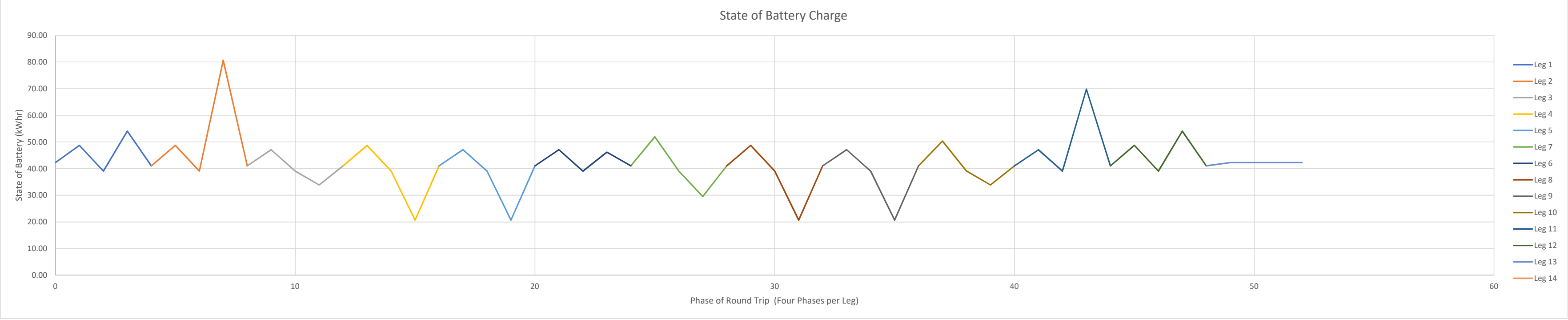
4	DoD/margin factor	MJ/m3
200	Batt Specific volume	MJ/kg
0.4	Battery Weight-Density	
3.6	MJ/kwhr	

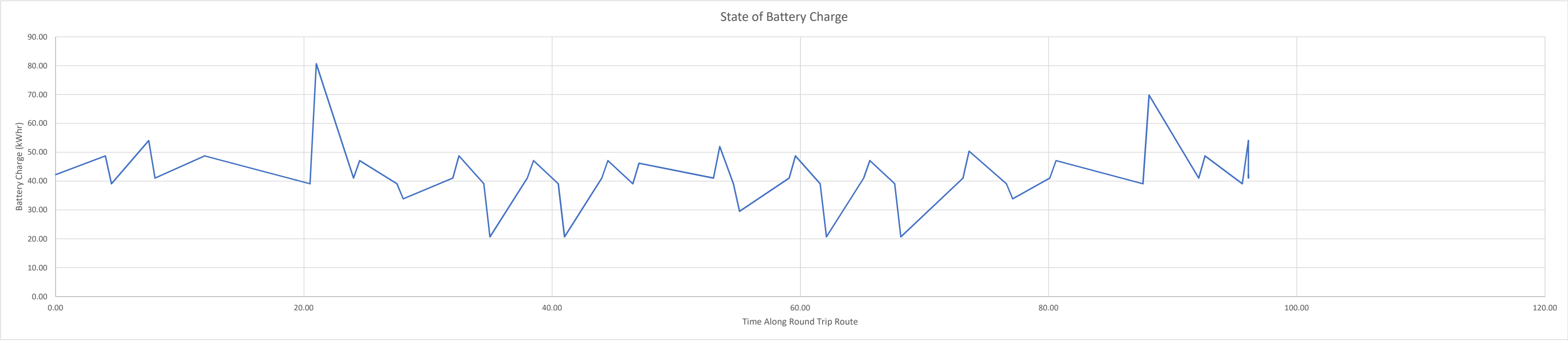
Hybrid Summary Table

		Required Battery Size [kWhr]	**Installed Propulsion Power [mkW]**	**Elec Plant Size [ekW]**	**Generator Size (2) [ekW]**
1	East River - Weekday	38.42	336.73	464.15	232.07
2	East River - Weekend	36.30	411.55	547.28	273.64
3	Rockaway - Weekday	132.55	938.07	1132.30	566.15
4	South Brooklyn - Weekday	66.37	383.12	515.69	257.85
5	South Brooklyn Weekend - Gove	29.07	444.86	584.29	292.15
6	Astoria - Weekday	124.74	447.35	587.06	293.53
7	Astoria - Weekend	124.74	447.35	587.06	293.53
8	Soundview - Weekday	61.71	616.42	774.91	387.46
9	Soundview - Weekend	61.71	616.42	774.91	387.46
10	Lower East Side - Weekday	59.77	382.46	514.95	257.48
11	Lower East Side - Weekend	60.38	373.29	504.77	252.38
12	Soundview - Throgs Neck 150	61.81	616.02	774.47	387.23
13	Soundview - Throgs Neck 350	41.83	783.88	960.98	480.49
14	St Georges - All Days	16.51	345.82	474.25	237.12
15	Coney Island - All Days	59.36	385.73	518.58	259.29

Hybrid - Battery Characteristics

Actual Capacity [kWhr]	**Weight [tons]**	**Volume [ft3]**
153.67	1.52	241.74
145.22	1.44	228.45
530.19	5.25	834.08
265.49	2.63	417.65
116.28	1.15	182.93
498.97	4.94	784.96
498.97	4.94	784.96
246.86	2.44	388.35
246.86	2.44	388.35
239.07	2.37	376.10
241.51	2.39	379.94
247.23	2.45	388.93
167.33	1.66	263.24
66.03	0.65	103.87
237.43	2.35	373.52





	Leg No.	**Battery Charge**	**Time**
Initial Charge	0	42.24	0.00
1	1	48.72	4.00
1	2	39.06	4.50
1	3	54.06	7.50
1	4	41.05	8.00
2	5	48.72	12.00
2	6	39.06	20.50
2	7	80.66	21.00
2	8	41.05	24.00
3	9	47.10	24.50
3	10	39.06	27.50
3	11	33.87	28.00
3	12	41.05	32.00
4	13	48.72	32.50
4	14	39.06	34.50
4	15	20.69	35.00
4	16	41.05	38.00
5	17	47.10	38.50
5	18	39.06	40.50
5	19	20.69	41.00
5	20	41.05	44.00
6	21	47.10	44.50
6	22	39.06	46.50
6	23	46.15	47.00
6	24	41.05	53.00
7	25	51.96	53.50
7	26	39.06	54.60
7	27	29.54	55.10
7	28	41.05	59.10
8	29	48.72	59.60
8	30	39.06	61.60
8	31	20.69	62.10
8	32	41.05	65.10
9	33	47.10	65.60
9	34	39.06	67.60
9	35	20.69	68.10
9	36	41.05	73.10
10	37	50.34	73.60
10	38	39.06	76.60
10	39	33.87	77.10
10	40	41.05	80.10
11	41	47.10	80.60
11	42	39.06	87.60
11	43	69.82	88.10
11	44	41.05	92.10
12	45	48.72	92.60
12	46	39.06	95.60
12	47	54.06	96.10
12	48	41.05	96.10
13	49	42.24	96.10
13	50	42.24	96.10
13	51	42.24	96.10
13	52	42.24	96.10
14	53	42.24	96.10
14	54	42.24	96.10
14	55	42.24	96.10
14	56	42.24	96.10

NYCF Fuel Cell Sizing Calculations

Tank Sizing Constants		
LHV Hydrogen	119.96	MJ/kg H2
Average fuel cell efficiency	0.45	
Density of Hydrogen	70.8	kg/m3
Gardner Cryogenics empty tank mass	8.7	kg/kgLH2 - taken from Sandia Report, table in OneNote
Outer tank volume	24.8	L/kg - taken from Sandia report, table in OneNote
	0.26417	gal/L
Approx vaporizer weight	2000	lbs - Thermax spec sheet, approximate value (not sized)

Fuel Cells Survey (Ref. SANDIA SF-BREEZE, 2014)

					2x 6M26.3 Power 1198		2x 12M26.3 Power 2058	
Type of Fuel Cell	Power (kW)	Gravimetric Spec kW/kg	Volumetric Spec kW/m3	Manufacturer/ model	Installed Weight [tons]	Installed Volume [m3]	Installed Weight [tons]	Installed Volume [m3]
210 kW SOFT (NG)	210	0.0119	4.83	Bloom Energy Model ES-5700	110.93	247.95	190.65	426.11
300kW MCFC	300	0.0188	9.26	Fuel Cell Energy, Model DFC300	70.22	129.33	120.67	222.26
440 kW PAFC (NG Fueled)	440	0.0162	6.56	Doosan, Model PureCell 400	81.49	182.56	140.04	313.74
105 kW PAFC (H2)	105	0.00827	2.51	Fuji Electric, Model FP-100i	159.63	477.13	274.33	819.97
90 kW PEM (H2)	90	0.352	181	Ballard, Model FC Velocity HD	3.75	6.62	6.45	11.37
33 kW PEM (H2)	33	0.448	566	Hydrogenics, Model HyPM HD 30	2.95	2.12	5.06	3.64
120 kW PEM (H2)	**120**	**0.15**	**73.97**	**Hydrogenics Power Rack (4 x HD30)**	**8.80**	**16.19**	**15.12**	**27.82**

			Daily Values						
		Round Trip Energy Consumption [MJ]	Daily Energy Consumption [MJ]	Required Stored Energy [MJ]	Required Stored Energy [kg of LH2]	Required Stored Energy [tons of LH2]	Volume [ft3 of LH2]	Volume [gal LH2]	Weight of tank [tons]
1	East River - Weekday	2,075.40	18,444.27	40,987.27	341.67	0.38	170.43	1274.78	3.28
2	East River - Weekend	2,980.41	21,715.18	48,255.96	402.27	0.44	200.65	1500.85	3.86
3	Rockaway - Weekday	6,677.16	40,062.97	89,028.83	742.15	0.82	370.18	2768.97	7.12
4	South Brooklyn - Weekday	2,144.38	19,305.09	42,900.20	357.62	0.39	178.38	1334.28	3.43
5	South Brooklyn Weekend	2,750.81	21,223.85	47,164.11	393.17	0.43	196.11	1466.89	3.77
6	Astoria - Weekday	2,317.07	22,808.67	50,685.93	422.52	0.47	210.75	1576.43	4.05
7	Astoria - Weekend	2,317.07	20,498.23	45,551.62	379.72	0.42	189.40	1416.74	3.64
8	Soundview - Weekday	3,697.83	27,622.07	61,382.37	511.69	0.56	255.23	1909.11	4.91
9	Soundview - Weekend	3,697.83	34,204.93	76,010.96	633.64	0.70	316.05	2364.09	6.08
10	Lower East Side - Weekday	1,776.40	18,051.36	40,114.13	334.40	0.37	166.80	1247.63	3.21
11	Lower East Side - Weekend	1,855.01	24,167.61	53,705.79	447.70	0.49	223.31	1670.35	4.29
12	Soundview - Throgs Neck 350	4,300.35	31,940.13	70,978.06	591.68	0.65	295.13	2207.56	5.67
13	Soundview - Throgs Neck 150	5,471.33	48,364.42	107,476.48	895.94	0.99	446.89	3342.73	8.59
14	St Georges - All Days	2,015.09	10,075.43	22,389.85	186.64	0.21	93.10	696.37	1.79
15	Coney Island - All Days	2,110.49	10,552.46	23,449.90	195.48	0.22	97.50	729.34	1.87

		No. Round trips	Round Trip Energy Consumption [MJ]	Required Stored Energy [MJ LH2]	Required Stored Energy [kg of LH2]	Required Stored Energy [tons of LH2]	Volume [ft3 of LH2]	Volume [gal LH2]	Fuel Cell Volume [ft3]	Tank Volume [gal]	Weight of tank [tons]
Best Case 150 River Class Vessel	Lower East Side - Weekday	1	1776	3948	32.91	0.04	16	122.78	572	216	0.32
Worst Case 150 River Class Vessel	Soundview - Weekend	1	3698	8217	68.50	0.08	34	255.58	572	449	0.66
Worst Case 350 Rockaway Vessel	Rockaway - Weekday	1	6677	14,838.14	123.69	0.14	61.70	461.49	982	810	1.19

Summary Table	Lower East Side - Weekday	Soundview - Weekend	Rockaway - Weekday	
	1	1	1	
Fuel Cell Volume (ft3)	572	572	982	*(ft3)*
Tank Volume	216	449	810	*[gal]*
Fuel Cells	8.80	8.80	15.12	*[tons]*
Vaporizers	2	2	2	*[tons] (redundant fuel system)*
Tank	0.32	0.66	1.19	*[tons]*
Fuel	0.04	0.08	0.14	*[tons]*
Subtotal	11.15	11.53	18.45	
Margin	1.12	1.15	1.84	*10%*
Total	**12.27**	**12.69**	**20.29**	*[tons]*

NYCF Weight and Volume Estimates

Weight Estimates		**150 River**	**350 Rockaway**	
Engines		1785	3215	*kg - 6M26.3/12M26.3 spec sheet*
		3935.2	7087.8	*lbs*
		1.97	3.54	*tons*
		3.94	**7.09**	*total tons (two engines)*
Fuel				
	No. Tanks	2	2	
	Volume	2840	3785	*L each*
		1500.49	1999.77	*gal*
	Weight	10393	13851	*lbs*
		5.20	**6.93**	*tons*
Auxiliary Equipment				
	7%	**0.275**	**0.496**	
Subtotal		9.41	14.51	*tons*
Margin		0.94	1.45	*tons (10% for auxiliaries)*
Total		**10.35**	**15.96**	

150 River Volume Estimate - Forward Voids

Tank Room	L	B	D	Volume	
150 River	4.8	2.2	2.5	26.4	[m3]
				932.448	[ft3]
				50%	% space taken by batteries
				466.2	[ft3 @ %]
				932.4	[both tanks]

150 Rockaway Volume Estimate - Forward Voids

Tank Room	L	B	D	Volume	
150 Rockaway	4.8	2.2	2.5	26.4	[m3]
				932.448	[ft3]
				50%	% space taken by batteries
				466.2	[ft3 @ %]
				932.4	[both tanks]

350 Rockaway Volume Estimate - Forward Voids + Forward Tank Room

Tank Room	L	B	D	Volume	
350 Rockaway	7.2	2.5	2.22	40.03	[m3]
				1413.93	[ft3]
				50%	% space taken by batteries
				707.0	[ft3 @ %]
				1413.9	[both tanks]

NYCF Seasonal Multiplication Factor

		Vessel No.	Fall	Winter	Summer
1	East River - Weekday	1		0	8.5
		2		7.5	4.5
		3	7	5	7
		4	8.5	8	8.5
		5	8	0	8
	Total Round Trips		23.5	20.5	36.5
2	East River - Weekend	1	7	8	6.5
		2	7.5	7.5	7
		3			6
	Total Round Trips		14.5	15.5	19.5
3	Rockaway - Weekday	1	8.5	8.5	8
		2		8	7.5
		4			2.5
	Total Round Trips		8.5	16.5	18
3a	Rockaway - Weekend	1	7.5	5.5	
		2	7.5	5	
	Total Round Trips		15	10.5	0
4	South Brooklyn - Weekday	1	7.5	6	8.5
		2	6.5	7.5	10
		3		8.5	7
	Total Round Trips		14	22	25.5
5	South Brooklyn Weekend - Gov	1	10.5	10.5	8.5
		2	10.5		8
		3			7
		4			6.5
	Total Round Trips		21	10.5	30
6	Astoria - Weekday	1	8.5	7.5	10.5
		2	6.5	6	10
		3	8.5	6.5	4.5
		4		1.5	9.5
	Total Round Trips		23.5	21.5	34.5
7	Astoria - Weekend	1	10.5	10.5	9.5
		2	9.5		9
		3	7.5		7
		4			6.5
	Total Round Trips		27.5	10.5	32
8	Soundview - Weekday	1	5.5	4.5	6
		2	7.5	9.5	7.5
		3	8	7.5	8
	Total Round Trips		21	21.5	21.5
9	Soundview - Weekend	1	9.5	9.5	9.5
		2	9		9
	Total Round Trips		18.5	9.5	18.5
10	Lower East Side - Weekday	1	9.5	10	9.5
		2	6.5	9.5	6.5
		3	11.5		11.5
	Total Round Trips		27.5	19.5	27.5
11	Lower East Side - Weekend	1	12	10.5	12
		2	11.5		11.5
	Total Round Trips		23.5	10.5	23.5
	Total		238	188.5	287
	Summer Baseline		83%	66%	100%

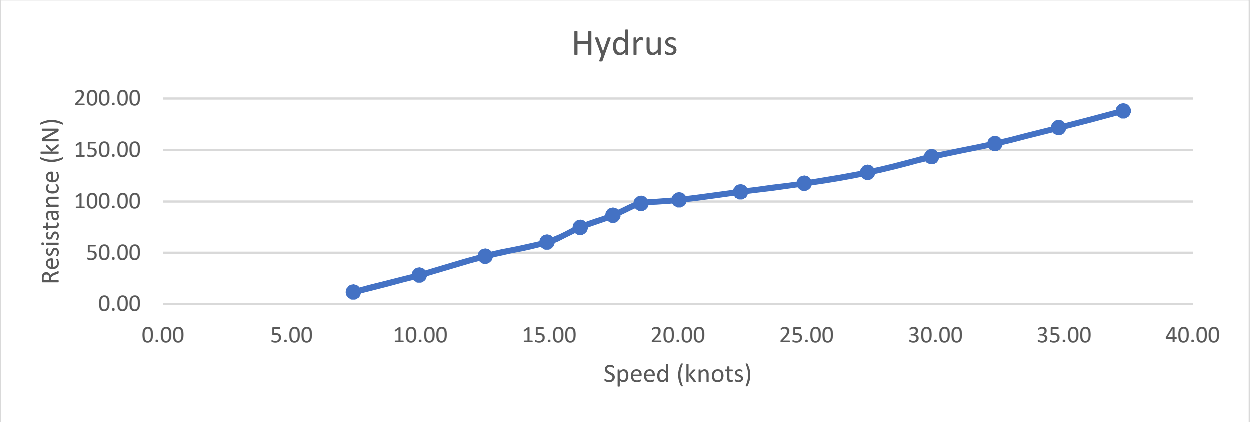
Assume Fall/Spring are similar shoulder season schedules.

Seasonal Multiplication Factor				
	% of summer season	No. Months	No. Weeks	Weighted Week
Summer Season	100%	3	13	12.96
Spring/Fall	83%	6	26	21.51
Winter	66%	3	13	8.55
			52	43.03

NYCF Resistance Scaling Calculations - 150 River

Hydrus data from ANNV

Speed (knots)	Resistance at 180 mton (kN)
7.39	11.85
9.95	28.33
12.51	46.71
14.91	60.37
16.20	74.81
17.47	86.37
18.57	98.05
20.04	101.44
22.43	109.28
24.90	117.44
27.36	128.02
29.85	143.39
32.31	156.19
34.79	171.57
37.29	187.90



Vessel Scaling Factors

	Hydrus	150 River Class		
L	41.00	26.00	*length, m*	
λ	1.58			
B_hull	3.47	2.20	*beam, m*	
A_hull ≈	457.79	184.10	*m^2*	
Δ	180.00	45.90	*tonne*	*assume roughly lightship*

Conversion Factors

1 knot =	0.51	*m/s*	
ν =	0.000001830	*m^2/s*	*kinematic viscocity of seawater*
ρ =	1025.00	*kg/m^3*	*of seawater*

Scaling Calcs

											kN	KW	knots
V_H	CT_H	RE_H	CF_H	CR_H	FN_H	V_RC	RE_RC	CF_RC	CR_RC	CT_RC	R_RC	P_RC	V_RC
3.80	0.00	8.52E+07	0.00213	0.00136	0.19	3.03	4.30E+07	0.00236	0.00136	0.00373	5.08	15.38	5.88
5.12	0.00	114680763.93	0.00204	0.00257	0.26	4.08	5.79E+07	0.00226	0.00257	0.00482	11.93	48.61	7.92
6.44	0.00	144186568.52	0.00198	0.00283	0.32	5.12	7.28E+07	0.00218	0.00283	0.00501	19.59	100.38	9.96
7.67	0.00	171848260.33	0.00193	0.00244	0.38	6.11	8.68E+07	0.00213	0.00244	0.00457	25.37	154.99	11.87
8.33	0.00	186716419.67	0.00191	0.00268	0.42	6.64	9.43E+07	0.00210	0.00268	0.00479	31.36	208.10	12.90
8.99	0.00	201354064.92	0.00189	0.00267	0.45	7.16	1.02E+08	0.00208	0.00267	0.00475	36.19	259.00	13.91
9.55	0.00	214032340.33	0.00187	0.00271	0.48	7.61	1.08E+08	0.00206	0.00271	0.00477	41.05	312.32	14.79
10.31	0.00	230975126.56	0.00185	0.00222	0.51	8.21	1.17E+08	0.00204	0.00222	0.00425	42.65	350.18	15.96
11.54	0.00	258521561.31	0.00182	0.00167	0.58	9.19	1.31E+08	0.00201	0.00167	0.00368	46.22	424.74	17.86
12.81	0.00	286990052.46	0.00180	0.00125	0.64	10.20	1.45E+08	0.00198	0.00125	0.00323	49.97	509.77	19.83
14.08	0.00	315343286.56	0.00178	0.00098	0.70	11.21	1.59E+08	0.00195	0.00098	0.00293	54.73	613.48	21.79
15.36	0.00	344042291.80	0.00176	0.00084	0.77	12.23	1.74E+08	0.00193	0.00084	0.00276	61.47	751.63	23.77
16.62	0.00	372395525.90	0.00174	0.00067	0.83	13.24	1.88E+08	0.00191	0.00067	0.00258	67.19	889.40	25.73
17.90	0.00	400979274.10	0.00172	0.00056	0.89	14.25	2.02E+08	0.00189	0.00056	0.00245	74.00	1054.70	27.70
19.18	0.00	429793536.39	0.00170	0.00047	0.96	15.28	2.17E+08	0.00187	0.00047	0.00234	81.23	1240.98	29.70

Kitsap Transit Check from CFD Data

L 21.335 *m*

Speed knots	m/s	Resistance (kN) Full load	Lightship	Resistance Scaling factor (for ~133% of lightship)
10.00	5.14	15.31		
12.00	6.17	30.27	23.14	1.31
14.00	7.20	43.02	29.57	1.45
16.00	8.23	46.45	32.24	1.44
18.00	9.26	45.62	32.53	1.40
20.00	10.29	45.20	32.65	1.38
22.00	11.32			
24.00	12.35			

Scaling the Resistance Scaling Factor for Different % of Deadweight

Max dwt	19.00 tonne		
	Max dwt	1/2 dwt	1/4 dwt
Percent of lightship	41%	21%	10%
knots	64.90	55.40	50.65 *[tonnes]*
12	1.38	1.20	1.09
14	1.56	1.29	1.14
16	1.55	1.28	1.13
18	1.50	1.26	1.12
20	1.48	1.24	1.12

Scaling Factors Based on Kitsap

1.0161	1.0726	1.1701
1.0863	1.1467	1.2509
1.0797	1.1397	1.2433
1.0612	1.1202	1.2220
1.0526	1.1111	1.2121
		0.4443

Inverse of Table

0.98	0.93	0.85
0.92	0.87	0.80
0.93	0.88	0.80
0.94	0.89	0.82
0.95	0.90	0.83

Engine MCR	803.00 hp
	598.80 kW

Power adjusted using Scaling Ratios from Kitsap Transit

V_RC		Resistance (kN)				Power (kW)			
knots	m/s	Max dwt	1/2 dwt	1/4 dwt	Lightship	Full load	1/2 dwt	1/4 dwt	Lightship
12.00	6.17	36.11	31.23	28.55	26.11	222.91	192.81	176.25	161.20
14.00	7.20	57.39	47.29	41.73	36.68	413.36	340.58	300.55	264.16
16.00	8.23	66.13	54.72	48.44	42.73	544.34	450.39	398.71	351.73
18.00	9.26	69.71	58.38	52.15	46.49	645.54	540.63	482.92	430.46
20.00	10.29	74.45	62.71	56.26	50.39	765.99	645.24	578.83	518.45
22.00	11.32	81.93	69.02	61.91	55.45	927.28	781.10	700.71	627.62
23.00	11.83	87.48	73.69	66.11	59.21	1035.11	871.93	782.19	700.60
23.50	12.09	89.64	75.51	67.74	60.67	1083.72	912.89	818.93	733.51
24.00	12.35	91.80	77.33	69.37	62.14	1133.45	954.78	856.51	767.17
24.25	12.48	92.88	78.24	70.19	62.87	1158.74	976.08	875.61	784.28
24.50	12.60	93.96	79.15	71.00	63.60	1184.30	997.61	894.93	801.58
25.00	12.86	96.12	80.97	72.64	65.06	1236.25	1041.37	934.19	836.75
25.50	13.12	98.28	82.79	74.27	66.52	1289.31	1086.07	974.28	872.66
26.00	13.38	100.65	84.79	76.06	68.13	1346.28	1134.06	1017.34	911.22

Use 20knot scaling factor beyond 20knots - trending down so this is conservative

Lightship is based on linear interpolation of resistance calculated with the scaling table

Power adjusted to match data (kW)

Full load	1/2 dwt	1/4 dwt	Lightship
222.91	219.37	207.82	190.51
413.36	380.51	360.48	330.44
544.34	504.16	477.62	437.82
645.54	608.32	576.30	528.27
765.99	727.69	689.39	631.94
927.28	880.91	834.55	765.00
1035.11	983.35	931.60	853.96
1083.72	1029.54	975.35	894.07
1133.45	1076.78	1020.11	935.10
1158.74	1100.80	1042.86	955.96
1184.30	1125.08	1065.87	977.04
1236.25	1174.44	1112.62	1019.90
1289.31	1224.85	1160.38	1063.68
1346.28	1278.97	1211.65	1110.68

Design No:	IC16019*		IC16018**		IC16112	
Vessel:	River 'T' (150 Pax)		Rockway 'T' (150 Pax)		Rockaway 'K' (350 Pax)	
	Speed (kts)		Speed (kts)		Speed (kts)	
	100% MCR	85% MCR	100% MCR	85% MCR	100% MCR	85% MCR
Max dwt	25.00	23.50	n/a	28.25	27.50	27.00
1/2 dwt	25.50	24.25	n/a	28.75	28.75	27.75
1/4 dwt	26.00	24.50	n/a	29.25	29.50	28.50
* IC16019 - Reflects reduction in propeller pitch as compared to original props						
** IC16018 - Reflects lightly pitched propellers that limit engine maximum load to ~85%						

150 River without Scaling from KT

	100%	85%	
MCR	1197.59	1017.96	*kW*
Max dwt	1.03	1.06	
1/2 dwt	0.91	0.96	
1/4 dwt	0.85	0.88	

150 River with Scaling Factors

	100%	85%	
MCR	1197.59	1017.96	*kW*
Max dwt	1.03	1.06	
1/2 dwt	1.02	1.08	
1/4 dwt	1.01	1.05	

Overpredicts, but good correlation within 1/2 kn

IC16019 Max dwt: 18,997 kg
IC16018 Max dwt: 20,552 kg
IC16112 Max dwt: 37,453 kg

NYCF Resistance Scaling Calculations - 350 Rockaway

Vessel Scaling Factors

	Hydrus	150 River Class	350 Rockaway	
L	41.00	26.00	29.60	*length, m*
λ	1.58	0.88		
B_hull	3.47	2.20	2.50	*beam, m*
A_hull ≈	457.79	184.10	230.10	*m^2*
Δ	180.00	45.90	67.73	*tonne, assume roughly lightship*
			65.22	*tonnes in Stability Letter*

Conversion Factors

1 knot =	0.51	*m/s*
v =	0.000001830	*m^2/s*
ρ =	1025.00	*kg/m^3*

150 Propulsion Resistance Values

		Full load	1/2 dwt	1/4 dwt	Lightship	CT_150
v_m/s	v_knots	kW	kW	kW	kW	kN
6.17	12.00	222.91	219.37	207.82	190.51	35.54
7.20	14.00	413.36	380.51	360.48	330.44	52.83
8.23	16.00	544.34	504.16	477.62	437.82	61.25
9.26	18.00	645.54	608.32	576.30	528.27	65.69
10.29	20.00	765.99	727.6865	689.3873	631.93831	70.73
11.32	22.00	927.28	880.91	834.55	765.00	77.84
11.83	23.00	1035.11	983.35	931.60	853.96	83.11
12.09	23.50	1083.72	1029.54	975.35	894.07	85.16
12.35	24.00	1133.45	1076.78	1020.11	935.10	87.21
12.48	24.25	1158.74	1100.80	1042.86	955.96	88.24
12.60	24.50	1184.30	1125.08	1065.87	977.04	89.27
12.86	25.00	1236.25	1174.44	1112.62	1019.90	91.32
13.12	25.50	1289.31	1224.85	1160.38	1063.68	93.37
13.38	26.00	1346.28	1278.97	1211.65	1110.68	95.62

Scaling Calcs

											kN	KW	knots
V_H	CT_H	RE_H	CF_H	CR_H	FN_H	V_RC	RE_RC	CF_RC	CR_RC	CT_RC	R_RC	P_RC	V_RC
velocity_150	*Coef (tot)_hydr*	*Ren_150*	*coef(fric)_hy*	*Coef(res)_hyd*	*Frn_hyd*	*vel_350*	*Ren 350*	*coef(fric)_r*	*coef(res)_r*	*coef(tot)_ri*	*Resi_riv*	*v*r*	*v_knots*
m/s													*knots*
6.17	0.0099	8.77E+07	0.00212	0.00776	0.39	6.59	1.07E+08	0.00206	0.00776	0.00982	44.15	290.80	12.80
7.20	0.0108	1.02E+08	0.00208	0.00872	0.45	7.68	1.24E+08	0.00202	0.00872	0.01074	65.68	504.75	14.94
8.23	0.0096	1.17E+08	0.00204	0.00755	0.52	8.78	1.42E+08	0.00198	0.00755	0.00953	76.11	668.44	17.07
9.26	0.0081	1.32E+08	0.00200	0.00612	0.58	9.88	1.60E+08	0.00195	0.00612	0.00807	81.56	805.83	19.21
10.29	0.0071	1.46E+08	0.00197	0.00511	0.64	10.98	1.78E+08	0.00192	0.00511	0.00703	87.74	963.17	21.34
11.32	0.0064	1.61E+08	0.00195	0.00449	0.71	12.08	1.95E+08	0.00190	0.00449	0.00639	96.50	1165.29	23.47
11.83	0.0063	1.68E+08	0.00194	0.00436	0.74	12.62	2.04E+08	0.00188	0.00436	0.00624	103.02	1300.65	24.54
12.09	0.0062	1.72E+08	0.00193	0.00425	0.76	12.90	2.09E+08	0.00188	0.00425	0.00612	105.56	1361.58	25.07
12.35	0.0061	1.75E+08	0.00192	0.00414	0.77	13.17	2.13E+08	0.00187	0.00414	0.00601	108.09	1423.89	25.61
12.48	0.0060	1.77E+08	0.00192	0.00409	0.78	13.31	2.15E+08	0.00187	0.00409	0.00596	109.35	1455.57	25.87
12.60	0.0060	1.79E+08	0.00192	0.00404	0.79	13.45	2.18E+08	0.00187	0.00404	0.00590	110.62	1487.59	26.14
12.86	0.0059	1.83E+08	0.00191	0.00394	0.81	13.72	2.22E+08	0.00186	0.00394	0.00580	113.15	1552.67	26.67
13.12	0.0058	1.86E+08	0.00191	0.00384	0.82	14.00	2.26E+08	0.00186	0.00384	0.00570	115.68	1619.12	27.21
13.38	0.0057	1.90E+08	0.00190	0.00376	0.84	14.27	2.31E+08	0.00185	0.00376	0.00561	118.45	1690.50	27.74

Installed Power	2058.13	kW
	100%MCR	85% MCR
1/2 dwt	28.75	27.75
kW	2058.13	1749.41
97%	**slightly underpredicts*	

NYCF Maintenance Costs

Estimated Annual Operating Hours

6M	3817.0
12M	3898.1

Baseline Capital Cost Estimate

			6M (per vessel)		12M (per vessel)	
	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost
Main Propulsion Diesel Engine						
Lube Oil Change	2000	hrs	$ 1,500	$ 2,863	$ 1,725	$ 3,362
Minor Overhaul 6M	10400	hrs	$ 35,000	$ 12,846	N/A	N/A
Minor Overhaul 12M	12000	hrs	-	-	$ 67,200	$ 21,830
Major Overhaul 6M	18000	hrs	$ 60,000	$ 12,723	-	-
Major Overhaul 12M	24000	hrs	-	-	$ 115,200	$ 18,711
Main Engine Subtotal				$ 28,432		$ 43,903
Cost per running hr				$ 7.45		$ 11.26
Ship Service Diesel Generator						
Lube Oil Change	1000	hrs	$ 1,000	$ 3,817	$ 1,000	$ 3,898
Minor Overhaul	5000	hrs	$ 3,000	$ 2,290	$ 3,000	$ 2,339
Major Overhual	10000	hrs	$ 7,000	$ 2,672	$ 7,000	$ 2,729
Alternator Overhaul	20000	hrs	$ 7,000	$ 1,336	$ 7,000	$ 1,364
SSDG Subtotal				$ 10,115		$ 10,330
Maintenance Total				$ 77,094		$ 108,465

Assumption - 12M is 15% more expensive

Assumption - 1 generator running at 50% load.

Option 1 - Emissions Control Upgrades

			6M (per vessel)		12M (per vessel)	
	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost
Main Propulsion Diesel Engine						
Baseline Annual Cost per Running hr			$ 7.45		$ 11.26	
Tier 4 Additional Cost per Running hr			$ 2.50		$ 2.50	
Subtotal Cost per Running hr			$ 9.95		$ 13.76	
Main Engine Subtotal						
Cost per running hr				$ 37,974		$ 53,648
Ship Service Diesel Generator						
Lube Oil Change	1000	hrs	$ 1,000	$ 3,817	$ 1,000	$ 3,898
Minor Overhaul	5000	hrs	$ 3,000	$ 2,290	$ 3,000	$ 2,339
Major Overhual	10000	hrs	$ 7,000	$ 2,672	$ 7,000	$ 2,729
Alternator Overhaul	20000	hrs	$ 7,000	$ 1,336	$ 7,000	$ 1,364
SSDG Subtotal				$ 10,115		$ 10,330
Maintenance Total				$ 96,179		$ 127,956

Values provided in Baudouin presentation on Tier 3 vs Tier 4

Assumption - 1 generator running at 50% load.

Option 2 - Biodiesel

			6M (per vessel)		12M (per vessel)	
	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost
Main Propulsion Diesel Engine						
Lube Oil Change	2000	hrs	$ 1,500	$ 2,863	$ 1,725	$ 3,362
Minor Overhaul 6M	10400	hrs	$ 35,000	$ 12,846	N/A	N/A
Minor Overhaul 12M	12000	hrs	-	-	$ 67,200	$ 21,830
Major Overhaul 6M	18000	hrs	$ 60,000	$ 12,723	-	-
Major Overhaul 12M	24000	hrs	-	-	$ 115,200	$ 18,711
Main Engine Subtotal				$ 28,432		$ 43,903
Cost per running hr				$ 7.45		$ 11.26
Ship Service Diesel Generator						
Lube Oil Change	1000	hrs	$ 1,000	$ 3,817	$ 1,000	$ 3,898
Minor Overhaul	5000	hrs	$ 3,000	$ 2,290	$ 3,000	$ 2,339
Major Overhual	10000	hrs	$ 7,000	$ 2,672	$ 7,000	$ 2,729
Alternator Overhaul	20000	hrs	$ 7,000	$ 1,336	$ 7,000	$ 1,364
SSDG Subtotal				$ 10,115		$ 10,330
Maintenance Total	2	engines		$ 77,094		$ 108,465

Assumption - 12M is 25% more expensive

Same as baseline

Option 3 - R50

			6M (per vessel)		12M (per vessel)	
	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost
Main Propulsion Diesel Engine						
Lube Oil Change	2000	hrs	$ 1,500	$ 2,863	$ 1,725	$ 3,362
Minor Overhaul 6M	10400	hrs	$ 35,000	$ 12,846	N/A	N/A
Minor Overhaul 12M	12000	hrs	-	-	$ 67,200	$ 21,830
Major Overhaul 6M	18000	hrs	$ 60,000	$ 12,723	-	-
Major Overhaul 12M	24000	hrs	-	-	$ 115,200	$ 18,711
Main Engine Subtotal				$ 28,432		$ 43,903
Cost per running hr				$ 7.45		$ 11.26
Ship Service Diesel Generator						
Lube Oil Change	1000	hrs	$ 1,000	$ 3,817	$ 1,000	$ 3,898
Minor Overhaul	5000	hrs	$ 3,000	$ 2,290	$ 3,000	$ 2,339
Major Overhual	10000	hrs	$ 7,000	$ 2,672	$ 7,000	$ 2,729
Alternator Overhaul	20000	hrs	$ 7,000	$ 1,336	$ 7,000	$ 1,364
SSDG Subtotal				$ 10,115		$ 10,330
Maintenance Total	2	engines		$ 77,094		$ 108,465

Assumption - 12M is 25% more expensive

Same as baseline

Option 4 - Gas Engines

			6M (per vessel)		12M (per vessel)	
	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost
Main Propulsion Diesel Engine						
Lube Oil Change	2000	hrs	$ 1,500.00	$ 2,863	$ 1,725	$ 3,362
Minor Overhaul 6M	10400	hrs	$ 35,000.00	$ 12,846	N/A	N/A
Minor Overhaul 12M	12000	hrs	-	-	$ 67,200	$ 21,830
Major Overhaul 6M	18000	hrs	$ 60,000.00	$ 12,723	-	-
Major Overhaul 12M	24000	hrs	-	-	$ 115,200	$ 18,711
Main Engine Subtotal				$ 28,432		$ 43,903
Cost per running hr				$ 7		$ 11
Ship Service Diesel Generator						
Lube Oil Change	1000	hrs	$ 1,000	$ 3,817	$ 1,000	$ 3,898
Minor Overhaul	5000	hrs	$ 3,000	$ 2,290	$ 3,000	$ 2,339
Major Overhual	10000	hrs	$ 7,000	$ 2,672	$ 7,000	$ 2,729
Alternator Overhaul	20000	hrs	$ 7,000	$ 1,336	$ 7,000	$ 1,364
SSDG Subtotal				$ 10,115		$ 10,330
Maintenance Total	2	engines		$ 77,094		$ 108,465

Assumption - 12M is 25% more expensive

Same as baseline

Option 5 - Plug in Electric

			6M (per vessel)		12M (per vessel)	
	Interval	Units	Cost (ea)	Cost	Cost (ea)	Cost
Main Propulsion Batteries						
Battery Replacement (665 kW	5	yrs	$ 630	$ 83,790		
Battery Replacement (920 kW	5	yrs	-	-	$ 630	$ 115,920
Installation Cost	5	yrs	$ 25,000	$ 5,000	$ 25,000	$ 5,000
Main Propulsion Subtotal				$ 88,790		$ 120,920
Cost per running hr				$ 23		$ 31
Maintenance Total				$ 88,790		$ 120,920
House loads are provided by battery banks						

NYCF Capital Costs

Baseline Capital Cost Estimate

	6M (per vessel)			12M (per vessel)		
	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
Equipment						
Engines	2	$ 100,000	$ 200,000	2	$ 192,000	$ 384,000
Subtotal			$ 200,000			$ 384,000
Installation (@ 30%)			$ 60,000			$ 115,200
Total			$ 260,000			$ 499,200

Notes:

ROM values for capital cost provided by Baudouin.

Option 1 - Emission Control Upgrades

	6M (per vessel)			12M (per vessel)		
	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
Equipment						
Engines	2	$ 55,000	$ 110,000	2	$ 78,000	$ 156,000
Subtotal			$ 110,000			$ 156,000
Installation (@ 30%)			$ 33,000			$ 46,800
Total			$ 143,000			$ 202,800

Notes:

ROM values for capital cost provided by Baudouin.

Baseline capital cost subtracted here, assume engine repower required on same timeline

Option 2 - B10

	6M (per vessel)			12M (per vessel)		
	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
Equipment						
		$ -	$ -		$ -	$ -
Subtotal			$ -			$ -
Installation (@ 30%)			$ -			$ -
Total			$ -			$ -

Option 3 - R50

	6M (per vessel)			12M (per vessel)		
	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
Equipment						
		$ -	$ -		$ -	$ -
Subtotal			$ -			$ -
Installation			$ -			$ -
Total			$ -			$ -

Option 4 - Gas Engines

	6M (per vessel)			12M (per vessel)		
	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
Equipment						
Equipment (250% Baseline)	2	$ 250,000	$ 500,000	2	$ 480,000	$ 960,000
Subtotal			$ 500,000			$ 960,000
Installation (@ 100%)			$ 500,000			$ 960,000
Total			$ 1,000,000			$ 1,920,000

Notes:

Equipment includes engines and supporting auxiliary equipment and bunkering equipment

Option 5 - Electric

	6M (per shipset)			12M (per shipset)		
	Qty	Cost (ea)	Cost	Qty	Cost (ea)	Cost
Equipment						
Batteries (in kWhrs)	630	$ 667	$ 420,210	917	667	$ 611,639
Battery installation	1	$ 25,000	$ 25,000	1	$ 25,000	$ 25,000
Propulsion Motors	2	$ 75,000	$ 150,000	2	$ 90,000	$ 180,000
Aux Elec Equip (25% battery cost)	2	$ 105,053	$ 210,105	2	$ 152,910	$ 305,820
Shipboard modifications	1	$ 250,000	$ 250,000	1	$ 250,000	$ 250,000
Subtotal (vessel)			$ 1,055,315			$ 1,372,459

Terminal Infrastructure	8	$ 2,000,000	$ 16,000,000			

Reference Information

Real Disc. Rate	1%	
Diesel Density	3.218	kg/gal
kgCO2perkgDiesel	3.206	
kgSO2perkgDiesel	3.00E-05	
kgCO2perMJGas	0.050253264	Source EPA - see onennote
Diesel LHV	145	MJ/gal
kgCO2perMJGas	0.050	Source EPA - see onenote
Methane GWP	28	

		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Routes	East River	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Rockaway	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	South Brooklyn	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Astoria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Soundview	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Lower East Side	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Soundview Expansion	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	St Georges	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Coney Island	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Total																					
Baseline Tier 3	6M	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14
	12M	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Tier 4 Upgrades	6M	0	0	0	0	0	0	0	0	0	2	4	4	4	0	0	0	0	0	0	0	0
	12M	0	0	0	0	0	0	0	0	0	0	3	3	3	0	0	0	0	0	0	0	0
Upgraded Fleet Composition	Tier 3 6M	14	14	14	14	14	14	14	14	14	12	8	4	0	0	0	0	0	0	0	0	0
	Tier 3 12M	9	9	9	9	9	9	9	9	9	9	6	3	0	0	0	0	0	0	0	0	0
	Tier 4 6M	0	0	0	0	0	0	0	0	0	2	6	10	14	14	14	14	14	14	14	14	14
	Tier 4 12M	0	0	0	0	0	0	0	0	0	0	3	6	9	9	9	9	9	9	9	9	9

Fuel Costs

based on AEO2019, 2018 dollars

		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
Diesel	(per gallon)	$ 2.56	$ 2.56	$ 2.54	$ 2.57	$ 2.62	$ 2.66	$ 2.68	$ 2.76	$ 2.78	$ 2.87	$ 2.89	$ 2.92	$ 2.96	$ 2.99	$ 3.00	$ 3.02	$ 3.06	$ 3.05	$ 3.07	$ 3.09	$ 3.10
Electricity	(per kwh)	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04	$ 0.04
LNG	(per GJ)	$ 11.20	$ 11.04	$ 11.03	$ 11.13	$ 11.28	$ 11.53	$ 11.62	$ 11.62	$ 11.69	$ 11.67	$ 11.71	$ 11.70	$ 11.82	$ 11.88	$ 11.93	$ 11.96	$ 12.03	$ 12.06	$ 12.06	$ 12.07	$ 12.10

Baseline

Fuel and Emissions		Total
Diesel	gal	65M
Fuel Energy	GJ	9M
NOx	MT	4977
HC	MT	104
PM	MT	113
CO	MT	769
CO2	MT	657K
SO2	MT	6.1
Costs - 20 yr NPV		$206.8M
Costs - Ops NPV		$206.8M
Costs - Capital		-

Diesel	(gal/year)	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M
NOx	(MT/year)	231.5	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3
HC	(MT/year)	4.8	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
PM	(MT/year)	5.2	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
CO	(MT/year)	35.8	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7
CO2	(MT/year)	30,722.70	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37	31,299.37
SO2	(MT/year)	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
Capital		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$7.8M	$8.0M	$7.9M	$8.0M	$8.2M	$8.3M	$8.3M	$8.6M	$8.6M	$8.9M	$9.0M	$9.1M	$9.2M	$9.3M	$9.3M	$9.4M	$9.5M	$9.5M	$9.5M	$9.6M	$9.6M
Maintenance		$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M
Ops Subtotal		$9.9M	$10.0M	$10.0M	$10.0M	$10.2M	$10.3M	$10.4M	$10.6M	$10.7M	$11.0M	$11.0M	$11.1M	$11.2M	$11.3M	$11.4M	$11.5M	$11.6M	$11.5M	$11.6M	$11.7M	$11.7M
Total		$9.9M	$10.0M	$10.0M	$10.0M	$10.2M	$10.3M	$10.4M	$10.6M	$10.7M	$11.0M	$11.0M	$11.1M	$11.2M	$11.3M	$11.4M	$11.5M	$11.6M	$11.5M	$11.6M	$11.7M	$11.7M
PV Total	(discounted to 2020)	$9.9M	$9.9M	$9.8M	$9.7M	$9.8M	$9.8M	$9.8M	$9.9M	$9.9M	$10.0M	$10.0M	$10.0M	$10.0M	$10.0M	$9.9M	$9.9M	$9.9M	$9.7M	$9.7M	$9.6M	$9.6M
PV Ops	(discounted to 2020)	$9.9M	$9.9M	$9.8M	$9.7M	$9.8M	$9.8M	$9.8M	$9.9M	$9.9M	$10.0M	$10.0M	$10.0M	$10.0M	$10.0M	$9.9M	$9.9M	$9.9M	$9.7M	$9.7M	$9.6M	$9.6M
PV Fuel		$7.8M	$7.9M	$7.7M	$7.8M	$7.8M	$7.9M	$7.9M	$8.0M	$8.0M	$8.2M	$8.1M	$8.1M	$8.2M	$8.2M	$8.1M	$8.1M	$8.1M	$8.0M	$8.0M	$7.9M	$7.9M

Option 1 - Emission Control Upgrades

Fuel and Emissions		Total	vs baseline	
Diesel	gal	60M	-8%	-5081K
NOx	MT	1044	-79%	-3,933
HC	MT	104	-	0
PM	MT	28	-75%	-85
CO	MT	769	-	0
CO2	MT	606K	-8%	-51,177
SO2	MT	5.7	-8%	-0.479
Costs - 20 yr NPV		$205.9M	-0%	
Costs - Ops NPV		$202.5M	-2%	
Costs - Capital		$3.8M		

Diesel	(gal/year)	2.8M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M	2.9M
NOx	(MT/year)	48.6	49.8	49.8	49.8	49.8	49.8	49.8	49.8	49.8	49.8	49.8	49.8	49.8	49.8	49.8	49.8	49.8	49.8	49.8	49.8	49.8
HC	(MT/year)	4.8	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
PM	(MT/year)	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
CO	(MT/year)	35.8	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7
CO2	(MT/year)	28,195.46	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90	28,866.90
SO2	(MT/year)	0.26	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Capital		-	-	-	-	-	-	-	-	-	$.3M	$1.2M	$1.2M	$1.2M	-	-	-	-	-	-	-	-
Fuel		$7.4M	$7.6M	$7.5M	$7.6M	$7.8M	$7.9M	$7.9M	$8.2M	$8.2M	$8.5M	$8.5M	$8.6M	$8.7M	$8.8M	$8.8M	$8.9M	$9.0M	$9.0M	$9.1M	$9.1M	$9.2M
Maintenance		$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.2M	$2.4M	$2.5M	$2.5M	$2.5M	$2.5M	$2.5M	$2.5M	$2.5M	$2.5M	$2.5M
Ops Subtotal		$9.5M	$9.7M	$9.6M	$9.7M	$9.8M	$9.9M	$10.0M	$10.2M	$10.3M	$10.6M	$10.8M	$11.0M	$11.2M	$11.3M	$11.3M	$11.4M	$11.5M	$11.5M	$11.6M	$11.6M	$11.6M
Total		$9.5M	$9.7M	$9.6M	$9.7M	$9.8M	$9.9M	$10.0M	$10.2M	$10.3M	$10.9M	$12.0M	$12.2M	$12.4M	$11.3M	$11.3M	$11.4M	$11.5M	$11.5M	$11.6M	$11.6M	$11.6M
PV Total	(discounted to 2020)	$9.5M	$9.6M	$9.4M	$9.4M	$9.4M	$9.5M	$9.4M	$9.5M	$9.5M	$9.9M	$10.8M	$10.9M	$11.0M	$9.9M	$9.9M	$9.8M	$9.8M	$9.7M	$9.7M	$9.6M	$9.5M
PV Ops	(discounted to 2020)	$9.5M	$9.6M	$9.4M	$9.4M	$9.4M	$9.5M	$9.4M	$9.5M	$9.5M	$9.7M	$9.8M	$9.9M	$10.0M	$9.9M	$9.9M	$9.8M	$9.8M	$9.7M	$9.7M	$9.6M	$9.5M

Option 2 - B10

Fuel and Emissions		Total	vs baseline	
B10	gal	66M	+1%	326K
NOx	MT	5027	+1%	50
HC	MT	96	-8%	-8
PM	MT	104	-7%	-8
CO	MT	711	-7%	-58
CO2	MT	624K	-5%	-32,836
SO2	MT	5.5	-10%	-1
Costs - 20 yr NPV		$210.6M	+2%	$3.8M
Costs - Ops NPV		$210.6M	+2%	$3.8M
Costs - Capital		-		

Fuel costs include extra $.05/gal

Gallons of B100 blended 13M

B10	(gal/year)	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M
NOx	(MT/year)	233.9	239.7	239.7	239.7	239.7	239.7	239.7	239.7	239.7	239.7	239.7	239.7	239.7	239.7	239.7	239.7	239.7	239.7	239.7	239.7	239.7
HC	(MT/year)	4.5	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
PM	(MT/year)	4.8	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
CO	(MT/year)	33.1	33.9	33.9	33.9	33.9	33.9	33.9	33.9	33.9	33.9	33.9	33.9	33.9	33.9	33.9	33.9	33.9	33.9	33.9	33.9	33.9
CO2	(MT/year)	29,186.57	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40	29,734.40
SO2	(MT/year)	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Capital		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$8.0M	$8.2M	$8.1M	$8.2M	$8.3M	$8.5M	$8.5M	$8.8M	$8.8M	$9.1M	$9.2M	$9.3M	$9.4M	$9.5M	$9.5M	$9.6M	$9.7M	$9.7M	$9.7M	$9.8M	$9.8M
Maintenance		$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M
Ops Subtotal		$10.0M	$10.2M	$10.2M	$10.2M	$10.4M	$10.5M	$10.6M	$10.8M	$10.9M	$11.2M	$11.2M	$11.3M	$11.4M	$11.5M	$11.6M	$11.7M	$11.8M	$11.7M	$11.8M	$11.9M	$11.9M
Total		$10.0M	$10.2M	$10.2M	$10.2M	$10.4M	$10.5M	$10.6M	$10.8M	$10.9M	$11.2M	$11.2M	$11.3M	$11.4M	$11.5M	$11.6M	$11.7M	$11.8M	$11.7M	$11.8M	$11.9M	$11.9M
PV Total	(discounted to 2020)	$10.0M	$10.1M	$10.0M	$9.9M	$10.0M	$10.0M	$10.0M	$10.1M	$10.1M	$10.2M	$10.2M	$10.2M	$10.2M	$10.1M	$10.1M	$10.0M	$10.0M	$9.9M	$9.9M	$9.8M	$9.8M
PV Ops	(discounted to 2020)	$10.0M	$10.1M	$10.0M	$9.9M	$10.0M	$10.0M	$10.0M	$10.1M	$10.1M	$10.2M	$10.2M	$10.2M	$10.2M	$10.1M	$10.1M	$10.0M	$10.0M	$9.9M	$9.9M	$9.8M	$9.8M

Option 3 - R50

Fuel and Emissions		Total	vs baseline	
R50	gal	65M	-	0K
NOx	MT	4853	-3%	-124
HC	MT	88	-15%	-16
PM	MT	96	-15%	-17
CO	MT	654	-15%	-115
CO2	MT	443K	-33%	-213,431
SO2	MT	3.1	-50%	-3
Costs - 20 yr NPV		$251.1M	+21%	$44.3M
Costs - Ops NPV		$251.1M	+21%	$44.3M
Costs - Capital		-		

Fuel costs include extra $1.50/gal

Gallons of B100 blended 13M

R50	(gal/year)	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M	3.1M
NOx	(MT/year)	225.7	231.3	231.3	231.3	231.3	231.3	231.3	231.3	231.3	231.3	231.3	231.3	231.3	231.3	231.3	231.3	231.3	231.3	231.3	231.3	231.3
HC	(MT/year)	4.1	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
PM	(MT/year)	4.4	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6
CO	(MT/year)	30.4	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2	31.2
CO2	(MT/year)	20,737.82	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08	21,127.08
SO2	(MT/year)	0.14	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Capital		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$10.1M	$10.3M	$10.2M	$10.3M	$10.5M	$10.6M	$10.7M	$10.9M	$11.0M	$11.2M	$11.3M	$11.4M	$11.5M	$11.6M	$11.6M	$11.7M	$11.8M	$11.8M	$11.9M	$11.9M	$12.0M
Maintenance		$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M
Ops Subtotal		$12.1M	$12.4M	$12.3M	$12.4M	$12.5M	$12.7M	$12.7M	$13.0M	$13.0M	$13.3M	$13.4M	$13.5M	$13.6M	$13.7M	$13.7M	$13.8M	$13.9M	$13.9M	$13.9M	$14.0M	$14.0M
Total		$12.1M	$12.4M	$12.3M	$12.4M	$12.5M	$12.7M	$12.7M	$13.0M	$13.0M	$13.3M	$13.4M	$13.5M	$13.6M	$13.7M	$13.7M	$13.8M	$13.9M	$13.9M	$13.9M	$14.0M	$14.0M
PV Total	(discounted to 2020)	$12.1M	$12.2M	$12.0M	$12.0M	$12.0M	$12.1M	$12.0M	$12.1M	$12.0M	$12.2M	$12.1M	$12.1M	$12.0M	$12.0M	$11.9M	$11.9M	$11.8M	$11.7M	$11.6M	$11.6M	$11.5M
PV Ops	(discounted to 2020)	$12.1M	$12.2M	$12.0M	$12.0M	$12.0M	$12.1M	$12.0M	$12.1M	$12.0M	$12.2M	$12.1M	$12.1M	$12.0M	$12.0M	$11.9M	$11.9M	$11.8M	$11.7M	$11.6M	$11.6M	$11.5M

Option 4 - Gas Engines

Fuel and Emissions		Total	vs baseline	
LNG	GJ	8.48M	-10%	
NOx	MT	4977	-	0
HC	MT	104	-	0
PM	MT	113	-	0
CO	MT	769	-	0
CO2e	MT	602K	-8%	-55,146
SO2	MT	0.0	-100%	-6
Costs - 20 yr NPV		$160.0M	-23%	-46,757,605
Costs - Ops NPV		$128.7M	-38%	-78,037,605
Costs - Capital		$31.3M		

LNG	(GJ/year)	397K	404K	404K	404K	404K	404K	404K	404K	404K	404K	404K	404K	404K	404K	404K	404K	404K	404K	404K	404K	404K
NOx	(MT/year)	231.5	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3	237.3
HC	(MT/year)	4.8	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
PM	(MT/year)	5.2	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4	5.4
CO	(MT/year)	35.8	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7	36.7
CO2e	(MT/year)	27,952.51	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57	28,680.57
SO2	(MT/year)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Capital		$31.3M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fuel		$4.44M	$4.46M	$4.46M	$4.50M	$4.56M	$4.66M	$4.69M	$4.70M	$4.72M	$4.72M	$4.73M	$4.73M	$4.78M	$4.80M	$4.82M	$4.83M	$4.86M	$4.87M	$4.87M	$4.88M	$4.89M
Maintenance		$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M	$2.1M
Ops Subtotal		$6.5M	$6.5M	$6.5M	$6.6M	$6.6M	$6.7M	$6.7M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.9M	$6.9M	$6.9M	$6.9M	$6.9M	$6.9M	$6.9M	$6.9M
Total		$37.8M	$6.5M	$6.5M	$6.6M	$6.6M	$6.7M	$6.7M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.9M	$6.9M	$6.9M	$6.9M	$6.9M	$6.9M	$6.9M	$6.9M
PV Total	(discounted to 2020)	$37.8M	$6.5M	$6.4M	$6.4M	$6.4M	$6.4M	$6.4M	$6.3M	$6.3M	$6.2M	$6.1M	$6.1M	$6.1M	$6.0M	$6.0M	$5.9M	$5.9M	$5.8M	$5.8M	$5.7M	$5.7M
PV Ops	(discounted to 2020)	$6.5M	$6.5M	$6.4M	$6.4M	$6.4M	$6.4M	$6.4M	$6.3M	$6.3M	$6.2M	$6.1M	$6.1M	$6.1M	$6.0M	$6.0M	$5.9M	$5.9M	$5.8M	$5.8M	$5.7M	$5.7M

Option 5 - Electric Plug-in (8 charging stations)

Fuel and Emissions		Total	vs baseline	
Energy	kWhr	910.11M		
NOx	MT	202	-96%	-4,775
HC	MT	6	-94%	-98
PM	MT	10	-91%	-103
CO	MT	133	-83%	-636
CO2	MT	181K	-72%	-475,599
SO2	MT	107.4	+1648%	101
Costs - 20 yr NPV		$172.2M	-17%	
Costs - Ops NPV		$129.1M	-38%	
Costs - Capital		$43.1M		

Energy	kwhr/year	43.2M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M	43.3M
NOx	(MT/year)	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6
HC	(MT/year)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
PM	(MT/year)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
CO	(MT/year)	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3
CO2	(MT/year)	8,602	8,625	8,625	8,625	8,625	8,625	8,625	8,625	8,625	8,625	8,625	8,625	8,625	8,625	8,625	8,625	8,625	8,625	8,625	8,625	8,625
SO2	(MT/year)	5.10	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11	5.11
Capital		$43.1M	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Energy Cost		$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M	$1.6M
Power Demand Cost		$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M	$2.83M
Maintenance		$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M	$2.3M
Ops Subtotal		$6.8M	$6.7M	$6.7M	$6.7M	$6.7M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M
Total		$49.9M	$6.7M	$6.7M	$6.7M	$6.7M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M	$6.8M
PV Total	(discounted to 2020)	$49.9M	$6.7M	$6.6M	$6.5M	$6.5M	$6.4M	$6.4M	$6.3M	$6.3M	$6.2M	$6.1M	$6.1M	$6.0M	$6.0M	$5.9M	$5.8M	$5.8M	$5.7M	$5.7M	$5.6M	$5.6M
PV Ops	(discounted to 2020)	$6.8M	$6.7M	$6.6M	$6.5M	$6.5M	$6.4M	$6.4M	$6.3M	$6.3M	$6.2M	$6.1M	$6.1M	$6.0M	$6.0M	$5.9M	$5.8M	$5.8M	$5.7M	$5.7M	$5.6M	$5.6M

Any formulas that differ from Baseline should be outlined in green

Seasonal Correction Factors - tally on Seasonal_Calcs Tab				
Summer Seas	100%	3	13	12.96
Spring/Fall	83%	6	26	21.5136
Winter	66%	3	13	8.5536
			52	43.03

Reference Data - values referenced from other sheets here to simplify lifecycle formulas to the left

Baseline Fuel and Emissions per Week	Gal	CO	PM	NOx	HC	CO2	SO2	Future Expansion - 1 additional vessel on route per day (reports weekly) Gal	CO	PM	NOx	HC	CO2	SO2	Annual Maintenance 6M	12M	Capital Cost 6M	12M
East River	10774.7	0.138332	0.02230225	0.895206	0.01934078	108.52853	0.001016	2473.1	0.032	0.005	0.205	0.004	24.911	0.0002	$ 77,093.76	$ 108,465.46	$ -	$ -
Rockaway	11195.0	0.121692	0.01698019	0.787521	0.0169707	112.76163	0.001055	3731.7	0.041	0.006	0.263	0.006	37.587	0.0004				
South Brooklyn	8357.1	0.103826	0.01619154	0.671904	0.01447032	84.177403	0.000788	2528.1	0.031	0.005	0.204	0.004	25.465	0.0002				
Astoria	11857.8	0.139759	0.01896495	0.904442	0.01692643	119.43758	0.001118	2964.4	0.035	0.005	0.226	0.004	29.859	0.0003				
Soundview	10225.7	0.107939	0.01346311	0.698523	0.01411748	102.99873	0.000964	3832.4	0.040	0.005	0.262	0.005	38.602	0.0004				
Lower East Side	6791.1	0.084186	0.0128157	0.544801	0.01129622	68.403034	0.00064	2561.1	0.032	0.005	0.206	0.004	25.796	0.0002				
Soundview Expansion								10374.4	0.119	0.017	0.769	0.017	104.497	0.0010				
St Georges								1330.6	0.021	0.004	0.133	0.003	13.402	0.0001				
Coney Island								1313.1	0.017	0.003	0.110	0.002	13.226	0.0001				

3	$/gal of urea
3%	Assume 3% of fuel consumption

Tier 4 Fuel and Emissions per Week	Gal	CO	PM	NOx	HC	CO2	SO2	Future Expansion - 1 additional vessel on route per day (reports weekly) Gal	CO	PM	NOx	HC	CO2	SO2	Annual Maintenance 6M	12M	Capital Cost 6M	12M
East River	10165.1	0.14	0.01	0.19	0.02	102.39	0.00	2334.0	0.032	0.001	0.043	0.004	23.5	0.0002	$ 96,178.80	$ 127,956.11	$ 143,000.00	$ 202,800.00
Rockaway	10319.0	0.12	0.00	0.17	0.02	103.94	0.00	3439.7	0.041	0.001	0.055	0.006	34.6	0.0003				
South Brooklyn	7917.7	0.10	0.00	0.14	0.01	79.75	0.00	2395.2	0.031	0.001	0.043	0.004	24.1	0.0002				
Astoria	10184.3	0.14	0.00	0.19	0.02	102.58	0.00	2546.1	0.035	0.001	0.047	0.004	25.6	0.0002				
Soundview	9400.7	0.11	0.00	0.15	0.01	94.69	0.00	3522.6	0.040	0.001	0.055	0.005	35.5	0.0003				
Lower East Side	6067.9	0.08	0.00	0.11	0.01	61.12	0.00	2289.4	0.032	0.001	0.043	0.004	23.1	0.0002				
Soundview Expansion								9728.0	0.119	0.004	0.161	0.017	98.0	0.0009				
St Georges								1549.3	0.021	0.001	0.028	0.003	15.6	0.0001				
Coney Island								1274.8	0.017	0.001	0.023	0.002	12.8	0.0001				

Biodiesel Fuel and Emissions per Week	Gal	CO	PM	NOx	HC	CO2	SO2	Future Expansion Gal	CO	PM	NOx	HC	CO2	SO2	Annual Maintenance 6M	12M	Capital Cost 6M	12M
	0.5%	-7.5%	-7.5%	1.0%	-7.5%	-5.0%	-10.0%	0.5%	-7.5%	-7.5%	1.0%	-7.5%	-5.0%	-10.0%	$ 77,093.76	$ 108,465.46	$ -	$ -
East River	10828.6	0.128	0.0206	0.9042	0.0179	103.1021	0.0009	2485.4826	0.0292	0.0047	0.2066	0.0041	23.6650	0.0002098				
Rockaway	11251.0	0.113	0.0157	0.7954	0.0157	107.1235	0.0009	3750.3171	0.0375	0.0052	0.2651	0.0052	35.7078	0.0003165				
South Brooklyn	8398.9	0.096	0.0150	0.6786	0.0134	79.9685	0.0007	2540.7826	0.0291	0.0046	0.2058	0.0041	24.1915	0.0002145				
Astoria	11917.1	0.129	0.0175	0.9135	0.0157	113.4657	0.0010	2979.2635	0.0323	0.0044	0.2284	0.0039	28.3664	0.0002515				
Soundview	10276.8	0.100	0.0125	0.7055	0.0131	97.8488	0.0009	3851.5576	0.0374	0.0047	0.2641	0.0049	36.6718	0.0003251				
Lower East Side	6825.0	0.078	0.0119	0.5502	0.0104	64.9829	0.0006	2573.8570	0.0294	0.0045	0.2077	0.0039	24.5064	0.0002172				
Soundview Expansion								10426.2869	0.1099	0.0160	0.7763	0.0153	99.2717	0.0008800				
St Georges								1337.2519	0.0191	0.0038	0.1348	0.0029	12.7324	0.0001129				
Coney Island								1319.6772	0.0157	0.0026	0.1113	0.0023	12.5650	0.0001114				

Renewable Diesel Fuel and Emissions per Week	Gal	CO	PM	NOx	HC	CO2	SO2	Future Expansion Gal	CO	PM	NOx	HC	CO2	SO2	Annual Maintenance 6M	12M	Capital Cost 6M	12M
	No change														$ 77,093.76	$ 108,465.46	$ -	$ -
East River	10774.7	0.1176	0.01896	0.87283	0.0164	73.26	0.0005	2473.1	0.0269	0.00431	0.19941	0.0037	16.81	0.0001				
Rockaway	11195.0	0.1034	0.01443	0.76783	0.0144	76.11	0.0005	3731.7	0.0345	0.00481	0.25594	0.0048	25.37	0.0002				
South Brooklyn	8357.1	0.0883	0.01376	0.65511	0.0123	56.82	0.0004	2528.1	0.0268	0.00418	0.19864	0.0037	17.19	0.0001				
Astoria	11857.8	0.1188	0.01612	0.88183	0.0144	80.62	0.0006	2964.4	0.0297	0.00403	0.22046	0.0036	20.16	0.0001				
Soundview	10225.7	0.0917	0.01144	0.68106	0.0120	69.52	0.0005	3832.4	0.0344	0.00428	0.25499	0.0045	26.06	0.0002				
Lower East Side	6791.1	0.0716	0.01089	0.53118	0.0096	46.17	0.0003	2561.1	0.0270	0.00412	0.20053	0.0036	17.41	0.0001				
Soundview Expansion								10374.4	0.1010	0.01472	0.74940	0.0140	70.54	0.0005				
St Georges								1330.6	0.0175	0.00351	0.13011	0.0026	9.05	0.0001				
Coney Island								1313.1	0.0145	0.00237	0.10740	0.0021	8.93	0.0001				

130	MJ gas / gal diesel	
5	g/kwhr	methane slip (Report Section 5.4.4)

PULLS DATA FROM BASELINE

Baseline Fuel and Emissions per Week	GJ	CO	PM	NOx	HC	CO2e	SO2	Future Expansion - 1 additional vessel on route per day (reports weekly) GJ	CO	PM	NOx	HC	CO2e	SO2	Annual Maintenance 6M	12M	Capital Cost 6M	12M
East River	1400.7	0.138332	0.02230225	0.895206	0.01934078	93.389	0								$ 77,093.76	$ 108,465.46	$ 1,000,000.00	$ 1,920,000.00
Rockaway	1455.3	0.121692	0.01698019	0.787521	0.0169707	105.854	0											
South Brooklyn	1086.4	0.103826	0.01619154	0.671904	0.01447032	77.707	0											
Astoria	1541.5	0.139759	0.01896495	0.904442	0.01692643	101.583	0											
Soundview	1329.3	0.107939	0.01346311	0.698523	0.01411748	88.237	0											
Lower East Side	882.8	0.084186	0.0128157	0.544801	0.01129622	58.655	0											
Soundview Expansion								1348.7	0.1187706	0.01731883	0.76861543	0.016529133	107.02557	0				
St Georges								173.0	0.0206205	0.00413058	0.1334438	0.003103778	16.92097	0				
Coney Island								170.7	0.0170214	0.00279313	0.11015293	0.002457291	17.196297	0				

Baseline Energy/week	kWhr	CO	PM	NOx	HC	CO2	SO2	Future Expansion - 1 additional vessel on route per day (reports weekly) kWhr	CO	PM	NOx	HC	CO2	SO2	Annual Maintenance 6M	12M	Capital Cost 6M	12M	Capital Cost	
		0.146	0.011	0.222	0.007	199	0.118		0.146	0.011	0.222	0.007	199	0.118						
East River	164277.2	0.023984	0.00180705	0.03647	0.00114994	32.691159	0.019385								$ 88,790	$ 120,920	$ 1,055,315	$ 1,372,459	Charging Stations	$ 16,000,000
Rockaway	233700.7	0.03412	0.00257071	0.051882	0.0016359	46.506435	0.027577													
South Brooklyn	165074.4	0.024101	0.00181582	0.036647	0.00115552	32.8498	0.019479													
Astoria	172266.4	0.025151	0.00189493	0.038243	0.00120587	34.281021	0.020327													
Soundview	153097.4	0.022352	0.00168407	0.033988	0.00107168	30.466387	0.018065													
Lower East Side	102066.9	0.014902	0.00112274	0.022659	0.00071447	20.311309	0.012044													
Soundview Expansion								11153.4	0.0016284	0.00012269	0.00247606	7.80739E-05	2.2195283	0.001316102						
St Georges								2798.7	0.0004086	3.0786E-05	0.00062132	1.95911E-05	0.5569474	0.00033025						
Coney Island								2931.2	0.000428	3.2244E-05	0.00065073	2.05187E-05	0.5833163	0.000345886						
Highest Electric Demand		16	MW																	