Investigation into the Advancement of the Decarbonization of Offshore Fast Support Vessels

By: Blue Ocean Transfers Group, LLC

Rutgers University, Department of Industrial & Systems Engineering

and

Incat Crowther

[This page left blank for two-sided printing]

Abstract

Fast Support Vessels (FSVs) are the workhorse of offshore industries - carrying crew, workers, gear, equipment and cargo to and from offshore sites during project phases of planning, exploration, installation, operations and decommissioning. These marine assets provide essential logistics activities throughout an offshore site's life. The FSV fleet has been operating in support of offshore oil and gas installations in all offshore US regions since the 1950s. Fleet numbers will grow in concert with additional demand for this type of vessel as Blue Economy applications further develop and materialize, including offshore wind, marine energy (e.g., tidal, wave), aquaculture, and floating solar projects. The need for competitive and efficient FSVs will continue to grow. Careful logistical planning of these vessels relies on accurate, data-driven simulation models of vessel operations which can rigorously account for the stochastic environmental parameters (i.e., met-ocean conditions) and operational parameters (e.g., route, activities, vessel speed and propulsion system).

The application of alternative energy sources to power high speed aluminum FSVs on offshore routes is the subject of this study. An investigation of alternative energy sources to power these vessels explores more cost effective and optimized provision of marine transport services. One of the primary objectives of this work was to realistically identify energy requirements resulting from US offshore deployments in actual sea states observed. Collectively, our analysis sheds light on the value of high-resolution met-ocean information and models in supporting offshore operations. In this study we developed a probabilistic environmental conditions model to demonstrate statistically significant differences in energy consumptions for FSVs considering offshore deployments in sea spectra as compared to calm water energy use.

The focus of the work described in the study is on electricity as an alternative energy source for propulsion. Dynamic sea states provide better information to inform on the design of electrified vessel systems, especially energy storage equipment. Along this line, we propose a data-driven simulation framework which integrates environmental and operational information to produce probabilistic characterizations of key vessel operational metrics, including serviceability, fuel consumption, emissions, and costs. We developed a simulation model for FSVs deployed on offshore mission profiles in dynamic sea states, across five different US offshore regions and for four increasingly electrified propulsion platforms from Tier 3 diesel to fully electric configuration. Results informed and quantified the types of deployments favoring electrification. Effective implementation of FSV electrification was investigated assuming use of the same vessel platform where installation of successive electrified configurations led to a fully electric vessel. The study suggests economic attractiveness of this approach in certain regions for specific deployments and a favorable investment opportunity.

[This page left blank for two-sided printing]

Table of Contents

TABLE OF FIGURES

TABLE OF TABLES

[This page left blank for two-sided printing]

Executive Summary

The application of alternative energy sources to power high speed aluminum fast support vessels (FSVs) on offshore routes is the subject of this study. FSVs are widely used in many offshore logistics applications to transport and transfer technicians, their gear, equipment and materials from shore facilities to offshore sites as part of installation, construction, operations and maintenance work scopes. Offshore infrastructure and locations including energy exploration and production, fishery facilities, aquaculture, research and survey are supported by these versatile craft. An investigation of alternative energy sources to power these vessels explores more cost effective and optimized provision of marine transport services.

One of the primary objectives of this work was to realistically identify energy requirements resulting from US offshore deployments in actual sea states observed understanding that for a given vessel, wave height is the principal factor in resistance and therefore power requirements. In this study we developed a probabilistic environmental conditions model to demonstrate statistically significant differences in energy consumptions for FSVs considering offshore deployments in sea spectra as compared to calm water energy use.

The focus of the work described in the study is on electricity as an alternative energy source for propulsion. Dynamic sea states provide better information to inform on the design of electrified vessel systems, especially with regard to energy storage equipment. We developed a simulation model for FSVs deployed on offshore mission profiles in dynamic sea states, across five different US offshore regions and for four increasingly electrified propulsion platforms from Tier 3 diesel to fully electric configuration. The results of the simulations helped to identify the types of deployments favoring electrification and quantify this effect for the different deployments and propulsion platforms.

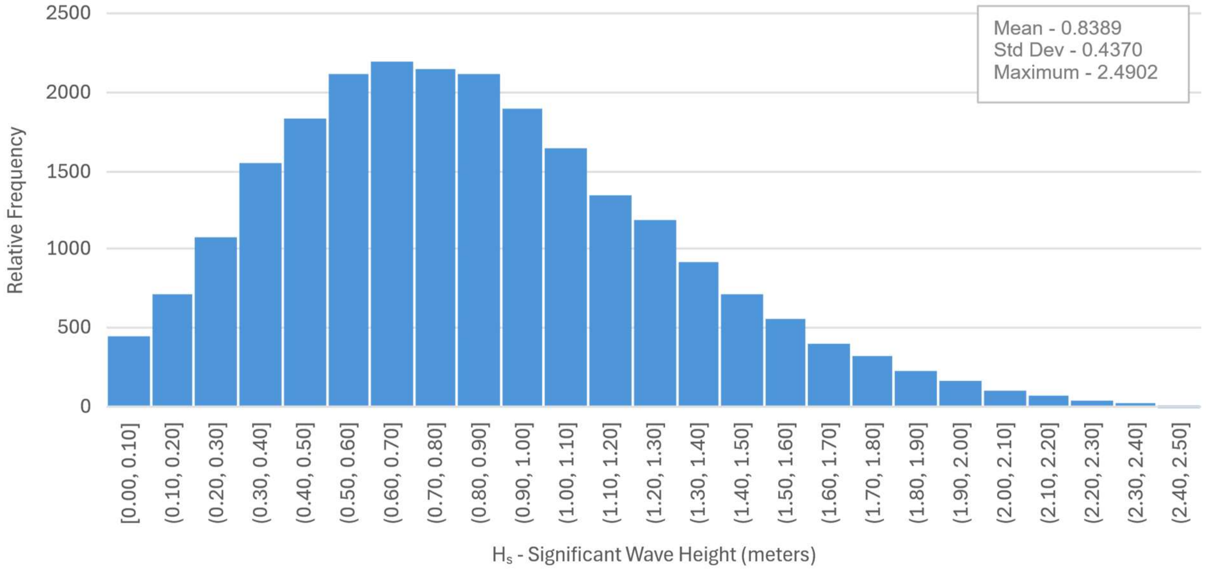
Finally, we investigated an effective implementation of FSV electrification assuming use of the same vessel platform where installation of successive configurations - starting with an initial diesel propulsion system then hybrid electric systems - led to a fully electric vessel. We then examined the economic attractiveness of this approach which suggested favorable investment. We looked at the sensitivity of the results to a number of economic parameters as well as the notion of the social cost of CO_2 emissions.

This brief has attempted to introduce a quantitative approach to the consideration of electrification of FSVs. As such we hope to advance the perspective forward from “hybrid ready” thinking to a realistic pathway forward towards electrification in concert with advancing technology.

Realistic Environmental Conditions Model

An empirical/numerical statistical modeling approach created in the study produces realistic met-ocean datasets which are trained to given regions identified by the proximity of the buoys employed for data collection. This approach is generalized to apply to coastwise US regions and also internationally, with numerical models trained by regional buoy data.

Figure ES-1 - Significant Wave Height Distribution – Mid-Atlantic Region (MAR) – Full Year



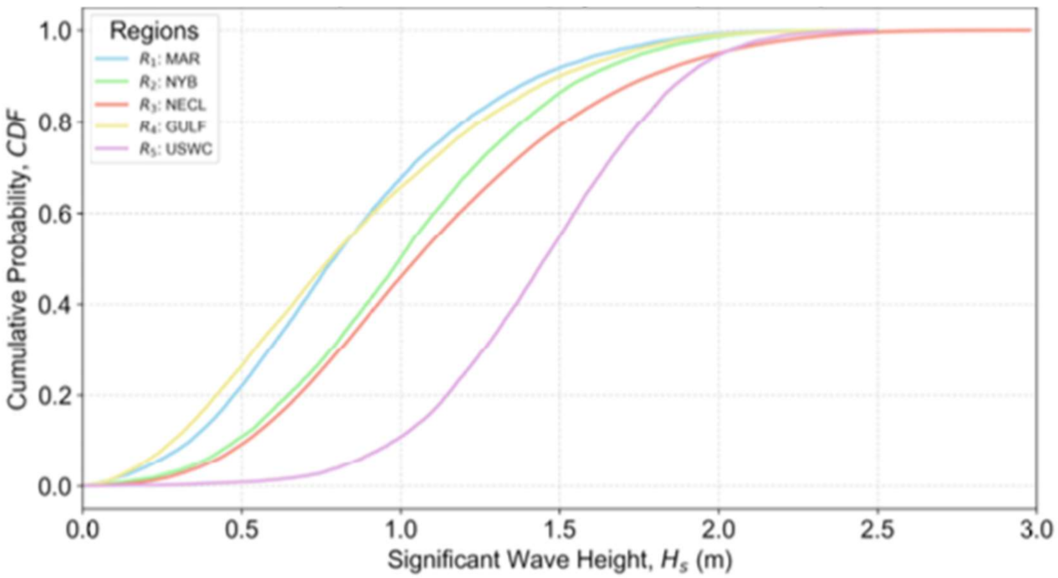
Source: Rutgers University

Figure ES-1 displays a frequency diagram of significant wave heights (H_s) for the Mid-Atlantic Region (MAR) off the US east coast, produced by the environmental conditions model in this study. In this region the mean H_s is 0.84 meters, with the preponderance of wave heights to the lower side of the distribution, indicating a relatively benign historical sea state.

Sea States

There are significant differences in sea spectra across regions with sea states varying from benign to severe – the models produced in this study allow for quantitative analysis of their comparative impact on the type and design of vessels deployed. In Figure ES-2, a cumulative density function (CDF) compares the behavior of sea states across several regions. This figure illustrates the relatively severe sea states experienced over time off the US west coast (purple line) with higher H_s values predominating as compared to the other plots, with the US Gulf indicating the most benign conditions offshore (yellow line).

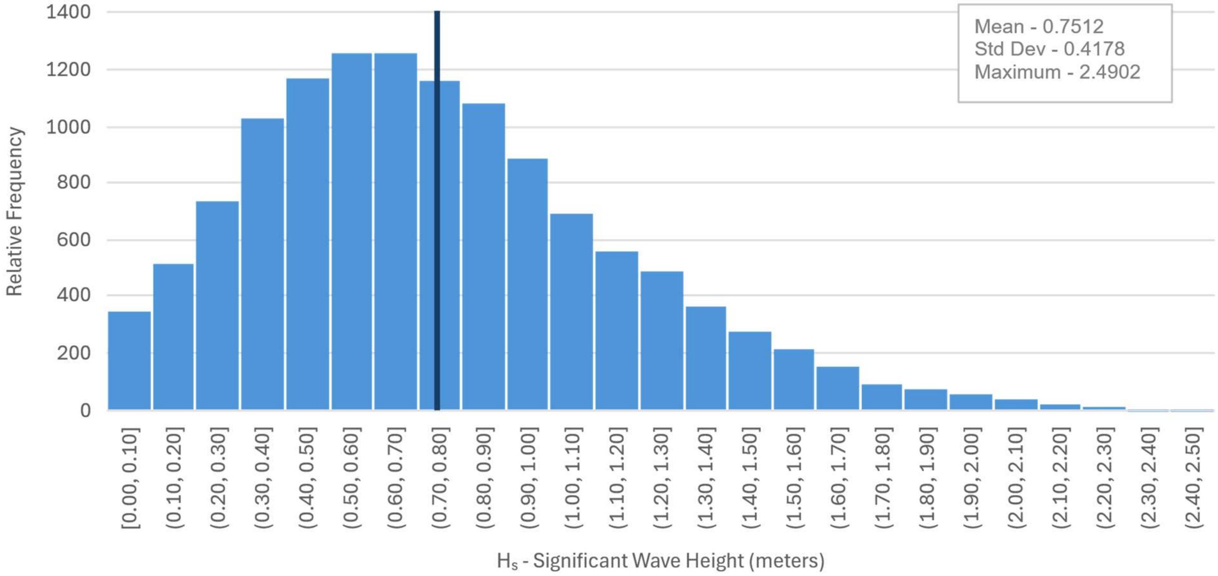
Figure ES-2 - Empirical Cumulative Density Function (CDF) of Significant Wave Height (Hs)



Source: Rutgers University

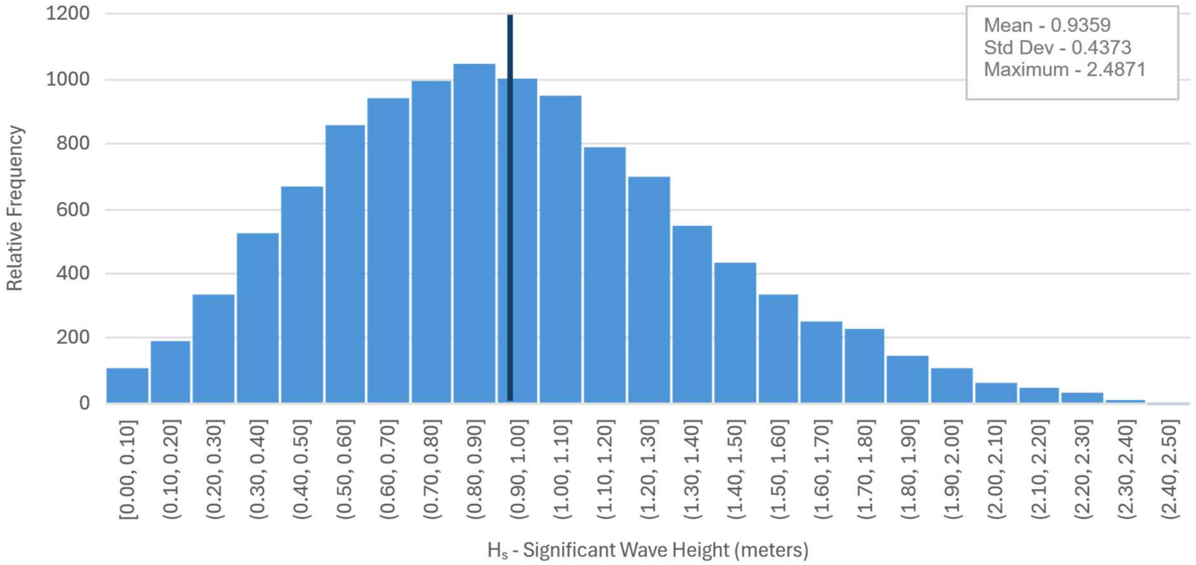
Seasonal variation of sea states exhibits the same behavior across all regions: winter conditions are more severe in general than summer conditions. In Figures ES-3 and ES-4 the summer and winter seasonal results are shown for the MAR. Note that H_s is 0.75 meters in the summer and 0.93 meters in the winter. In the figures the bars represent the number of simulations with results for H_s in the ranges indicated.

Figure ES-3 - Total Diesel Consumption Distribution – MAR Summer Season



Source: Rutgers University

Figure ES-4 - Total Diesel Consumption Distribution – MAR Winter Season

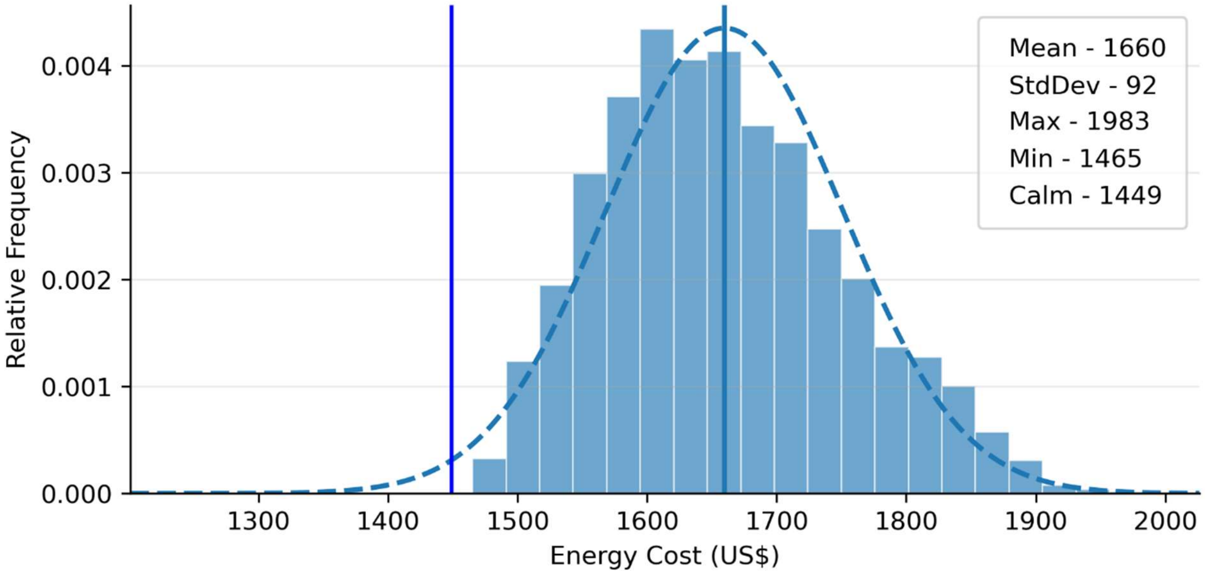


Source: Rutgers University

Simulation Model Results

The simulation model developed in the study produced energy consumption and emissions distributions and then total energy cost distributions for deployments in dynamic sea states that were useful as input parameters to the design process for FSV propulsion. In the figure the bars represent the number of simulation runs with results for total energy cost in the ranges indicated.

Figure ES-5 - Total Diesel Consumption distribution – MAR (Full Year Season)



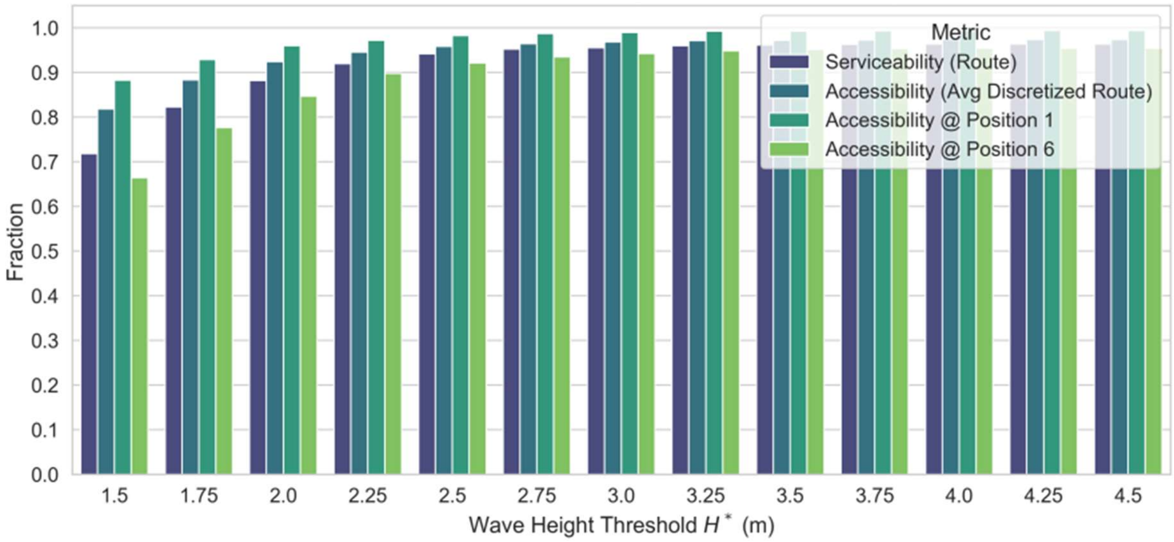
Source: Rutgers

In Figure ES-5 the energy consumption for a diesel propulsion driven FSV is a distribution resulting from operating in dynamic sea states during the course of its mission. The mean energy consumption is US$ 1,660 for each round trip in the MAR. In the figure the calm water energy consumption is shown as the vertical blue line – a value of US$ 1,449. The difference between the statistical conditions model mean and the calm water result is statistically significant – meaning that the distribution generated by the conditions model represents a more realistic estimation of actual consumptions on the voyage.

A New Parameter: Serviceability

Accessibility and approachability, measurements used to determine the likelihood of completion of a vessel's mission, are limited to spatial and temporal factors at one specific location and are therefore insufficient to characterize regional deployments to offshore sites. A new measure – serviceability – considers sea state conditions that the vessel will experience along its entire route, not just at a specific location or time.

Figure ES-6 – Multivariate (Wind and Wave) – Mid-Atlantic Region Full-Year Serviceability vs. Accessibility



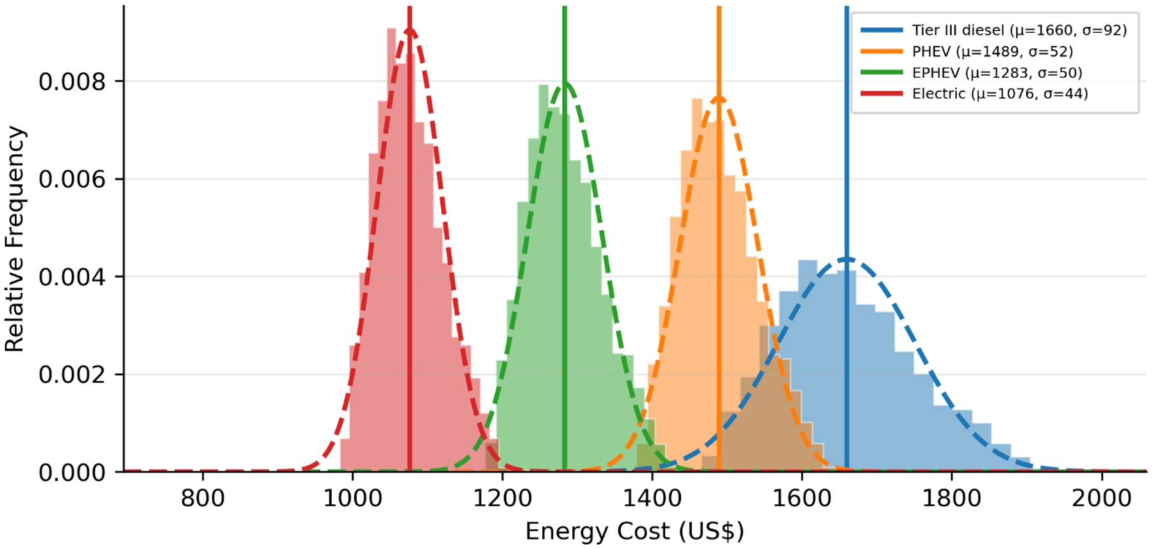
Source: Rutgers University

Serviceability is most closely related to accessibility at the offshore site, reflecting the prolonged time the vessel spends at the offshore site in harsh met-ocean conditions. However, a vessel operator would have a less accurate projection if focusing solely on accessibility at the site since it represents a lower likelihood of mission completion. Therefore, serviceability, which encompasses environmental factors during the entire mission, is a more useful tool for strategic planning of construction and operations & maintenance (O&M) phases of offshore sites. Note that in the case of failed missions when the vessel has gone out but was forced to return to shore because of unexpected harsh conditions, the energy consumption and resulting emissions must also be accounted for.

Electrification

As the level of propulsion platform electrification increases, the total energy cost and total emissions declines. Figure ES-7 illustrates the total energy cost for four different propulsion platforms, from right to left: fully diesel, hybrid, advanced hybrid and fully electric propulsion. The frequency diagrams include estimates of diesel fuel cost and electricity cost per simulation run for each propulsion platform. The dashed line plots are normal curve distributions confirming the central tendency of the distribution around mean values. Energy cost distributions for each of the platforms show the decreasing total energy cost as the propulsion platforms become increasingly electrified.

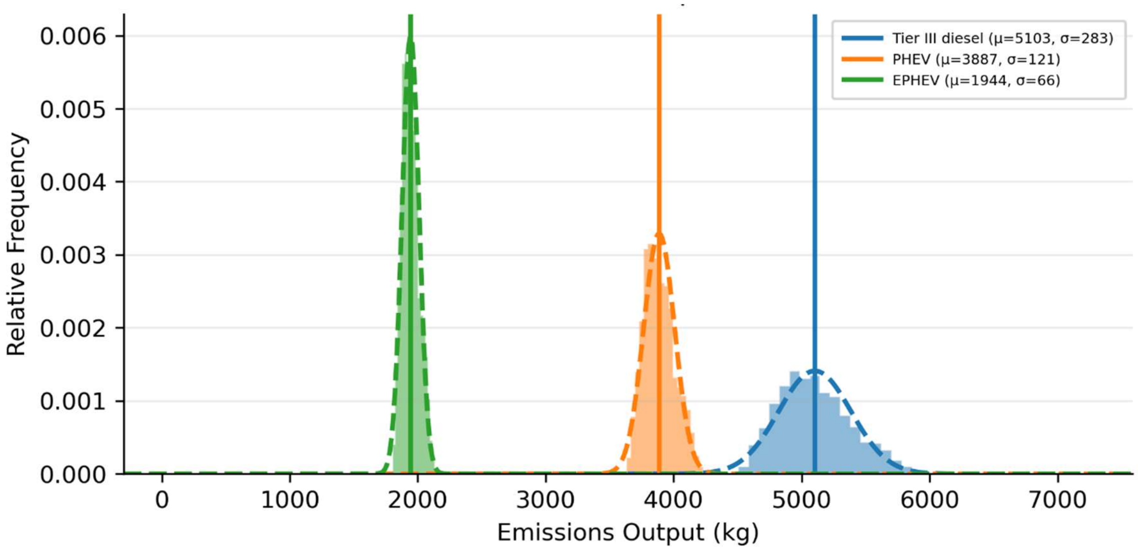
Figure ES-7 - MAR Total Energy Cost by Propulsion Type (Full Year Sea State)



Source: Rutgers University

The same behavior is seen for CO_2 emissions – as the propulsion platform moves to greater levels of electrification, the emissions reduce correspondingly. Note that no emission distribution is shown in Figure ES-8 for the fully electric platform.

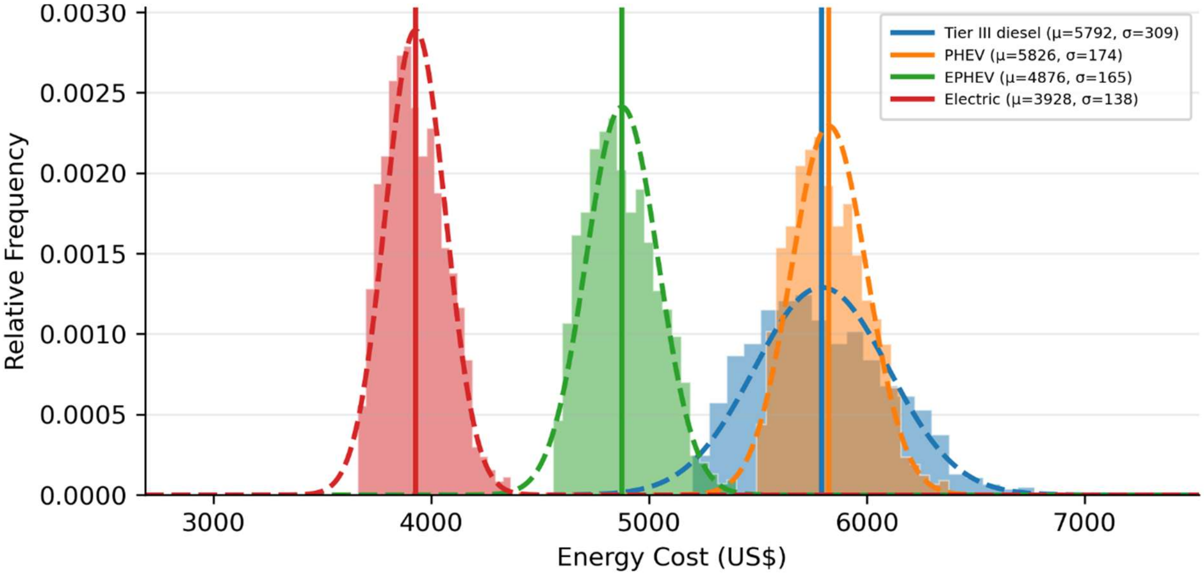
Figure ES-8 - MAR Total Emissions by Propulsion Type (Full Year Sea State)



Source: Rutgers University

Deployment Criteria

Figure ES-9 - GULF Total Energy Cost by Propulsion Type (Full Year Sea State)



Source: Rutgers University

Regional deployments with high speed transits representing large portions of the operational profile are not ideal candidates for electrification. Figure ES-9 illustrates the total energy cost for a simple hybrid electric propulsion configuration (orange distribution) is about the same as for a fully diesel driven platform (blue distribution) on a US Gulf support deployment for an oil rig. This is because the majority of this voyage is conducted at high speed where the diesel engines provide 100% of the energy. In this case, there is very little benefit from hybridization.

This finding provides quantitative information for marine logistics providers regarding when electrification is favored - and justified - for offshore vessel deployments. In some cases, especially those voyages with high energy-intensity, high speed legs of long duration, electrification would not be indicated. While the red distribution in Figure ES-9 illustrates theoretical energy consumption for an all-electric propulsion platform, the energy storage density (ESD) required to achieve this is not currently commercially available and may not be well into the future, beyond the timescales discussed in this study (10 years).

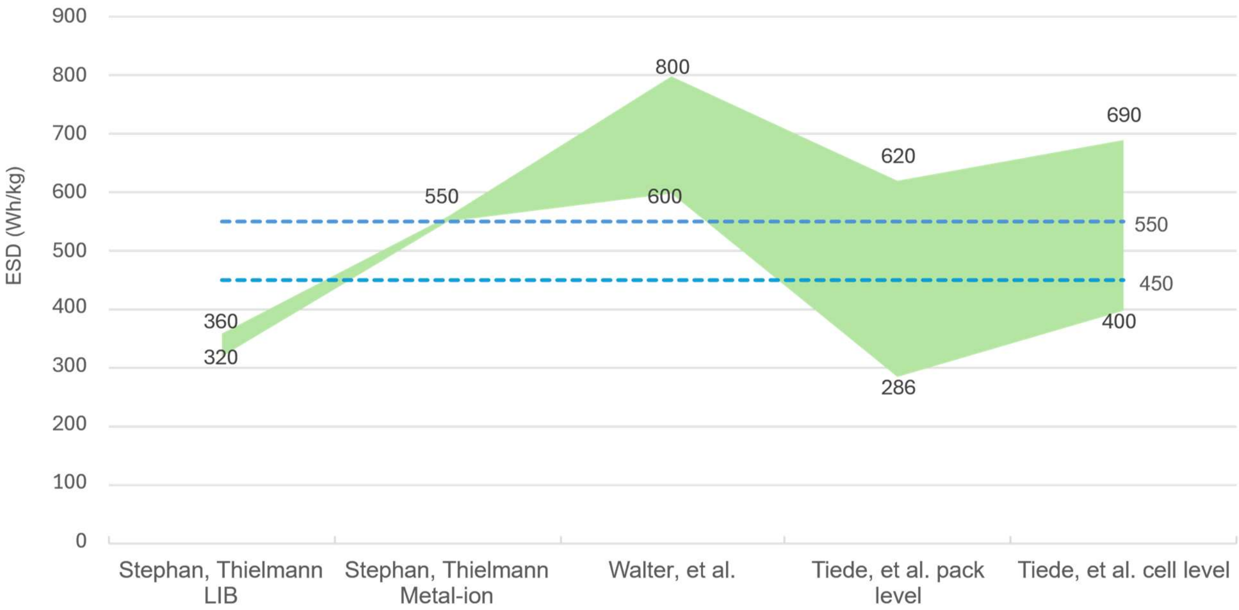
Roadmap to Full Electrification of FSVs

Current industry experience provides an assessment as to where electrification is most applicable today. Recent newbuilding projects and current orders signal shorter voyage distances, lower speeds, access to fast charging and limited payloads as criteria favorable to electrification of marine transport solutions. Mission requirements for passenger and car ferries, excursion boats for day trips, short sea cargo carrying deployments and other cases can be effectively addressed by vessels with increasingly electrified propulsion platforms. As ESD improves (as it has been improving, exponentially), more marine applications will qualify for this energy source going forward.

In this study, two regional deployments were determined to be unfavorable candidates for electrification at current technology levels (for ESD), due primarily to long transit legs at high speed relative to the total duration of the voyages. The US Gulf deployment (GULF), while in relatively benign sea states, was composed almost entirely of a full speed (25 knots) run out to the site 108 nautical miles from shore. The second deployment was off the US west coast (USWC) where the voyage was shorter (48 nautical miles one-way), but still the majority of the voyage duration is accomplished at high speed. In these cases, current ESD technology cannot support the energy requirements nor is it anticipated in the foreseeable future.

Nonetheless, there are deployments for FSVs that are good candidates for electrification. The remaining three deployments off the US east coast (Northeast Corridor - NECL; New York Bight – NYB; and Mid-Atlantic Region - MAR) all represent feasible routes for deployment of electrified FSVs. The challenge is to increasingly electrify the propulsion platform of the FSV in concert with the ESD technology level existing at the time to do so. Current energy storage density (ESD) technology does not presently support feasible offshore deployments of fully electrified high speed aluminum catamaran service vessels. However, a fully electric FSV is feasible within a 10-year timeframe for selected offshore deployments with required onshore and offshore charging infrastructure, based on projections of ESD improvements over time.

Figure ES-10 - BOT Estimation of Commercially Available ESD in 2035

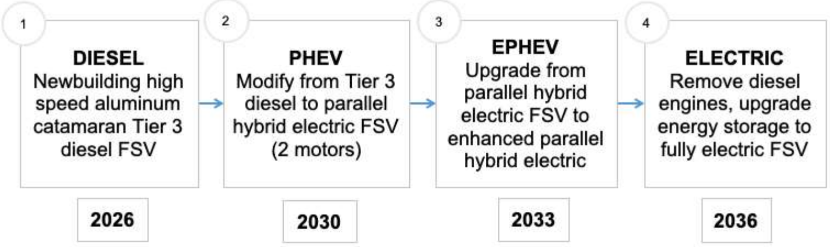


Source: BOT

Phased Electrification

Rather than wait, electrification can be pursued in phases beginning with initial construction of a diesel driven FSV or a parallel hybrid propulsion platform (PHEV), then progressing to an enhanced parallel hybrid (EPHEV) and finally to a fully electric configuration.

Figure ES-10 - Phased Electrification Approach



Component	#	#	#	#	Remarks
Hamilton LTX 53 Water Jet Drives	4	4	4	4	Can be substituted with twin CPP or quad Volvo IPS drives
Tier 3 Diesel Engines	4	4	2	0	Scania DI16082M-588kW@2100 RPM
AC Electric Motor	0	2 x 230 kW	2 x 625 kW	4 x 625 kW	Scania e-Motor or similar
DC to AC Inverter	0	2	4	4	For electric motors
DC Link Switchboard	0	2	2	2	One in each hull
DC to AC Inverter	0	2	2	2	To convert from DC bus to AC for domestic accommodation / hotel loads
AC Switchboards	2	2	2	2	For domestic accommodation / hotel loads
2 x Battery Packs @ kWh each	0	490	~ 1000	3410	One in each hull
High Capacity Charging Connection	0	1	1	1	Wired into both DC Links, provides connection to onshore fast charging stations and to offshore fast charging stations
Temporary Containerized 1000 kW Generator	0	0	0	1	For discretionary & emergency use to reposition vessel or other non-mission deployments

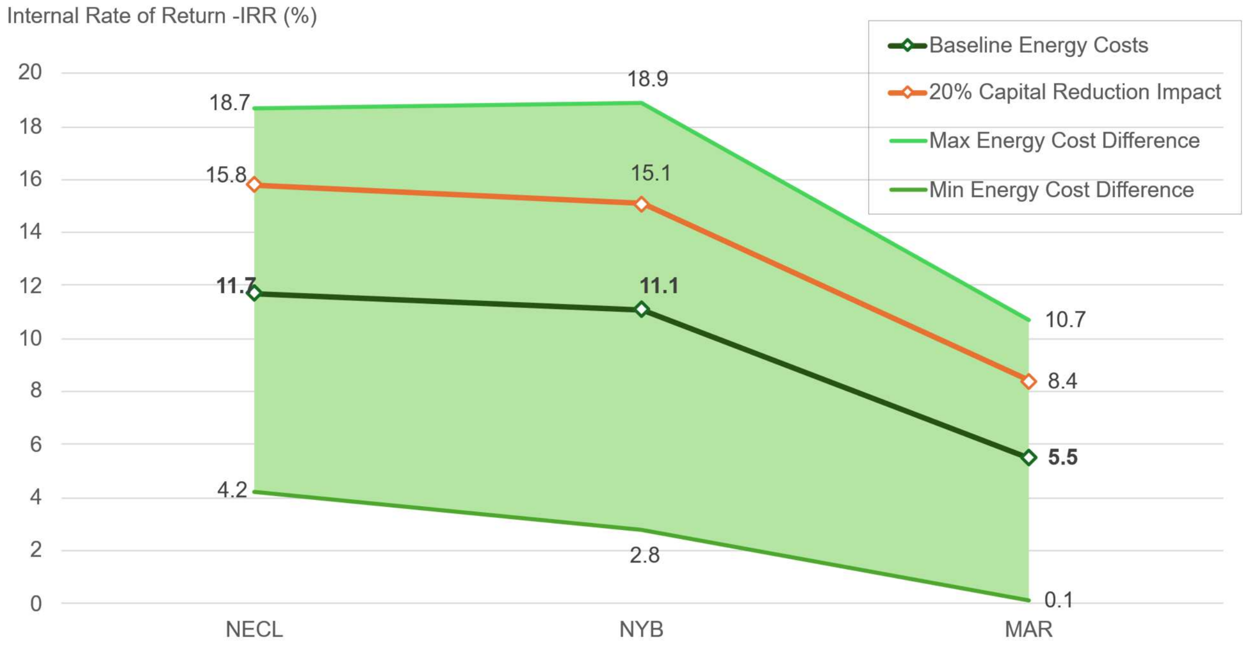
Source: BOT

Electrification Value Proposition

To cost effectively evolve from Tier 3 diesel propulsion to full electric, we assumed use of the same vessel platform and future-proofed the design by working backwards from a fully electric configuration in 10 years' time. We then examined the economic attractiveness of this approach which yielded favorable investment signals when considered as a series of initial capital investments followed by a stream of positive cash flows from reduced energy costs inside a discounted cash flow framework. Sensitivity to investment levels, energy pricing and the social cost of CO_2 emissions were evaluated. Lower capital costs, achieved through subsidy or technology improvement produced outsized incremental returns. Results were very sensitive to the pricing spread between the cost of diesel fuel and electricity. Finally, surprisingly low social costs of CO_2 emissions, when factored into the cost/benefit analysis, produce significant investment returns.

There is an attractive value proposition when considering full electrification achieved in stages over a 10-year timeline even without consideration of the social cost of emissions. Figure ES-11 illustrates the range of internal rates of return on an unlevered investment in electrification for an FSV on three US east coast offshore deployments. Base case assumptions produce a 5-12% return on investment and sensitivity analysis yields returns in excess of 18%. Relatively low social costs of emissions can produce 20% returns on capital employed.

Figure ES-11 - IRR Range with Capital Cost and Energy Cost Variation
(20%) Capital Cost Variation, +/- 10% Energy Cost Variation



Source: BOT

Table ES-1 - Discounted Cash Flow Analysis Results NECL-NYB-MAR – Solving for Social Cost of Emissions

US$ Million	NECL	NYB	MAR
Cash Flow Valuation - All Equity			
Capital Invested (PHEV, EPHEV, Electric)	5.0	5.0	5.0
PV of Capital Invested	2.7	2.7	1.7
Total Present Value Energy Savings	3.0	2.9	1.9
IRR	20%	20%	20%
Total Social Cost of Emissions Required for 20% IRR	US$ 62.73/mt	US$ 61.40/mt	US$ 155.20/mt

Source: BOT

Future Work

The subject matter addressed in this study is broad: Environmental conditions modelling; spatio-temporal vessel deployment modeling and simulation; technical feasibility of FSV propulsion system electrification including a survey of current industry experience and projection of energy storage density levels into future; and financial analysis of vessel design alternatives. Each of these areas represents opportunities for further work to extend the thinking around what is possible for marine equipment electrification now and in the near future.

Further work addressing the incorporation of additional sea state and weather variables into the environmental conditions modeling is an area with substantial scope. The addition of wave direction, wave period and current may increase model utility in describing the total impact of environmental conditions on vessel performance and requirements.

Three regions and five locations were evaluated in this study, all offshore the continental United States. A worthwhile endeavor would be to expand the analysis to include offshore Alaska and the Great Lakes, as well as selected international regions/locations.

Key variables of energy consumption and emissions production were estimated using the Delphi approach. There are large reservoirs of empirical data housed in private companies related to vessel speed and performance in sea states. Use of this data to develop parametric estimations of consumption and emissions would likely produce more realistic results. It would also aid in the incorporation of additional variables into the environmental conditions model such as wave direction since the direction required is actually a relative direction of the wave heading versus the vessel heading.

Serviceability is a new measure developed as a result of this study – there is a broad scope of work in furthering attention on the serviceability parameter and its use in logistics planning, site evaluation, vessel spread analysis, and operational deployment planning and scheduling.

1 Background

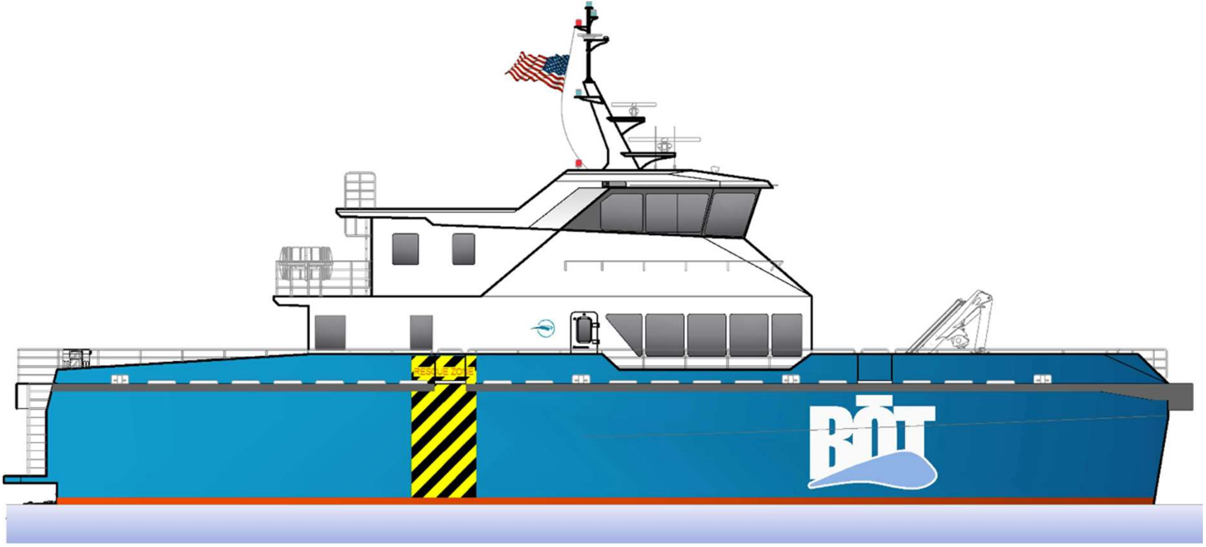
1.1 Offshore Infrastructure Marine Logistics Support

Fast Support Vessels (FSVs) are the workhorse of various offshore industries - carrying crew, offshore workers and numerous cargoes to and from offshore sites during the various project phases of planning, exploration, construction and installation. These multi-purpose marine assets remain an essential mode of transportation through each project's operations & maintenance period and eventual decommissioning given their speed, compliment and dynamic operating profiles. Numerous FSVs are operating in support of offshore oil and gas installations in all offshore US regions. By the end of 2026 about a dozen newbuild US flag Jones Act FSVs built for wind field installation, operations and maintenance will be operational, deployed off the US east coast. This number will grow in concert with additional demand in this market segment. Additionally, as Blue Economy applications further develop and materialize, including marine energy (e.g., tidal, wave), aquaculture, and floating solar projects, the need for competitive and efficient FSVs will continue to grow.

All offshore sites require frequent site visits for transport of technicians and other personnel, and the delivery of tools, consumables, parts and supplies shuttled by vessels from shore bases to the various offshore locations. Furthermore, the likelihood of co-location of such projects (such as offshore wind energy and aquaculture) suggests that FSVs continue to be sought after, potentially increasing both numbers of vessels and time spent in the field per individual vessel trip to accomplish mission requirements and proactively service the offshore infrastructure.

As the offshore energy procurement industry continues to develop, the size, speed and performance abilities of FSVs must keep pace with industry growth to allow the further advancement of offshore energy procurement technologies and methods. FSVs will remain a valuable contributor to productive offshore marine logistics with efficiencies in FSV vessel design and performance driving their effectiveness and in turn, their overall competitiveness.

Figure 1 - Blue Ocean Transfers Fast Service Vessel



Source: BOT, Incat Crowther

There is currently limited available data on how varying sea state and weather conditions impact the efficiency and productivity of marine equipment acting in support of offshore energy procurement. Offshore support vessel operational profiles are in general greatly impacted by the sea state and weather conditions experienced during their transit and mission offshore which influence the required energy consumption needed for propulsion during transit and transferring personnel and cargo to offshore installations. In traditional transit and energy consumption modeling, vessel emissions can be directly correlated to the energy consumption required to propel and maneuver the vessel safely and effectively. For vessel design purposes, especially powering calculations, either calm water parameters are typically employed or expensive theoretical computational fluid dynamics (CFD) models are required. It was clear that further modeling of conditions based on dynamic buoy data and other historical reference systems such as horizontal radar and LiDar data was needed: this was a main feature of this study, to better characterize offshore conditions and evaluate vessel operating profiles corresponding to mission requirements using empirical data from weather buoys stationed offshore. Additionally, our objective was to generalize the approach, so that sea state models could be trained for specific regions with this data. The results are sharpened expectations of the required energy and resulting emission discharge to successfully complete vessel missions which can improve vessel designs and performance, facilitating a more competitive, capable and efficient offshore support vessel fleet into the future. This is particularly relevant as alternative energy sources for vessels are considered.

1.2 Project Team

1.2.1 Blue Ocean Transfers

Blue Ocean Transfers Group LLC (BOT) is an asset manager in the marine equipment space that invests in the equipment being managed and chartered to offshore developers and their suppliers. BOT is a recent, US-flagged, Jones Act-compliant shipping company and a wholly owned subsidiary of McQuilling Partners, Inc., a privately held US marine transportation services company with more than 50 years of international maritime transactional, advisory and operating experience. The BOT business model leverages the specific knowledge, experience and skills of different organizations. It brings together targeted expertise in capital deployment, financing, ship construction, vessel management and commercial employment and is designed to ensure scalability to support a growing offshore vessel market while providing competitive hire rates to charterers on safe, reliable and modern marine assets.

1.2.2 Rutgers University

Rutgers, the State University of New Jersey supported this research through multiple programs including the Department of Industrial and Systems Engineering, providing students with a broad engineering education and specialization in the industrial engineering, manufacturing, financial and energy fields; the Department of Marine and Coastal Sciences, which explores critical processes of oceans around the world; and Rutgers University Center for Ocean Observing Leadership (RUCOOL), a renowned center focused on forging academic, industry and government partnerships for the future Blue Economy.

1.2.3 Incat Crowther

Incat Crowther (IC) is one of the top international vessel designers of offshore support vessels, providing robust, durable designs and vessel operating characteristics, with offices in the UK, Australia, and the US. The firm has deep commercial experience, delivering custom ships from partner shipyards in many parts of the world. More than 600 Incat Crowther ships have been built across 102 shipyards globally, for 201 operators. As of 2025, 145 additional vessels were under construction in 25 shipyards for 19 countries of operation. Incat Crowther has extensive experience in the delivery of hybrid and all electric vessels both in the US and around the world, including large serial and parallel hybrid FSVs.

1.2.4 Shared Goals

Incat Crowther was selected by BOT after carrying out substantial due diligence on top FSVs designers due to their robust, durable design and operating characteristics, along with the organizational capacity of the firm for design acumen and significant local supply chain experience in the US. With BOT's objective to comprehensively address maximizing the consumption of energy from sustainable and emissions-free sources, IC has provided expertise in future-proofing the platforms against a background of rapidly changing technology and operational criteria. Regarding the deployment of FSVs, this objective is primarily manifested in FSV vessel design; programs targeting ship construction activities; and operationally, to evolve step-by-step through generations of propulsion and powering solutions towards zero emission operations. Incat Crowther supported the project through energy consumption and emissions estimates across vessel propulsion systems in varying sea states as well as preliminary design work for a fully electric FSV and hybrid system configuration(s) leading to the fully electrified vessel.

In 2024 meetings between BOT and Rutgers, the organizations immediately found opportunities for collaboration through their shared goals of vessel operational efficiencies as well as clean propulsion technology and related infrastructure to support the Blue Economy. Throughout this project, Rutgers University spearheaded the design, development, and implementation of a probabilistic predictive model for the offshore met-ocean conditions and operability windows experienced by FSVs, and their impact on key O&M metrics, such as accessibility, environmental footprint, efficiency, and cost.

[This page left blank for two-sided printing]

2 Objectives and Hypotheses

2.1 Objectives

This study had three primary objectives: First to demonstrate and quantify the impact of environmental conditions (weather and sea state) on key design parameters of energy consumption and emissions production. Commonly, vessel design parameters are based on assumptions of calm water resistance, propulsion and powering for offshore service vessels, with margins built in for reserves in the case of more challenging environmental conditions. Computational fluid dynamics and other modeling may be employed in the design process but are expensive and can overwhelm design budgets in this sector. With conventional propulsion systems, increasing the power delivered to the drive train, and perhaps increasing fuel tankage, would normally address concerns over the incremental requirements of weather and sea state on a vessel's operational profile. As alternative energy sources are explored for application to offshore service vessels, especially in the case of electrified propulsion, the limitation of electrical energy storage systems drives the need to better understand the incremental power and energy requirements from actual weather and sea states that will be experienced.

The second objective was to comparatively analyze energy consumption and emissions production results for different offshore deployments and propulsion solutions to inform on optimal vessel design. BOT's previous commercial experience responding to bid requests for offshore marine support vessel services uncovered much "talk" about the desire to electrify, but little "walk" in that regard. There was certainly interest, but the industry lacked data or a proof-of-concept that hybrid or fully electric FSVs were feasible, and if so, superior both economically and well as environmentally. Our second objective speaks to this challenge. In this study our focus was on electrification as an alternative energy source for propulsion of an offshore service vessel, specifically a 32-meter high speed aluminum catamaran Fast Service Vessel (FSV). We evaluated different propulsion platforms starting with conventional Tier 3 diesel propulsion and then considered hybrid-electric propulsion and fully electric propulsion. Our intent was to produce quantitative results that could initiate the process of moving from hybrid ready to electrification of fast offshore support vessels.

Thirdly, our objective was to propose a hybrid electric propulsion systems design concept that could be built today with currently available equipment and evolve into a fully electric configuration in cadence with technology advancements over a 10-year period. These systems should be increasingly more energy efficient and emissions limited. The challenge in this case was to devise a vessel design and step-by-step evolution from diesel-driven to fully electric in a cost effective and investment attractive manner.

2.2 Hypotheses

Three hypotheses were identified: First, that consideration of dynamic sea state and weather conditions would yield more meaningful design parameters for high speed aluminum catamaran offshore support vessels; Second, that electrification of propulsion systems on these vessels is more cost effective and with a lower carbon footprint than conventionally powered vessels; and Third, that evolution from diesel propulsion to fully electric propulsion can be achieved cost effectively using one vessel platform.

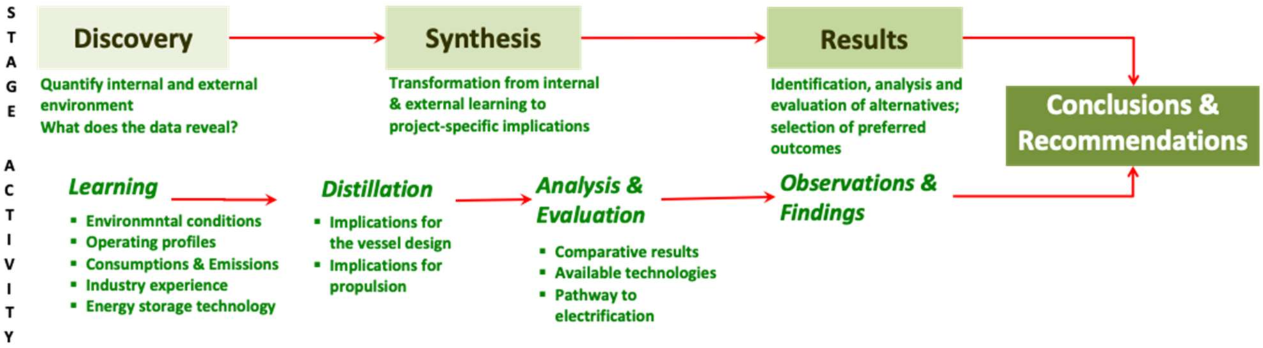
[This page left blank for two-sided printing]

3 Methodology

3.1 Summary

We followed a systematic approach in the study methodology, progressing from discovery to conclusions and recommendations as illustrated in Figure 2.

Figure 2 - BOT Project Management Methodology



Source: McQuilling Services LLC

To demonstrate and quantify the impact of environmental conditions (weather & sea state) on key design parameters of energy consumption and emissions production and test the first hypothesis, the study established a met-ocean conditions model and deployment simulator to approximate realistic weather and sea states from historical buoy data and physics modeling that would be experienced by support vessels servicing offshore energy installations (Sections 3.2 and 3.3).

We comparatively analyzed energy consumption and emissions production results for different offshore deployments and increasingly electrified propulsion solutions to test our second hypothesis that propulsion systems on these vessels are more cost effective with a lower carbon footprint than conventionally powered vessels (Section 3.3).

The third objective of this study was to devise a plan to evolve to a full electric vessel at a point in the future starting with conventional diesel driven propulsion system. Our hypothesis was that this evolution could be achieved using one vessel platform. The challenge in this case was to devise a vessel design and step-by-step evolution from diesel-driven to fully electric in a cost effective and increasingly beneficial manner (Section 3.4).

3.2 Discovery: Environmental Conditions Assessment

3.2.1 Summary

The purpose of developing an environmental conditions assessment was to suggest weather and sea states that would be observed going to, at, and returning from offshore locations based on historically recorded results. This information could then be used to estimate energy consumption and emissions resulting from FSVs transiting offshore in realistic and observed weather and sea states. The approach was to select weather buoys located in or around regions of interest in coastal or near-coastal waters around the United States and collect historical data for weather and sea states observed at the buoy locations. These regions were identified based on the proximity of likely coastal and near-coastal offshore activity related to offshore energy, aquaculture, survey, research or other work carried out in support of current and future offshore installations or activity. Since observed data from the buoys experienced significant periods of missingness, they were combined with numerical model data from NOAA's Global Forecast System (GFS) and the GFS-driven WaveWatch III wave model for wind and wave data, respectively (Petersen et al., 2025a).

Project partners Rutgers Department of Industrial & Systems Engineering, the State University of New Jersey, United States, collected buoy data and employed a two-phase methodological framework using a time-series regression model which leverages both observational and numerical model data. Firstly, this modeling approach accounts for seasonal and temporal trends, while correcting the biases of numerical model outputs, thereby producing high-resolution time series of met-ocean conditions for use in subsequent logistical analysis and planning. Secondly, the statistical model outputs, namely the high-resolution time series of met-ocean conditions, are used to evaluate operational metrics such as approachability, accessibility, and serviceability. Approachability and accessibility are defined in existing literature, while serviceability is a new concept developed through the course of this research and explained in Section 4.2.7.

3.2.2 Environmental Conditions Modeling

3.2.2.1 Regional Selection Criteria

Weather buoys were identified in coastal and near-coastal waters along the US east coast, in the US gulf, and on the US west coast. This selection was used to ensure a broad application of model results for US offshore regions. Attention was given to select buoys located in proximity to likely coastal and near-coastal offshore activity related to offshore energy, aquaculture, survey, research or other work carried out in support of current and future offshore installations or activity. One region selected off the US east coast, the Mid-Atlantic Region (MAR), was used for the initial model development.

Five different regions in US coastal waters were considered, each with region-specific weather and sea state conditions. Realistic vessel deployment scenarios of actual voyages and operating profiles conducted to/from shore bases and offshore energy installations on a high speed aluminum catamaran support vessel were developed for each of these regions.

3.2.2.2 Variables Considered/Selected

We surmise that dynamic sea state and weather conditions would yield more meaningful design parameters for high speed aluminum catamaran offshore support vessels as they would produce more realistic effects than an assumption of calm water operating conditions. To test this hypothesis, measurable conditioning variables that impact the performance of the vessel while undertaking its mission were selected. Weather at sea and sea states are characterized by several variables including significant wave height and direction; wave period; current; wind speed and direction; temperature, humidity, dew point, barometric pressure and others. Another consideration in the selection of environmental variables is the ease and cost of collection and modeling. In Section 4.1.2 we discuss the weather and sea state variables included in this study and why.

3.2.2.3 Buoy Selection

Three regions of strategic importance to the US Blue Economy are analyzed in this study: Offshore US east coast; Offshore US gulf coast; and Offshore US west coast. Offshore US east coast includes three different cases of FSV deployment to offshore installations. One of these, the Mid-Atlantic region (MAR) off the state of Virginia, was used in the development of the models in the study. For this route/region, five years of observational data, from January 2019 to December 2023, are collected from three main sources: (*i*) The National Data Buoy Center (NDBC) maintained by The National Oceanic and Atmospheric Administration (NOAA) (a total of 7 buoys), providing wind data at a height of 3 meters as well as wave-related data; (*ii*) ASOW (Atlantic Shores Offshore Wind) buoys (a total of 4 buoys), providing wind data at 10-meters above the sea level, as well as wave data; and (*iii*) New York State Energy Research and Development Authority (NYSERDA)-supported buoys (a total of 2 buoys), providing wind data at the 10-meter elevation, as well as wave data (Petersen et al., 2025a) (internal citations omitted). Buoys in other regions are identified in Section 4.1.3, Table 1.

3.2.2.4 Data Collection

Note that in this study, an even larger number of buoys in the MAR was initially considered, but some buoys were eliminated due to severe data missingness or insufficient temporal coverage as described in Petersen et al, 2025a. Additionally, considering that the ASOW buoys are in close proximity to one another, their data have been pooled for increased data coverage into a central location, which we refer to as “ASOW-pooled.” Data pooling was implemented by averaging the four ASOW datasets while excluding null entries: if only one buoy reported a value at a given timestamp, that value was used; if more than one buoy reported a value, the average of all non-null values was recorded as the pooled entry. In total, five-year data from 10 different locations were selected after the pooling process was complete, starting from January 2019 to December 2023. The data from all three sources were recorded in either 10-minute or 1-hour intervals. All 10-minute data were processed into hourly averages. Additional data pre-processing was carried out to discard erroneous or physically implausible values to ensure the quality of the input met-ocean datasets (Petersen et al., 2025a).

3.2.2.5 Met-Ocean Model Development

In this step, we conduct analysis of the buoy data and numerical model (GFS) data led model development. Observational (buoy) data provides high-fidelity information about met-ocean conditions, but solely using them to estimate accessibility restricts the evaluation to time periods where measurements are available. Since these time periods only span for limited periods of time and contain fairly long streaks of missing data, this would result in misleading estimates due to missing important temporal features, such as season-to-season and year-to-year variations. A viable alternative is to use numerical model data, which are fairly abundant and do not significantly suffer from data missingness issues relative to observational data. However, numerical models exhibit considerable biases that can largely inflate the accessibility estimation errors.

To address these limitations, a statistical framework was used to combine the high-fidelity (but scarce) observations with the fairly abundant (but lower-fidelity) numerical model data, for improved accessibility estimates. The first step was to extract site-specific time series comprising observational and numerical model data at periods where both sets of data are available. These observations were regressed on the numerical model data at each site using a time series regression (TSR) model. Additional terms capture monthly and yearly seasonalities, autocorrelations and diurnal seasonality. The goal of the formulation is to calibrate the numerical model output and account for the remaining temporal variability that is not fully explained by the numerical model.

3.2.2.6 Introduction to Approachability and Accessibility

Having established the TSR models, they are used to make predictions for the multi-year met-ocean conditions at each location, then to compute important operational metrics for each site. One metric is *approachability*, a familiar construct in the offshore industry defined as the fraction of time that the met-ocean conditions are below their prescribed safety limits at the offshore location.

Petersen et al. explain that approachability, albeit a useful metric, is not sufficient to inform offshore construction and O&M planning, because offshore operations such as maintenance tasks require sustained access to the offshore asset for a sufficiently long period of time (2025a). Hence, *accessibility* is the metric that reflects this additional requirement by searching for consecutively approachable met-ocean behavior for the minimum duration of the weather window. Unlike approachability, estimating accessibility considers the intersection of timesteps and met-ocean covariates, where a location is only considered accessible at a mission start time if the safety limit for each met-ocean variable is not exceeded for the entire duration of the mission (Petersen et al., 2025a).

In this study, we evaluate approachability and accessibility and introduce a new parameter of greater utility in identifying mission success or failure.

3.2.3 Deployment Simulation Model

3.2.3.1 Summary

Against a backdrop of stochastic weather and sea state conditions, utility vessels servicing offshore installations must deliver technicians and equipment from supply bases ashore to the offshore installations and back again. To examine the energy consumption and emissions impact of operating in probabilistic conditions suggested by the environmental conditions model we started with creation of standard operating profiles for the FSVs in each of the regions under the specific mission requirements identified for the location. For each of these deployments, distributions of expected energy consumptions and emissions production were calculated using a stochastic deployment simulation model developed by the Rutgers team as part of the study. These results were compared to the consumptions and emissions resulting from traditional calm water assumptions. We ran numerous scenarios and case analyses comparing deployments across regions, and across propulsion platforms, including seasonality.

3.2.3.2 Defining Operational Profiles

Operational profiles developed by BOT for each of the five regional deployments contain route-specific data detailing mission characteristics such as route legs, activities, and durations for each activity within the mission. Each operating profile identifies a sequential set of activities carried out by the vessel from departing the dock ashore to the offshore installation and back. Each activity (e.g., transiting, idling, loading/unloading) is represented as a discrete segment with well-defined start and end coordinates, transit distance in nautical miles (nm), vessel speed (kts), and duration in minutes (mins). Operational profiles are unique to the mission in terms of the duration of each of the activities in the profile and the geographical location in which they occur. Thus, one profile may represent a 12-hour window of elapsed time while another may be 16 hours or 24 hours in duration.

Note that some activities appear twice in the operating profile because they are conducted twice by the vessel: once for the port-to-destination journey, and once on the vessel's journey back to port. Overall, there are five operational profiles corresponding to five routes examined in this work (three on the East Coast, one on the West Coast, and one in the US Gulf).

3.2.3.3 Simulation Model Development

The simulation framework comprises three logic components: (1) The met-ocean model (MTM), which is a time series model to estimate the met-ocean conditions experienced by a vessel along its full route (from port to site and back). The MTM represented a further development of the environmental conditions modeling that developed significant wave height distributions based on buoy data and numerical sea state modeling; (2) The spatio-temporal route mapper (SRM), which is a mapping algorithm to determine the expected vessel position and activity at each hourly interval based on route-level operational profile information; and (3) the conditions-consumption-emissions (CCE) model, which is a suite of statistical models linking vessel activities and met-ocean conditions to fuel consumption and emissions for different propulsion systems. The CCE model is based on a Delphi approach to providing the data, comprising fuel consumptions and emissions for the FSV at various speeds in various sea states (including calm water). Further work as identified in Section 7.1.2 would substitute empirical observations for the Delphi data while adding a relative heading variable to condition the consumptions and emissions further.

For cost calculations, we use a standard conversion based on regional historical averages, which translate to \$1.06 per liter of diesel and \$0.16 per kWh of electric energy (US EIA, 2025). In the context of this paper, we generally refer to fuel-related costs (diesel and/or electric) as operating costs, without considering other non-fuel-related operating costs such as crew wages, insurance, maintenance, port usage, etc.

A single simulation run is completed once the vessel has progressed through all required times and positions in the operating profile along the route for the full mission duration. At the end of each run, we calculate the cumulative fuel consumption and emissions and determine whether the mission was completed successfully. The simulation is then run for a sufficiently large number of iterations (~2,000) producing probabilistic characterizations of consumption, emissions, costs, and mission success for different scenarios varying regions, operational profiles, propulsion platforms and seasonality. Utilization parameters described in 3.2.2.6 were produced by the modeling that highlighted and quantified inefficiencies (time, cost, environmental impact) from the inability to complete vessel voyages due to weather and sea state conditions.

3.3 Learning: Propulsion Solutions to Inform on Optimal Vessel Design

Our second hypothesis that electrification of propulsion systems on these vessels is more cost effective and has a lower carbon footprint than conventionally powered vessels was quantitatively investigated using the results of the models developed in the study. Energy consumption and emissions production across four increasingly electrified propulsion platforms were compared in simulations. This approach was applied to each regional deployment of the vessel. Additionally, market research revealed existing hybrid electric and fully electric vessel deployments in US waters and abroad, representing the current state-of-play in marine electrification.

A recognition that current energy storage density (ESD) technology does not presently support feasible offshore deployments of fully electrified high speed aluminum catamaran service vessels – FSVs – led to research on current ESD developments from various chemistries and trajectories for the future. A phased approach, with platform evolution through four stages beginning with Tier 3 diesel propulsion today, then parallel-hybrid electric propulsion, advanced parallel-hybrid electric propulsion to fully electric propulsion is envisioned over a 10-year period. We comparatively analyzed results for the five different offshore deployments in five areas offshore US for each of the four propulsion platforms to test our thesis and determine the best platform and feasible deployments over time.

3.4 Distillation & Synthesis: Propulsion Electrification Design Concept in Cadence with Technology Advancements

3.4.1 Summary

The third hypothesis addressed an important consideration regarding the execution efficiency of the steps to evolve from diesel to fully electric propulsion. A restriction imposed on the evaluation was that each propulsion configuration employed the same aluminum catamaran vessel hull. This assumption helped ensure an apples-to-apples comparison of consumption/emissions results. It also underlies a key study objective to facilitate an economic and efficient evolution from conventional diesel to fully electric propulsion. (Re)Using the same vessel for each propulsion configuration avoids additional capital expense and construction periods. However, the design process must ensure that a vessel built in the near-term with diesel propulsion must be able to be iteratively modified cost effectively to support a fully electric propulsion platform in the future. Utilizing the same existing hull would help ensure this.

3.4.2 Roadmap to Fully Electric From Fully Diesel

BOT's vessel designer Incat Crowther carried out the analysis on BOTs FSV design to "future proof" the vessel for repeated iterations of increasingly electrified propulsion platforms. Starting with a conceptual design for a fully electric FSV ten years from now and an FSV operational profile developed in the study (using simulation results for consumption requirements), we solved for the ESD parameters required for a feasible electric vessel in 10 years' time. We then compared these ESD results to the projections for ESD from the industry and literature research conducted. A fully electric propulsion platform was designed into the existing BOT FSV design ten years in the future.

Beginning with a Tier 3 diesel propulsion platform, the next logical and technologically available step that could incrementally move towards electrification and still take advantage of installed equipment was a parallel hybrid electric vessel (PHEV), followed after some years with an enhanced parallel hybrid electric vessel (EPHEV), still relying on equipment from previous installs and when the appropriate energy storage density was commercially available. The final iteration was to the fully electric vessel – again, when the appropriate energy storage density was expected to be commercially available. This evolution was envisioned over a 10-year period. To note, we included that fast charging of the batteries shoreside was a requirement of the PHEV and later platform versions and that for EPHEV and fully electric platforms offshore charging would also be required.

[This page left blank for two-sided printing]

4 Technical Outcomes – Findings & Observations

4.1 Assessment

One of the primary objectives of the study was to demonstrate and quantify the impact of environmental conditions (weather & sea state) on key design parameters of energy consumption and emissions production. We posited that a quantitative assessment of historical weather and sea states could be of greater utility in the design of propulsion and powering for offshore service vessels than existing approximating and/or costly approaches. This is especially true as alternative energy sources are explored for application to offshore service vessels, specifically in the case of electrified propulsion. The limitation of electrical energy storage systems drives the need to better understand the incremental power and energy requirements from actual weather and sea states that will be experienced.

Analysis of historical buoy data led model development. Observational (buoy) data provides high-fidelity information about met-ocean conditions but contains fairly large tracks of missing data, including season-to-season and year-to-year variations. Nonetheless, these (albeit incomplete) observations of actual weather and sea states provide the foundation for a realistic environmental conditions model. Further precision in modeling sea states is elaborated on in Section 4.1.4.

4.1.1 Region Selection

Weather and sea state conditions vary considerably across offshore regions. In the interest of providing a broad set of results to represent this variation, we chose regions located around the continental US offshore the US east coast, US gulf coast and US west coast. Five representative routes from three regions of strategic importance to the US Blue Economy are analyzed, which are described in Sections 4.1.4 and 4.2.1

Figure 3 - US Offshore Regions in the Study

Source: MARCO Portal, BOT

4.1.2 Variables Considered

Weather at sea and sea states are characterized by several variables including significant wave height and direction; wave period; current; wind speed and direction; temperature, humidity, dew point, barometric pressure and others. Those primarily impacting the energy consumption and emissions of a vessel transiting in these conditions are those that most increase the resistance of the vessel passing through the water. Another consideration in the selection of environmental variables is the ease and cost of collection and modeling.

Resistance of a vessel hull in fluid results from three components: frictional resistance arising from the hull passing through the water; wave-making resistance (energy lost creating waves); and viscous pressure resistance (form drag - pressure differences and turbulence from flow separation, often grouped with wave resistance). Of these, wave-making resistance is the greatest component of total resistance and the only one materially affected by weather and sea state conditions.

As resistance increases, more power is required to maintain a given speed through the water. As wave heights increase, wave-making resistance also increases significantly and non-linearly. The greatest effect is in a head-sea – where the waves are coming in the opposite direction as the vessel is traveling. The period of the waves - the time from one crest to another - makes for a rougher ride when the period is short and less so with longer period swells. Current can adversely affect energy consumption as more power is required if current is going against the direction of the boat. Wind speed can have an effect on increased resistance moving forward, especially if the wind is blowing the opposite direction that the vessel is traveling, but it is a fraction of that experienced from waves.

Wave characteristics represent a primary factor influencing energy consumption and emissions of vessels at sea. For this initial project we selected significant wave height as the principle data to model in this study and use in the simulation. Additionally, we collected wave period (frequency), wave heading and wind speed data to use in the formulation of the environmental conditions model. These data are readily available from offshore weather buoys. While other variables are available and play a part in influencing vessel performance, data collection and synthesis is more costly and difficult. These additional variables such as current provide excellent opportunities for follow-on work as described in Section 7.1.2 later in this brief.

Wave heading is an important parameter in determining resistance, but use of this data is complicated by the fact that vessel heading must also be considered, resulting in *relative* heading results. Use of this data would be preferred but vessel heading data is largely proprietary information collected by private companies for operations use and performance analysis, and not readily available. Therefore, head-on waves were assumed in this study which would yield the greatest resistance effect.

The data collected on wave height is expressed as significant wave height, H_s. H_s is the average of the highest one-third (33%) of waves (measured from trough to crest) that occur in a given period. Since the significant wave height is an average of the largest waves, many individual waves will probably be higher. On average, about 15% of waves will equal or exceed the significant wave height. Occasional seas are the average height of the highest 10 percent of the waves and could be 25-30% higher than the significant wave height. As a general rule, the largest individual wave that may be encountered is approximately twice as high as H_s (National Weather Service (NWS), n.d.)

4.1.3 Buoy Data

We use five-year observations of wind and wave data, from 2019 to 2023, recorded at 21 ocean buoys across the three main regions: US East Coast, West Coast, and the US Gulf. Table 1 displays the buoy information and data sources. The buoys have been selected based on multiple considerations including sufficient time coverage, proximity to strategic offshore industries, and data resolution.

Table 1 - Description of Observational Buoy Data Used in This Work

Region	Buoy ID	Coordinates (LAT/LON)	Data Source
US East Coast	44005	43.20, -69.13	NDBC (NOAA, n.d.)
	44008	40.50, -69.25	
	44009	38.46, -74.69	
	44014	36.60, -74.84	
	44017	40.69, -72.05	
	44018	42.20, -70.15	
	44025	40.26, -73.18	
	E05N	39.97, -72.72	NYSERDA, n.d
	E06	39.55, -73.43	
	ASOW	39.34, -74.03	ASOW, 2020
US Gulf Coast	42036	28.50, -84.51	NDBC (NOAA, n.d.)
	42040	29.21, -88.24	
	42055	22.14, -94.11	
	42056	19.82, -84.98	
US West Coast	46011	34.94, -121.00	NDBC (NOAA, n.d.)
	46012	37.36, -122.88	
	46013	38.24, -123.32	
	46089	45.93, -125.82	
	46041	47.35, -124.74	
	46028	35.77, -121.90	
	46259	34.77, -121.49	

Source: Petersen, et al., 2025b

4.1.4 Environmental Conditions Model Results by Region

The environmental conditions model (later incorporated into the simulation model as the Met-Ocean Model – MTM) was developed to realistically assess weather and sea states based on historical buoy data. To address the limitations of the observational buoy data, a statistical framework was used to combine the high-fidelity (but scarce) buoy observations with fairly abundant (but lower-fidelity) numerical model data, for improved results. Numerical model outputs from NOAA's GFS and WaveWatch III models are obtained at the nearest grid point to the buoy coordinates (NOAA, 2022).

The first step was to extract site-specific time series comprising observational and numerical model data at periods where both sets of data are available. These observations were regressed on the numerical model data at each site using a time series regression (TSR) model. In the exploratory data analysis, two main features were noticed: seasonal variability and significant auto-correlations. This motivated the inclusion of Fourier terms, of which the trigonometric functions can capture monthly and yearly seasonalities. Additional terms capture autocorrelations diurnal seasonality. The goal of the formulation is to calibrate the numerical model output, whereas the trigonometric series terms account for the remaining temporal variability that is not fully explained by the numerical model.

The environmental conditions model is a time series regression model, which regresses the observational data on lagged numerical model predictors and seasonal effects. The following describes the equation developed by Rutgers University representing the behavior of significant wave height, wave period and wind speed.

$$\boldsymbol{y_t} = \beta_0 + \alpha_1 \boldsymbol{\hat{y}_t} + \alpha_2 \boldsymbol{\hat{y}_{t-1}} + \alpha_3 \boldsymbol{\hat{y}_{t-24}} + \sum_{k=1}^{8} \left(\beta_{1,\mathrm{k}} \cos\left(\frac{2\pi kt}{8760}\right) + \beta_{2,\mathrm{k}} \sin\left(\frac{2\pi kt}{8760}\right)\right) + \sum_{k=1}^{8} \left(\beta_{3,\mathrm{k}} \cos\left(\frac{2\pi kt}{720}\right) + \beta_{4,\mathrm{k}} \sin\left(\frac{2\pi kt}{720}\right)\right) + \varepsilon_t$$

In the equation above, α_1, α_2, α_3 are regression coefficients, with time periods *(t-1)* and *(t-24)* addressing autocorrelation of the variables one hour and 24-hours previous with the trigonometric terms capturing monthly and annual seasonalities. K is the number of Fourier pairs, chosen as eight to balance over- and under-fitting.

The utility of the above model for approximating realistic sea state variables across the different regions of the study is summarized in Table 2.

Table 2 - Comparison of Sea State Variable Utility

Buoy Location	Significant Wave Height	Wave Period	Wind Speed
Atlantic Model Average (Test)	R^2= 0.89 RMSE = 0.26 Bias = 0.03	R^2 = 0.52 RMSE = 1.75 Bias = -0.21	R^2 = 0.75 MSE = 1.63 Bias = -0.04
Pacific Model Average (Test)	R^2 = 0.92 RMSE = 0.33 Bias = -0.08	R^2 = 0.56 RMSE = 0.65 Bias = -0.35	R^2 = 0.79 RMSE = 1.57 Bias = 0.01
Gulf Model Average (Test)	R^2 = 0.91 RMSE = 0.2 Bias = -0.03	R^2 = 0.67 RMSE = 0.89 Bias = -0.08	R^2 = 0.75 RMSE = 1.34 Bias = -0.03

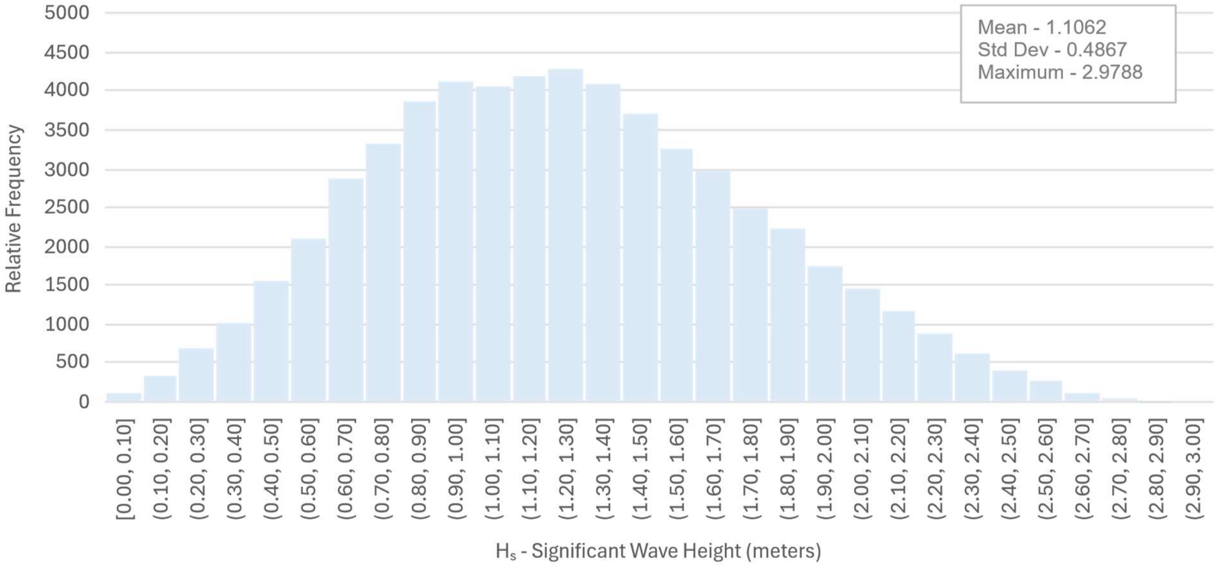
Source: Rutgers University

Results for correlation coefficient (R^2), root mean square error (RMSE) and Bias are included. Model results demonstrate the high precision across the three main variables we have considered important predictors for consumption. The model shows high explanatory nature without significant error or bias. Note the robust performance of the model in predicting significant wave height. More details on the sources for the environmental datasets and the pre-processing steps carried out can be found in Petersen et al., 2025a. A detailed description of the significant wave height model is included in Section 4.2.4.2.

In Section 4.1.2.1 we illustrate the significant wave height spectra full-year results from the environmental conditions model for the offshore areas containing the five offshore sites in the study, and in Section 4.1.2.2 we illustrate seasonal wave spectra for the MAR site.

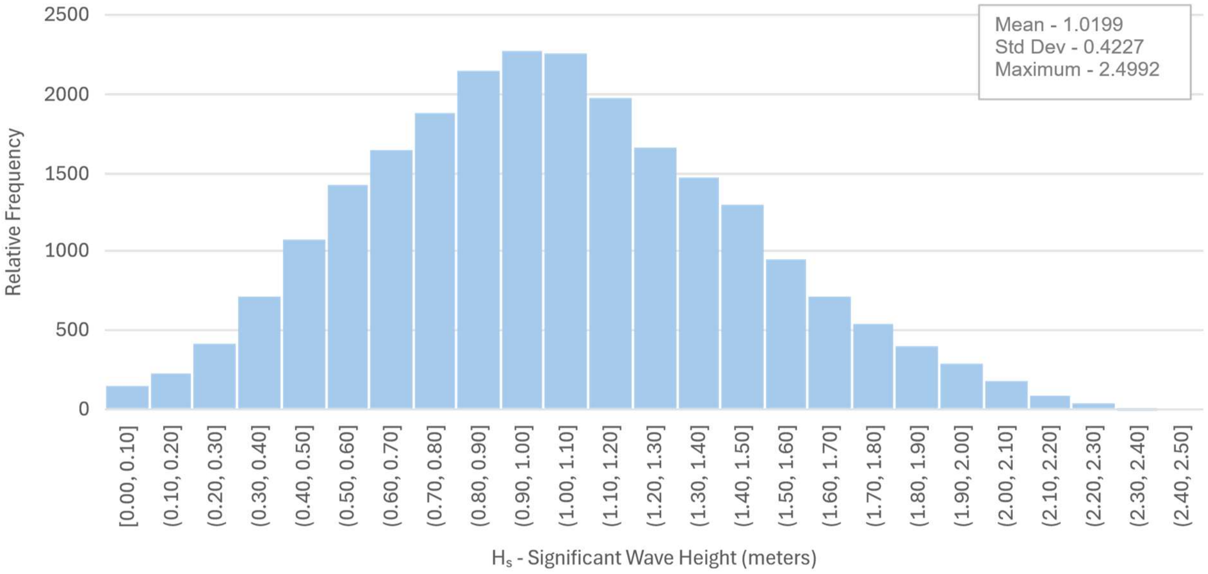
4.1.2.1 Full Year Significant Wave Height Distributions (H_s) – 5 Regions

Figure 4 - Significant Wave Height Distribution – Northeast Cluster (NECL)



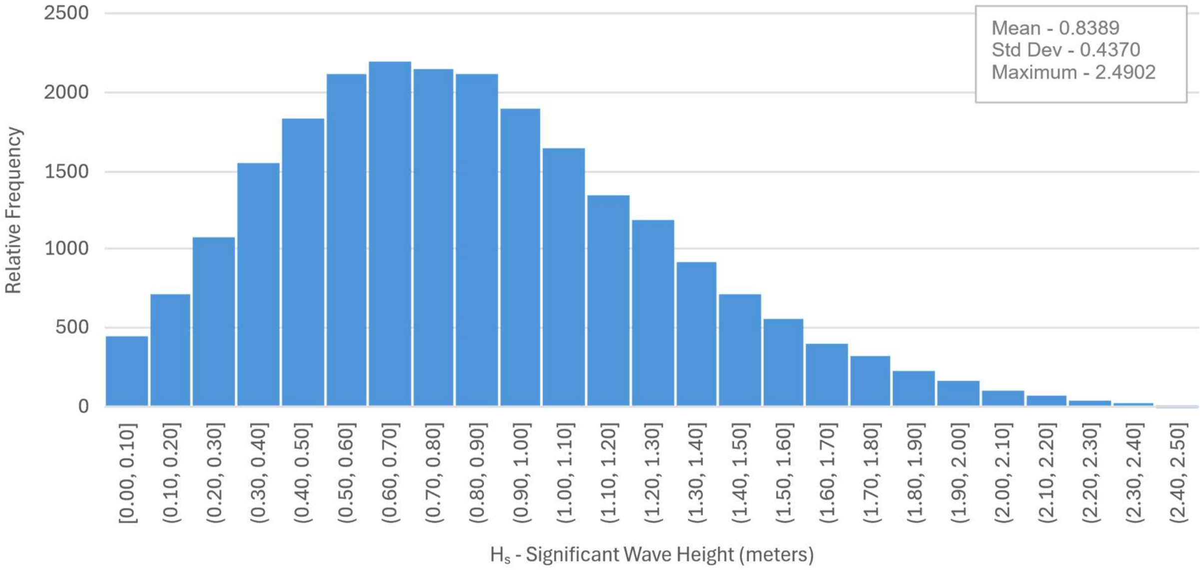
Source: Rutgers University

Figure 5 - Significant Wave Height Distribution – New York Bight (NYB)



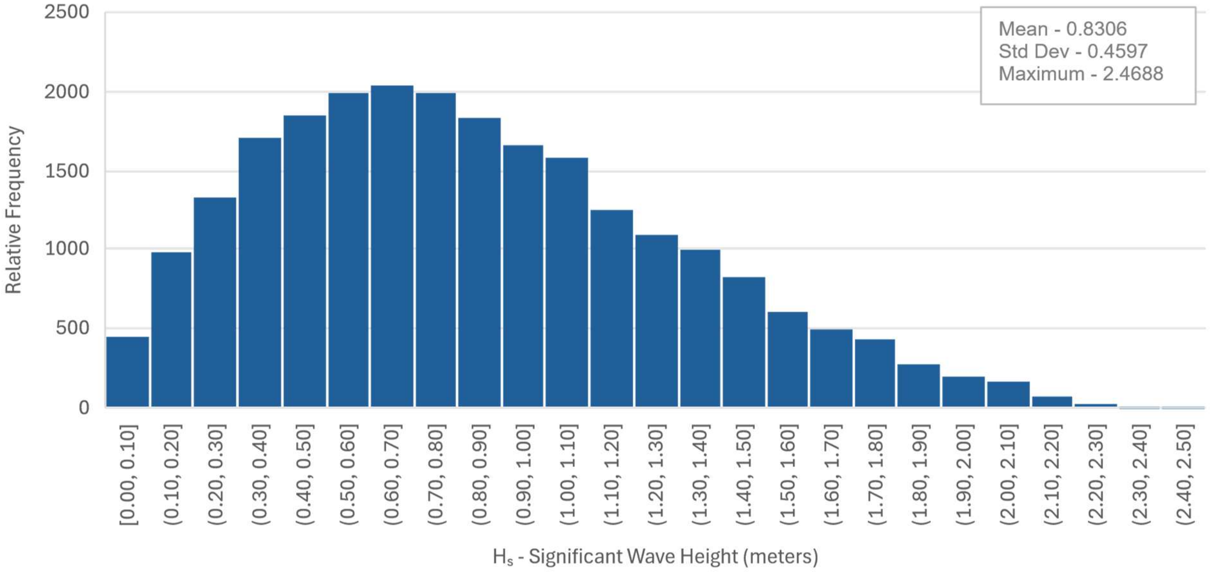
Source: Rutgers University

Figure 6 - Significant Wave Height Distribution – Mid-Atlantic Region (MAR)



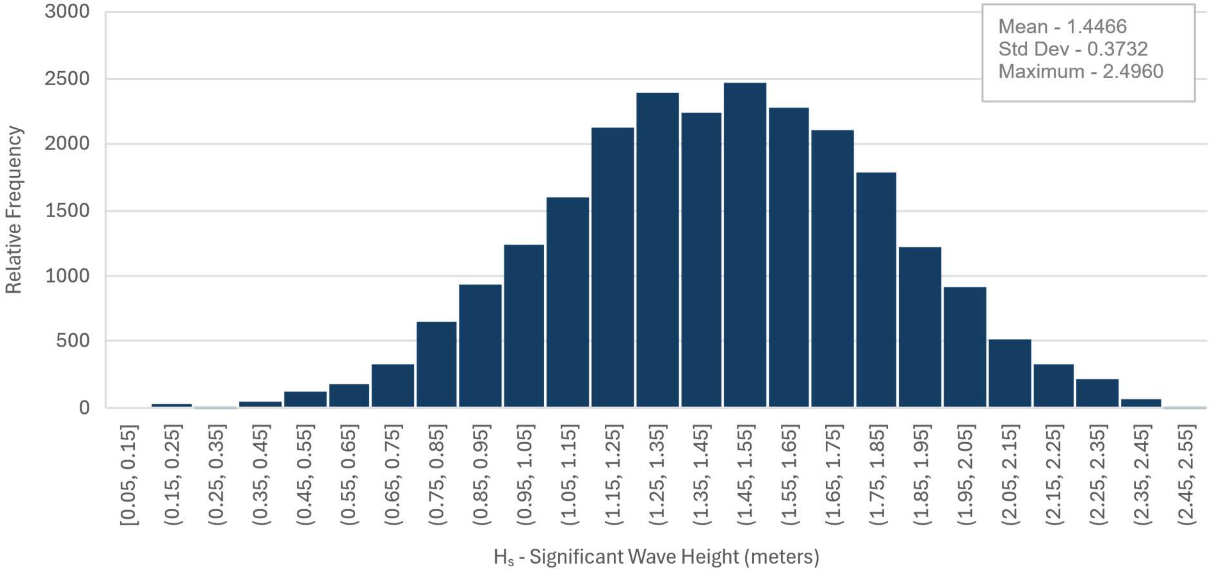
Source: Rutgers University

Figure 7 - Significant Wave Height Distribution – US Gulf (GULF)



Source: Rutgers University

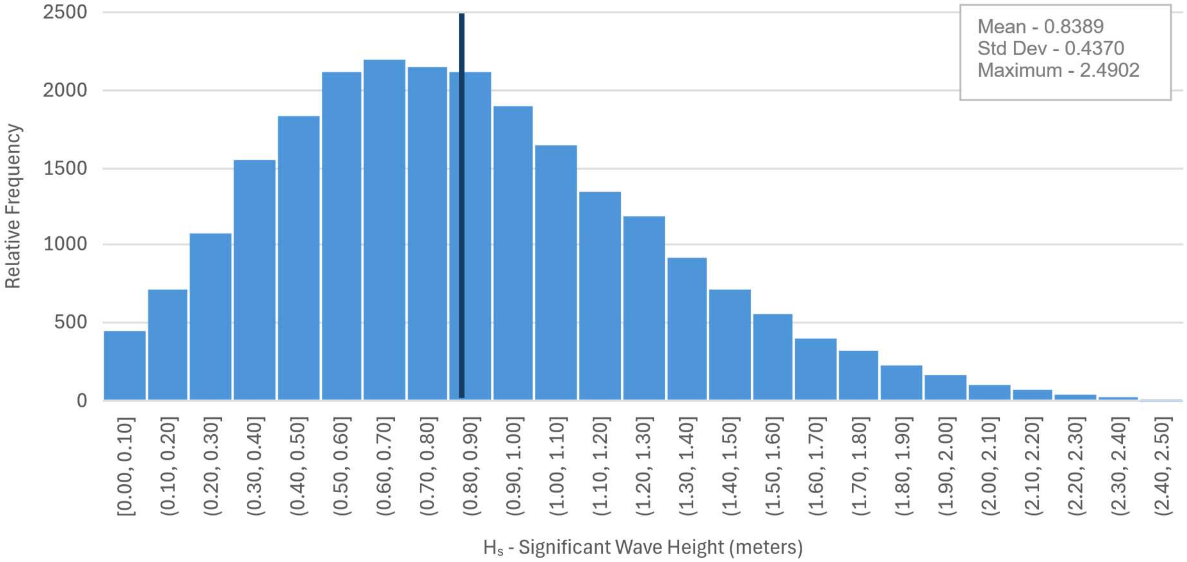
Figure 8 - Significant Wave Height Distribution – US West Coast (USWC)



Source: Rutgers University

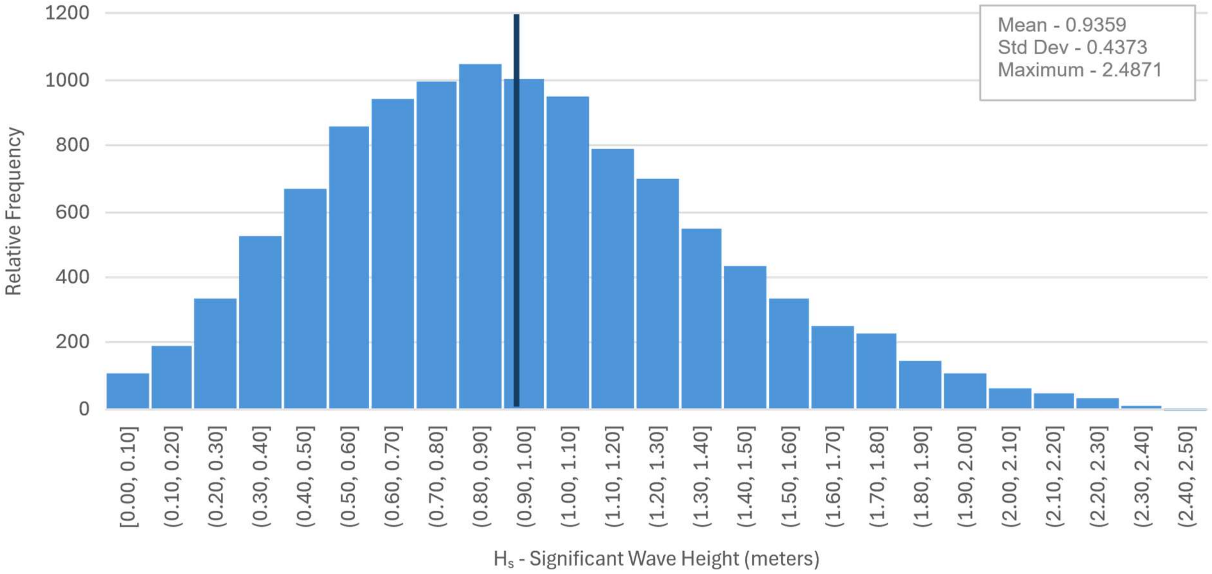
4.1.2.2 Seasonal Significant Wave Height Distributions (H_s) Comparison – MAR

Figure 9 - Significant Wave Height Distribution – MAR – Full Year



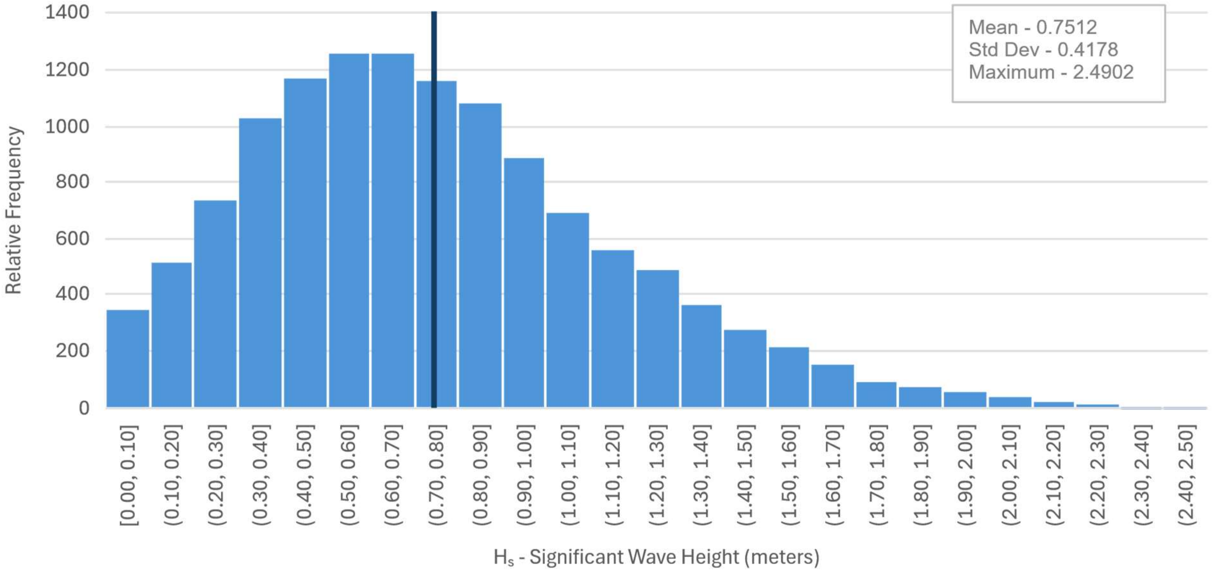
Source: Rutgers University

Figure 10 - Significant Wave Height Distribution – MAR – Winter



Source: Rutgers University

Figure 11 - Significant Wave Height Distribution – MAR – Summer



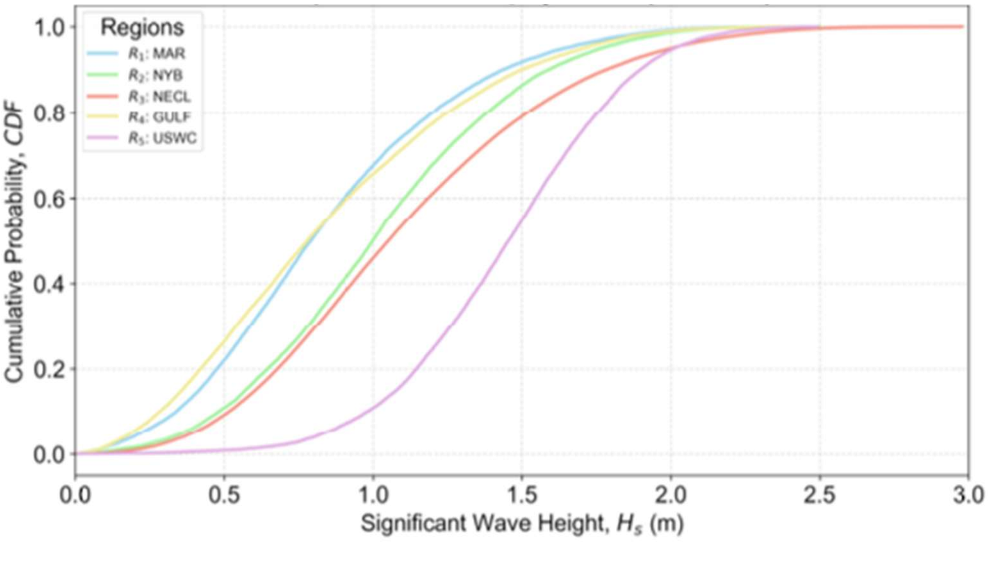
Source: Rutgers University

4.1.5 Regional Comparison of Environmental Conditions

Of the five areas illustrated in Section 4.1.4.1, the model indicates the USWC experiences the highest probability of the most consistent severe conditions with the highest mean H_s at 1.45 meters and standard deviation of 0.39 meters. A right-skewed distribution indicates the preponderance of sea states is challenging for mid-to-smaller size vessels such as FSVs. On the other side of the severity range are the MAR and GULF areas, both with similar, relatively benign wave spectra results having a mean of the H_s distribution of 0.83-0.84 meters. Left-skewed distributions indicate higher probabilities of wave heights in these areas towards the lesser size, but the MAR sees a small number of occurrences of significant wave heights up to 2.49 meters, on par with the USWC. In the northeast, both the NECL and NYB areas have relatively symmetric distributions with mean H_s in the NYB at 1.02 meters as compared to the NECL region further offshore with H_s of 1.11 meters. The NECL also includes the largest H_s observed of all the datasets at 2.98 meters.

In another perspective, Figure 12 shows the empirical cumulative density function (CDF) of significant wave height (H_s) across all five routes. The distributions illustrate how regional sea states differ in both mean and variability. This perspective confirms the USWC route exhibits the harshest met-ocean behavior, with the largest probability of exceedance at 2 meters. On the contrary, the GULF regions demonstrate relatively calmer met-ocean conditions. This probabilistic description is more relevant to vessel operations than deterministic assessments (e.g., based on average statistics). One example is the GULF route, where the mean significant wave height is 0.84 meters. While FSVs can safely navigate at this value, a risk-averse planner should primarily focus on the probability of observing conditions below a threshold (i.e, 1.5 meters or 2 meters), providing a more relevant description of mission disruptions and crew safety.

Figure 12 - Empirical Cumulative Density Function (CDF) of Significant Wave Height (Hs)



Source: Rutgers University

When comparing seasonal variation of sea states in Section 4.1.2.2 (full year; winter – November through April; and summer - May through October), sea spectra distributions show results that are common to all regions (and propulsion platform performance). While the overall shape of the distributions is preserved season to season, winter conditions are more severe than summer conditions. For example, Figures 10 through 11 show MAR winter mean Hs = 0.94 meters compared to a summer mean Hs = 0.75 meters with the full-year result between the two at 0.84 meters (Figure 9). Seasonal results for other regions can be found in the Appendix.

An important finding from these discussions is that location matters as the conditions offshore and hence performance results and input to design parameters, vary considerably from harsh to benign from place to place. Another perhaps intuitive take-away is that seasonal variation is material in terms of sea spectra results with winter conditions more extreme than summer conditions offshore.

4.2 Deployment Simulation Model

Against a backdrop of stochastic weather and sea state conditions developed in the environmental conditions model, we started with voyage descriptions to/from offshore sites in each of the regions of the study. Following this was the creation of standard operating profiles for the specific FSV voyage based on mission requirements for each regional site as to calculate the energy consumption and emissions impact of operating in probabilistic conditions. This information served as input to a stochastic deployment spatio-temporal simulation model developed by the Rutgers team as part of the study. Numerous scenarios comparing deployments across regions, across propulsion platforms and including seasonality were carried out using the simulation model to inform on vessel propulsion design.

4.2.1 Site Selection

Fast Support Vessels (FSVs) service offshore energy infrastructure, aquaculture, research and other requirements across offshore regions. To evaluate energy consumption and emissions of an FSV deployed in offshore service, the details of the specific mission and routing need to be identified and quantified. Five case studies were developed in three US offshore regions representing five different mission requirements and vessel deployments. These are summarized in Table 3 and further described in this section.

Table 3 - Selected Regions, Routes and Deployments

Region	Site Description
Northeast Cluster Region	Long distance wind field Install/O&M work, 5-day offshore deployment, depart day 1 @ 0700, return day 5 @ approx. 1900. Overnight in field or at SOV loitering 12 hours/night x 4 nights. Restricted speed transit only.
New York Bight Region	Short distance wind field O&M daywork including restricted speed transit.
Mid-Atlantic Region	Medium distance wind field crew change at SOV including restricted speed transit.
US Gulf Region	Long distance oil field crew change mission, 16-hour duty cycle. Vessel departs port, transits at design speed to destination, crew change and unloading/loading supplies at rig, return trip at design speed.
US West Coast Region	Medium distance wind field O&M daywork including restricted speed transit.

Source: BOT

In the following figures, the one-way voyage route trace can be seen as a thin black line with distance and heading information indicated for each leg of the journey.

4.2.2 Route Selection

The following operational profiles and regions have been selected based on their proximity to offshore energy projects particularly the density of projects in the northeast as well as proven and currently operating projects in the US Gulf. The voyage routing of these operational profiles has been implemented based on navigational and operational criteria to allow for the safe passage of vessels to and from specific offshore energy installations or clusters of offshore energy project development activity at the time of this project. To allow for navigational safety and voyage planning due diligence, each route to and from a specific site or region reflects navigational routing and voyage planning consistent with normal practices of safe passage at sea for vessels considering local and regional traffic patterns and density, adhering to the following regulations enacted and governed by local and international agencies promoting safe navigation at sea as applicable:

- Adherence to International Maritime Organization (IMO) vessel traffic separation schemes (IMO, n.d.)
- Adherence to safety fairway routing particularly applicable in the US Gulf of Mexico (Code of Federal Regulations (CFR) Title 33, Part 166, February 12, 2026)
- International Regulations for Prevention of Collisions at Sea, 1972 (72COLREGS) including United States Coast Guard (USCG) U.S. Inland Navigation Rules (USCG, n.d.)
- NOAA National Fisheries Seasonal and Dynamic management areas designed and implemented to reduce the number of vessel strikes to North Atlantic right whales where applicable regionally, limiting speed to 10 knots (NOAA, 2026).

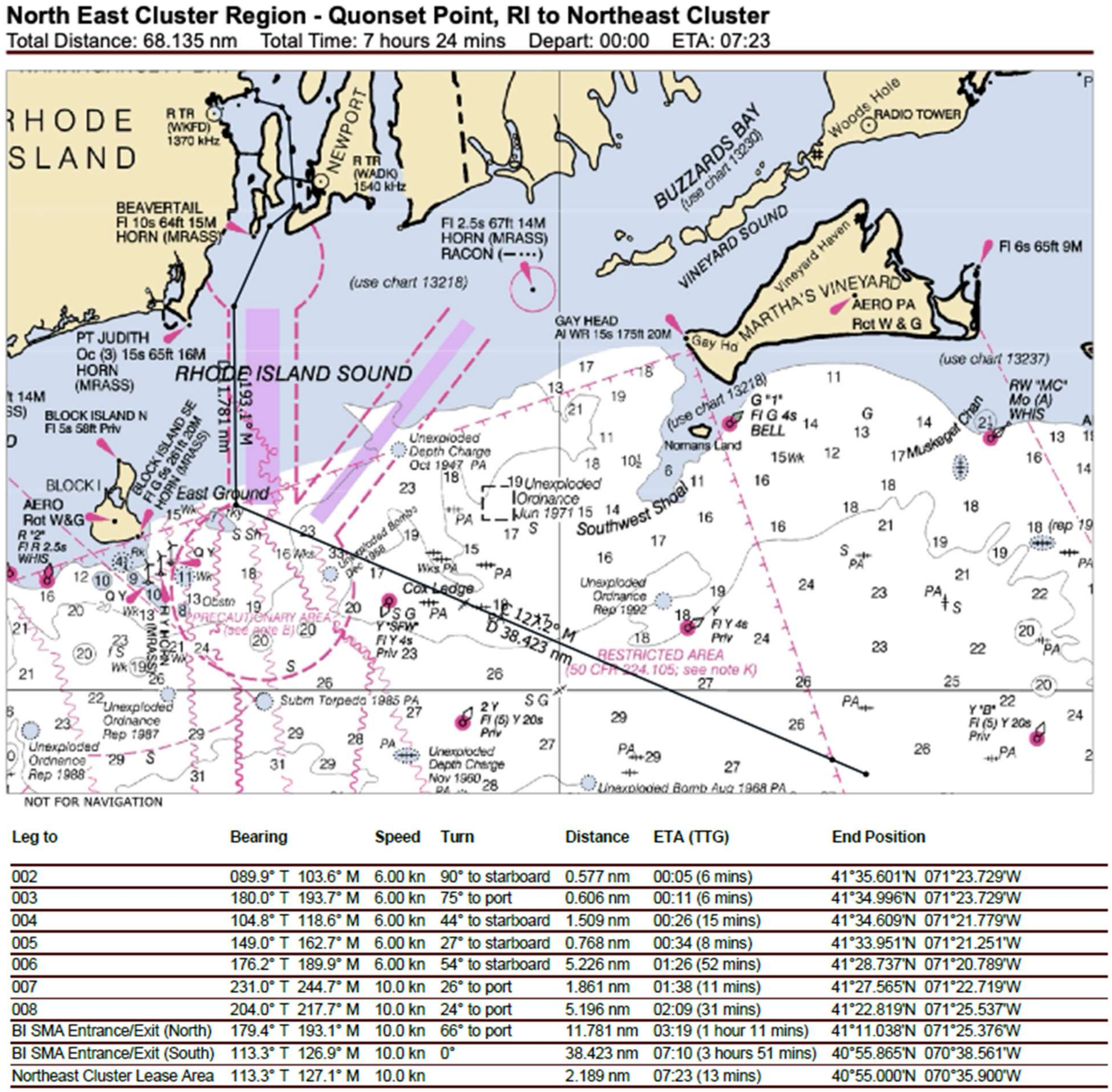
To note, relevant Seasonal Management Areas (SMAs) that were active from November 1, 2024 to April 30, 2025 are included in the voyage routing considerations in this report and include the Mid-Atlantic SMAs outside of Block Island, affecting the New England Cluster; and the entrance to the Chesapeake Bay outside of Norfolk, VA affecting the Coastal Virginia Offshore Wind (CVOW) project. These address marine mammal protection policies, specifically North Atlantic right whales that are notably vulnerable to vessel strikes in the identified regions.

In Sections 4.2.2.1 through 4.2.2.5, route definitions and details are displayed on one-way transit activity. The full voyage is used in the simulation model and consists of a round-trip transit and activities conducted at the offshore location consistent with the operational profile associated with each deployment (described further in Table 7 and Appendix 4). In the following figures the ETA (TTG) column shows elapsed time, not time of day.

4.2.2.1 North East Cluster (NECL)

This 108-hour route extends from Massachusetts ports to offshore wind lease areas near Nantucket and Georges Bank. These missions represent longer transits, exposing vessels to severe met-ocean conditions and longer delays. The route also overlaps with highly productive fisheries near Georges Bank, making it a focal point for balancing energy growth with ecosystem awareness.

Figure 13 - North East Cluster (NECL)



North East Cluster Region - Quonset Point, RI to Northeast Cluster

Total Distance: 68.135 nm Total Time: 7 hours 24 mins Depart: 00:00 ETA: 07:23

NOT FOR NAVIGATION

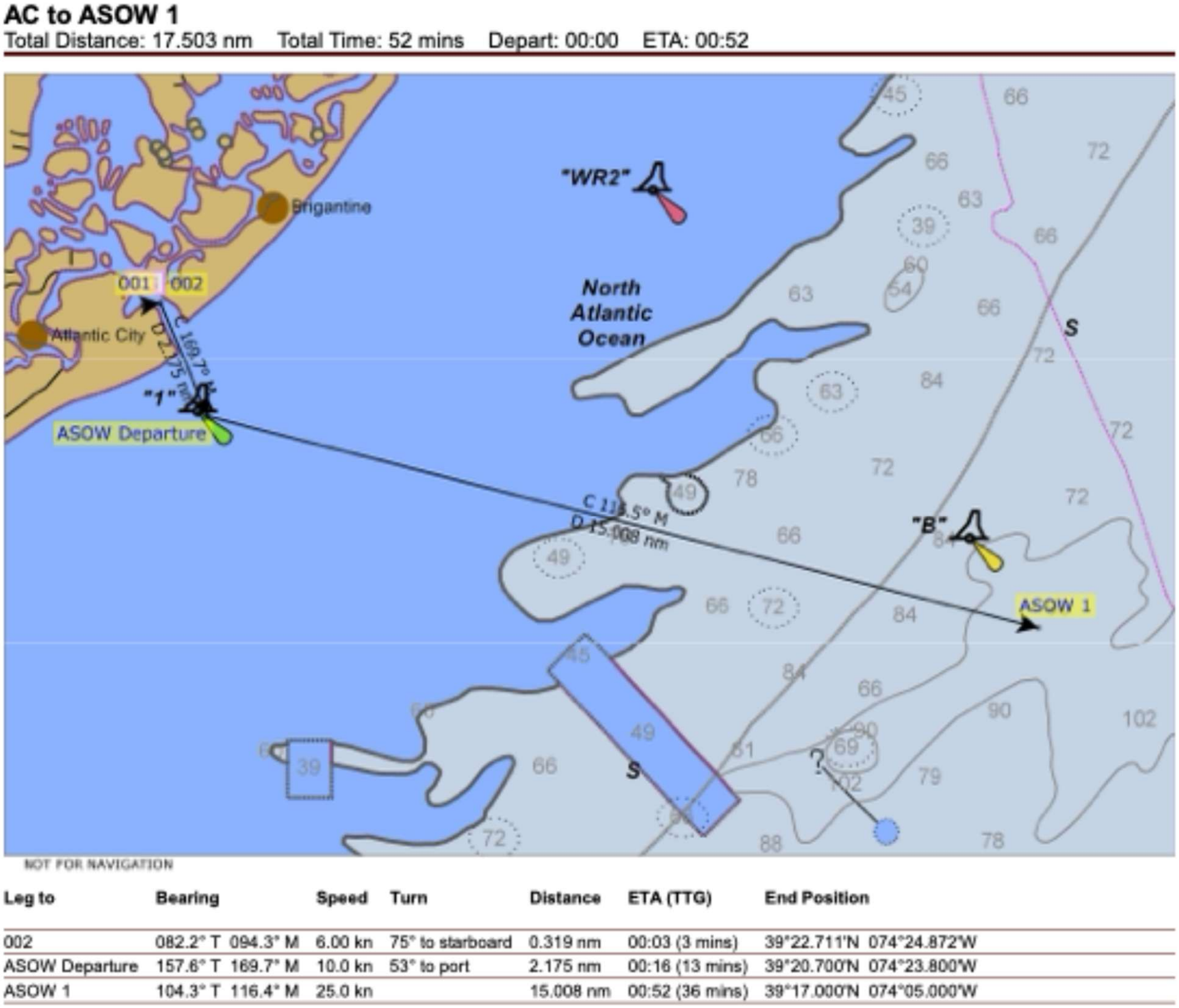
Leg to	Bearing	Speed	Turn	Distance	ETA (TTG)	End Position
002	089.9° T 103.6° M	6.00 kn	90° to starboard	0.577 nm	00:05 (6 mins)	41°35.601'N 071°23.729'W
003	180.0° T 193.7° M	6.00 kn	75° to port	0.606 nm	00:11 (6 mins)	41°34.996'N 071°23.729'W
004	104.8° T 118.6° M	6.00 kn	44° to starboard	1.509 nm	00:26 (15 mins)	41°34.609'N 071°21.779'W
005	149.0° T 162.7° M	6.00 kn	27° to starboard	0.768 nm	00:34 (8 mins)	41°33.951'N 071°21.251'W
006	176.2° T 189.9° M	6.00 kn	54° to starboard	5.226 nm	01:26 (52 mins)	41°28.737'N 071°20.789'W
007	231.0° T 244.7° M	10.0 kn	26° to port	1.861 nm	01:38 (11 mins)	41°27.565'N 071°22.719'W
008	204.0° T 217.7° M	10.0 kn	24° to port	5.196 nm	02:09 (31 mins)	41°22.819'N 071°25.537'W
BI SMA Entrance/Exit (North)	179.4° T 193.1° M	10.0 kn	66° to port	11.781 nm	03:19 (1 hour 11 mins)	41°11.038'N 071°25.376'W
BI SMA Entrance/Exit (South)	113.3° T 126.9° M	10.0 kn	0°	38.423 nm	07:10 (3 hours 51 mins)	40°55.865'N 070°38.561'W
Northeast Cluster Lease Area	113.3° T 127.1° M	10.0 kn		2.189 nm	07:23 (13 mins)	40°55.000'N 070°35.900'W

Source: BOT

4.2.2.2 New York Bight (NYB)

This 12-hour route links Atlantic City, New Jersey to planned and leased offshore wind areas in the NYB. It showcases the challenges of coordinating FSV operations within one of the busiest maritime regions in the world, where congestion, as well as adverse met-ocean conditions, must be carefully managed.

Figure 14 - New York Bight (NYB)



AC to ASOW 1

Total Distance: 17.503 nm Total Time: 52 mins Depart: 00:00 ETA: 00:52

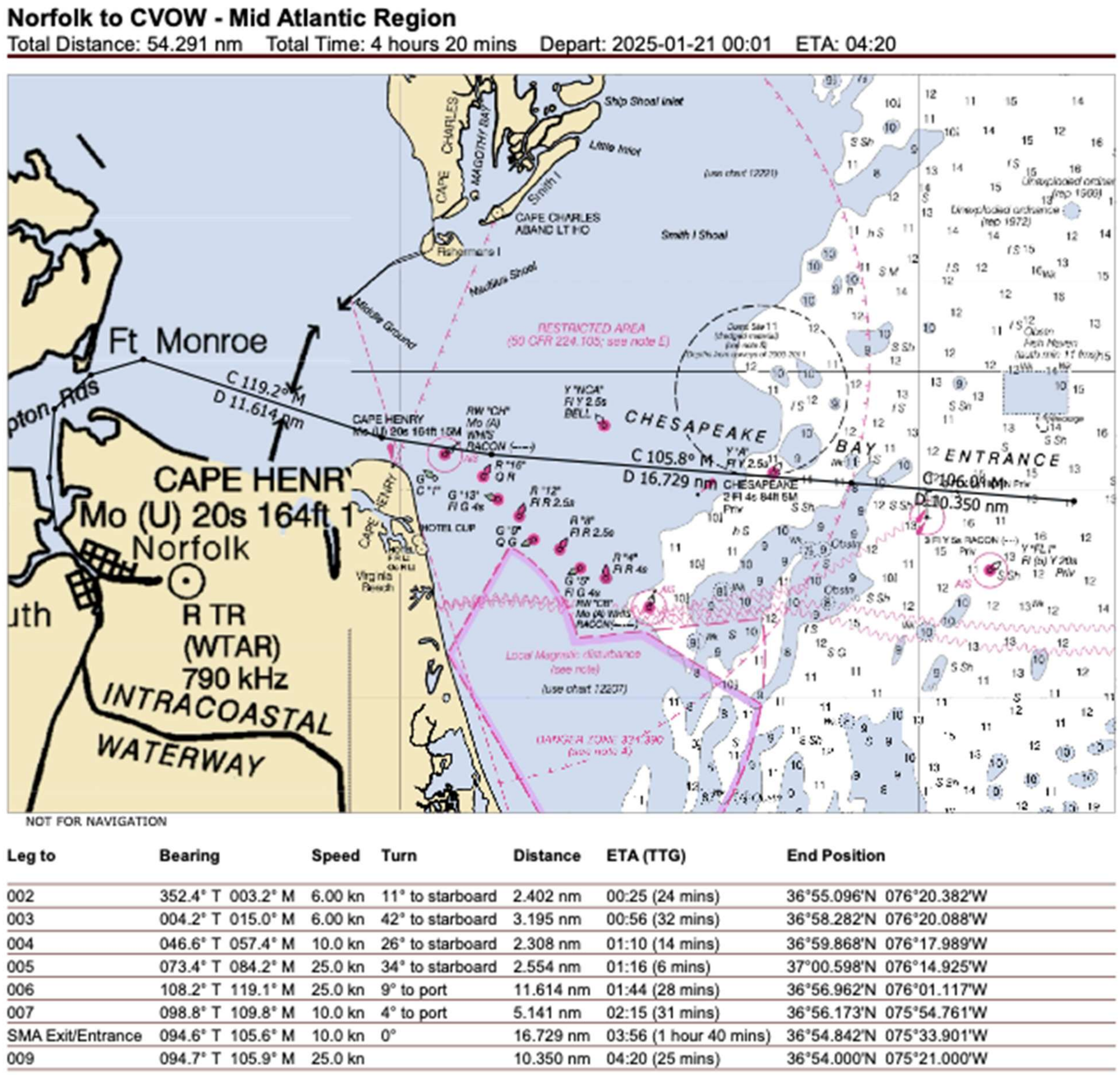
Leg to	Bearing	Speed	Turn	Distance	ETA (TTG)	End Position
002	082.2° T 094.3° M	6.00 kn	75° to starboard	0.319 nm	00:03 (3 mins)	39°22.711'N 074°24.872'W
ASOW Departure	157.6° T 169.7° M	10.0 kn	53° to port	2.175 nm	00:16 (13 mins)	39°20.700'N 074°23.800'W
ASOW 1	104.3° T 116.4° M	25.0 kn		15.008 nm	00:52 (36 mins)	39°17.000'N 074°05.000'W

Source: BOT

4.2.2.3 Mid-Atlantic Route (MAR)

This 12-hour route connects the Norfolk Harbor area, Virginia to the Coastal Virginia Offshore Wind (CVOW) lease area - the largest commercial offshore wind project under construction in the US at the time of writing. CVOW's proximity to the port reduces transit times, but its exposure to coastal weather calls for accurate modeling to capture highly variable met-ocean conditions.

Figure 15 - Mid-Atlantic Route (MAR)



Norfolk to CVOW - Mid Atlantic Region

Total Distance: 54.291 nm Total Time: 4 hours 20 mins Depart: 2025-01-21 00:01 ETA: 04:20

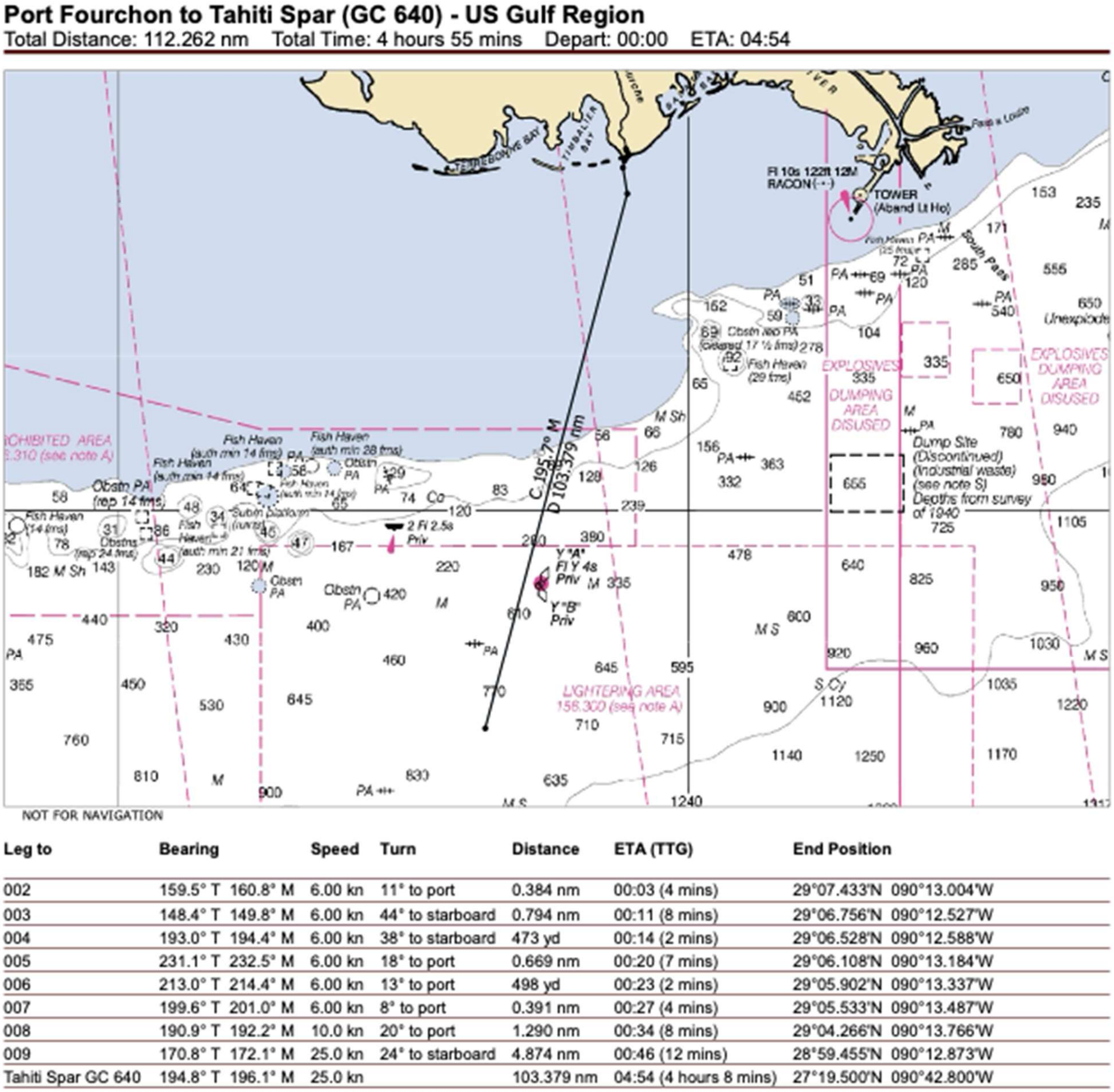
Leg to	Bearing	Speed	Turn	Distance	ETA (TTG)	End Position
002	352.4° T 003.2° M	6.00 kn	11° to starboard	2.402 nm	00:25 (24 mins)	36°55.096'N 076°20.382'W
003	004.2° T 015.0° M	6.00 kn	42° to starboard	3.195 nm	00:56 (32 mins)	36°58.282'N 076°20.088'W
004	046.6° T 057.4° M	10.0 kn	26° to starboard	2.308 nm	01:10 (14 mins)	36°59.868'N 076°17.989'W
005	073.4° T 084.2° M	25.0 kn	34° to starboard	2.554 nm	01:16 (6 mins)	37°00.598'N 076°14.925'W
006	108.2° T 119.1° M	25.0 kn	9° to port	11.614 nm	01:44 (28 mins)	36°56.962'N 076°01.117'W
007	098.8° T 109.8° M	10.0 kn	4° to port	5.141 nm	02:15 (31 mins)	36°56.173'N 075°54.761'W
SMA Exit/Entrance	094.6° T 105.6° M	10.0 kn	0°	16.729 nm	03:56 (1 hour 40 mins)	36°54.842'N 075°33.901'W
009	094.7° T 105.9° M	25.0 kn		10.350 nm	04:20 (25 mins)	36°54.000'N 075°21.000'W

Source: BOT

4.2.2.4 US Gulf (GULF)

This is a 16-hour route servicing the offshore energy industry in the US Gulf. Met-ocean conditions are fairly calmer, but distances between ports and lease areas are comparatively long, necessitating the majority of the deployment conducted at high speed.

Figure 16 – US Gulf (GULF)



Port Fourchon to Tahiti Spar (GC 640) - US Gulf Region

Total Distance: 112.262 nm Total Time: 4 hours 55 mins Depart: 00:00 ETA: 04:54

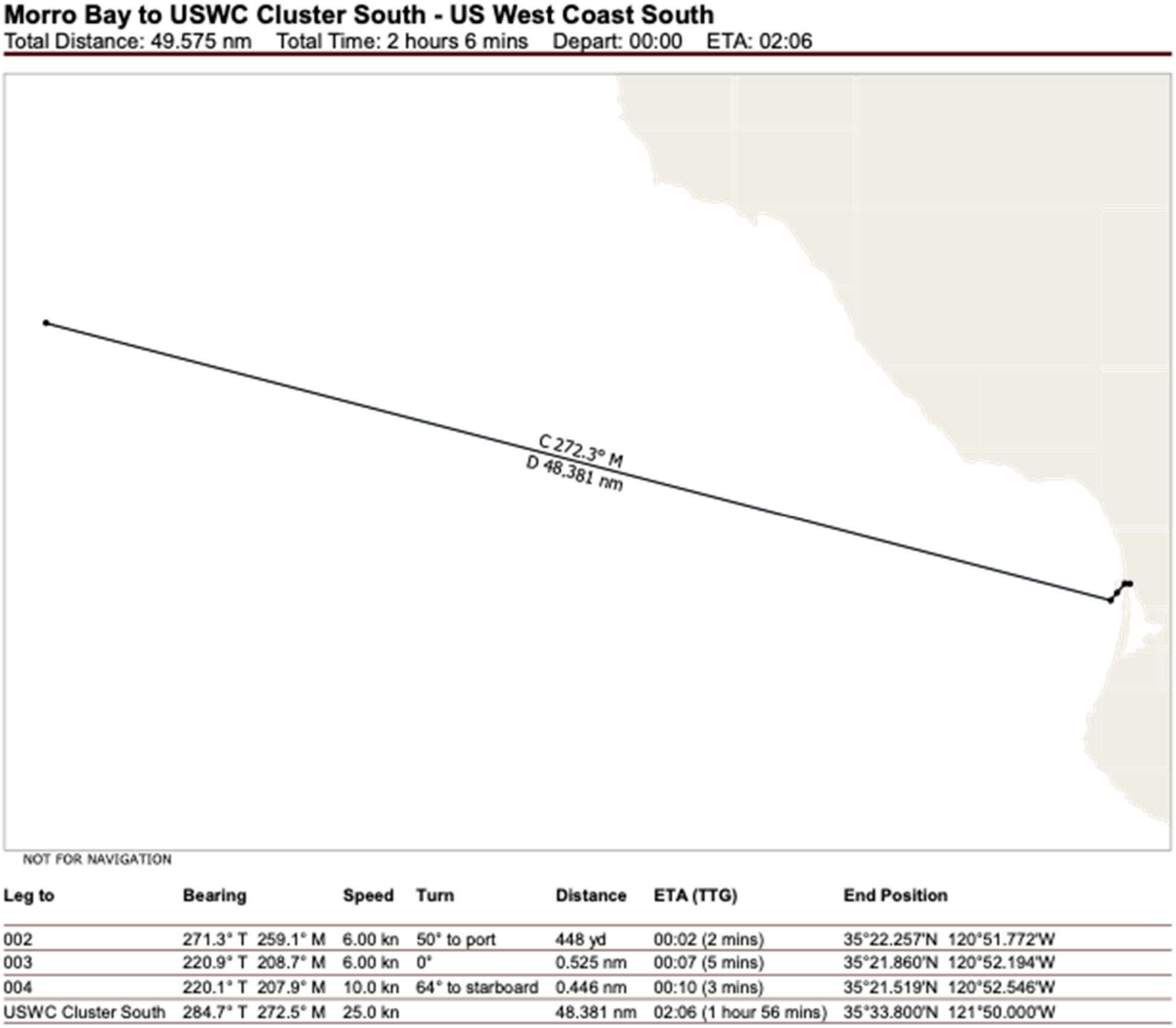
Leg to	Bearing	Speed	Turn	Distance	ETA (TTG)	End Position
002	159.5° T 160.8° M	6.00 kn	11° to port	0.384 nm	00:03 (4 mins)	29°07.433'N 090°13.004'W
003	148.4° T 149.8° M	6.00 kn	44° to starboard	0.794 nm	00:11 (8 mins)	29°06.756'N 090°12.527'W
004	193.0° T 194.4° M	6.00 kn	38° to starboard	473 yd	00:14 (2 mins)	29°06.528'N 090°12.588'W
005	231.1° T 232.5° M	6.00 kn	18° to port	0.669 nm	00:20 (7 mins)	29°06.108'N 090°13.184'W
006	213.0° T 214.4° M	6.00 kn	13° to port	498 yd	00:23 (2 mins)	29°05.902'N 090°13.337'W
007	199.6° T 201.0° M	6.00 kn	8° to port	0.391 nm	00:27 (4 mins)	29°05.533'N 090°13.487'W
008	190.9° T 192.2° M	10.0 kn	20° to port	1.290 nm	00:34 (8 mins)	29°04.266'N 090°13.766'W
009	170.8° T 172.1° M	25.0 kn	24° to starboard	4.874 nm	00:46 (12 mins)	28°59.455'N 090°12.873'W
Tahiti Spar GC 640	194.8° T 196.1° M	25.0 kn		103.379 nm	04:54 (4 hours 8 mins)	27°19.500'N 090°42.800'W

Source: BOT

4.2.2.5 US West Coast (USWC)

This 12-hour route services California's emerging offshore renewable energy projects, with deeper waters and harsher met-ocean conditions.

Figure 17 - US West Coast (USWC)



Morro Bay to USWC Cluster South - US West Coast South

Total Distance: 49.575 nm Total Time: 2 hours 6 mins Depart: 00:00 ETA: 02:06

Leg to	Bearing	Speed	Turn	Distance	ETA (TTG)	End Position
002	271.3° T 259.1° M	6.00 kn	50° to port	448 yd	00:02 (2 mins)	35°22.257'N 120°51.772'W
003	220.9° T 208.7° M	6.00 kn	0°	0.525 nm	00:07 (5 mins)	35°21.860'N 120°52.194'W
004	220.1° T 207.9° M	10.0 kn	64° to starboard	0.446 nm	00:10 (3 mins)	35°21.519'N 120°52.546'W
USWC Cluster South	284.7° T 272.5° M	25.0 kn		48.381 nm	02:06 (1 hour 56 mins)	35°33.800'N 121°50.000'W

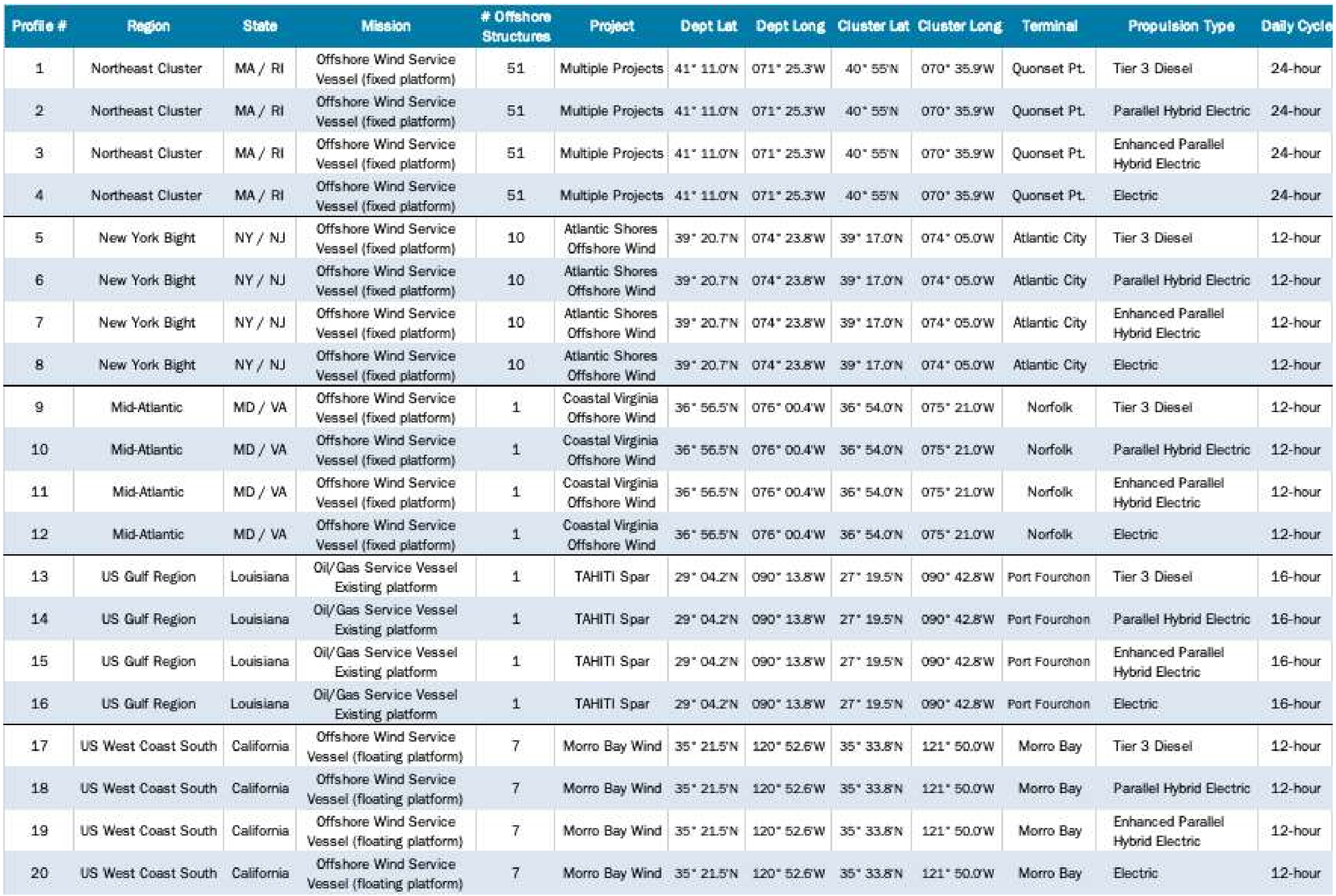
Source: BOT

4.2.3 Operating Profile Development

Twenty different operating profiles were considered in the study, differentiated by regional site deployments (5), and propulsion platforms (4) (Table 4). The MAR profile is illustrated in Table 5 and remaining profiles are located in Appendix 4. Each profile describes a sequential series of spatio-temporal activities consisting of logistics elements such as idling alongside, maneuvering in port, slow speed transit, high speed transit, dropping off, picking up and loitering. Each activity will have a duration of time associated with it, the speed and distance traveled, and geographical positions that can be calculated during a particular activity. In the case of the Northeast Cluster, the FSV deployment consists of a 108-hour round trip – one voyage out to the offshore site, three days on site offshore transiting to 51 offshore structures, and one voyage back from the offshore site to shore. Note that some activities appear twice in the operating profile because they are conducted twice by the vessel: once for the port-to-destination journey, and once on the vessel's journey back to port. For the New York Bight and US West Coast, the FSV would service multiple offshore structures. In the Mid-Atlantic, the FSV would support one offshore asset such as a Service Operation Vessel (SOV) for crew change while in the Gulf, the FSV would support the offshore structure Tahiti Spar, an offshore oil and gas site.

4.2.3.1 Operating Profiles

Table 4 - Operating Profiles Summary



Profile #	Region	State	Mission	# Offshore Structures	Project	Dept Lat	Dept Long	Cluster Lat	Cluster Long	Terminal	Propulsion Type	Daily Cycle
1	Northeast Cluster	MA / RI	Offshore Wind Service Vessel (fixed platform)	51	Multiple Projects	41° 11.0'N	071° 25.3'W	40° 55'N	070° 35.9'W	Quonset Pt.	Tier 3 Diesel	24-hour
2	Northeast Cluster	MA / RI	Offshore Wind Service Vessel (fixed platform)	51	Multiple Projects	41° 11.0'N	071° 25.3'W	40° 55'N	070° 35.9'W	Quonset Pt.	Parallel Hybrid Electric	24-hour
3	Northeast Cluster	MA / RI	Offshore Wind Service Vessel (fixed platform)	51	Multiple Projects	41° 11.0'N	071° 25.3'W	40° 55'N	070° 35.9'W	Quonset Pt.	Enhanced Parallel Hybrid Electric	24-hour
4	Northeast Cluster	MA / RI	Offshore Wind Service Vessel (fixed platform)	51	Multiple Projects	41° 11.0'N	071° 25.3'W	40° 55'N	070° 35.9'W	Quonset Pt.	Electric	24-hour
5	New York Bight	NY / NJ	Offshore Wind Service Vessel (fixed platform)	10	Atlantic Shores Offshore Wind	39° 20.7'N	074° 23.8'W	39° 17.0'N	074° 05.0'W	Atlantic City	Tier 3 Diesel	12-hour
6	New York Bight	NY / NJ	Offshore Wind Service Vessel (fixed platform)	10	Atlantic Shores Offshore Wind	39° 20.7'N	074° 23.8'W	39° 17.0'N	074° 05.0'W	Atlantic City	Parallel Hybrid Electric	12-hour
7	New York Bight	NY / NJ	Offshore Wind Service Vessel (fixed platform)	10	Atlantic Shores Offshore Wind	39° 20.7'N	074° 23.8'W	39° 17.0'N	074° 05.0'W	Atlantic City	Enhanced Parallel Hybrid Electric	12-hour
8	New York Bight	NY / NJ	Offshore Wind Service Vessel (fixed platform)	10	Atlantic Shores Offshore Wind	39° 20.7'N	074° 23.8'W	39° 17.0'N	074° 05.0'W	Atlantic City	Electric	12-hour
9	Mid-Atlantic	MD / VA	Offshore Wind Service Vessel (fixed platform)	1	Coastal Virginia Offshore Wind	36° 56.5'N	076° 00.4'W	36° 54.0'N	075° 21.0'W	Norfolk	Tier 3 Diesel	12-hour
10	Mid-Atlantic	MD / VA	Offshore Wind Service Vessel (fixed platform)	1	Coastal Virginia Offshore Wind	36° 56.5'N	076° 00.4'W	36° 54.0'N	075° 21.0'W	Norfolk	Parallel Hybrid Electric	12-hour
11	Mid-Atlantic	MD / VA	Offshore Wind Service Vessel (fixed platform)	1	Coastal Virginia Offshore Wind	36° 56.5'N	076° 00.4'W	36° 54.0'N	075° 21.0'W	Norfolk	Enhanced Parallel Hybrid Electric	12-hour
12	Mid-Atlantic	MD / VA	Offshore Wind Service Vessel (fixed platform)	1	Coastal Virginia Offshore Wind	36° 56.5'N	076° 00.4'W	36° 54.0'N	075° 21.0'W	Norfolk	Electric	12-hour
13	US Gulf Region	Louisiana	Oil/Gas Service Vessel Existing platform	1	TAHITI Spar	29° 04.2'N	090° 13.8'W	27° 19.5'N	090° 42.8'W	Port Fourchon	Tier 3 Diesel	16-hour
14	US Gulf Region	Louisiana	Oil/Gas Service Vessel Existing platform	1	TAHITI Spar	29° 04.2'N	090° 13.8'W	27° 19.5'N	090° 42.8'W	Port Fourchon	Parallel Hybrid Electric	16-hour
15	US Gulf Region	Louisiana	Oil/Gas Service Vessel Existing platform	1	TAHITI Spar	29° 04.2'N	090° 13.8'W	27° 19.5'N	090° 42.8'W	Port Fourchon	Enhanced Parallel Hybrid Electric	16-hour
16	US Gulf Region	Louisiana	Oil/Gas Service Vessel Existing platform	1	TAHITI Spar	29° 04.2'N	090° 13.8'W	27° 19.5'N	090° 42.8'W	Port Fourchon	Electric	16-hour
17	US West Coast South	California	Offshore Wind Service Vessel (floating platform)	7	Morro Bay Wind	35° 21.5'N	120° 52.6'W	35° 33.8'N	121° 50.0'W	Morro Bay	Tier 3 Diesel	12-hour
18	US West Coast South	California	Offshore Wind Service Vessel (floating platform)	7	Morro Bay Wind	35° 21.5'N	120° 52.6'W	35° 33.8'N	121° 50.0'W	Morro Bay	Parallel Hybrid Electric	12-hour
19	US West Coast South	California	Offshore Wind Service Vessel (floating platform)	7	Morro Bay Wind	35° 21.5'N	120° 52.6'W	35° 33.8'N	121° 50.0'W	Morro Bay	Enhanced Parallel Hybrid Electric	12-hour
20	US West Coast South	California	Offshore Wind Service Vessel (floating platform)	7	Morro Bay Wind	35° 21.5'N	120° 52.6'W	35° 33.8'N	121° 50.0'W	Morro Bay	Electric	12-hour

Source: BOT

Table 5 - MAR Operating Profile

Description	**#**	**# of Dest.**	**Prop**	**Daily Cycle**	**(min)**				
MA - Mid-Atlantic Wind Field - CVOW	9	1	3 DSL	12	720				
Medium distance wind field crew change at SOV including restricted speed transit. Propulsion 100% Tier 3 diesel.	Distance (nm)	Speed (Kts)	Start Coordinates (Lat/Long)	End Coordinates (Lat/Long)	Heading (Degrees)	Minutes	Cumulative Minutes	Cumulative Hours	
Idle Alongside						30	30	0.5	In Port, alongside
Port transit	5.60	6				56	86	1.4	In Port, transiting @ maneuvering speed
Restricted Transit Leg	24.18	10				145	231	3.9	In Seasonal Management Areas, etc.
Design Transit Leg	24.52	25				59	290	4.8	At Design Speed
Number of Offshore Destinations						1			SOV
Drop-off Operation Duration						20			Pushing against SOV @ 80% power
Total Drop-off Duration						20	310	5.2	Pushing against SOV for crew transfer
Drop-off Destination-to-Destination Transit	1	10				6			At restricted speed
Total Drop-to-Drop Transit Duration						6	316	5.3	At Dest-to-Dest Transit speed
Loitering						88	404	6.7	At offshore location, maneuvering speed
Pick-Up Operation Duration						20			Pushing against SOV @ 80% power
Total Pick-Up Duration						20	424	7.1	Pushing against SOV for crew transfer
Pick-Up Destination-to-Destination Transit	1	10				6			At restricted speed
Total Pick-to-Pick Transit Duration						6	430	7.2	At Dest-to-Dest Transit speed
Design Transit Leg	24.52	25				59	489	8.1	At Design Speed
Restricted Transit Leg	24.18	10				145	634	10.6	In Seasonal Management Areas, etc.
Port transit	5.60	6				56	690	11.5	In Port, transiting @ maneuvering speed
Idle Alongside						30	720	12.0	In Port, alongside
					ok	720	ok	ok	kg

Source: BOT

4.2.3.2 Propulsion Platforms

Table 6 - Propulsion Platforms Considered in This Study

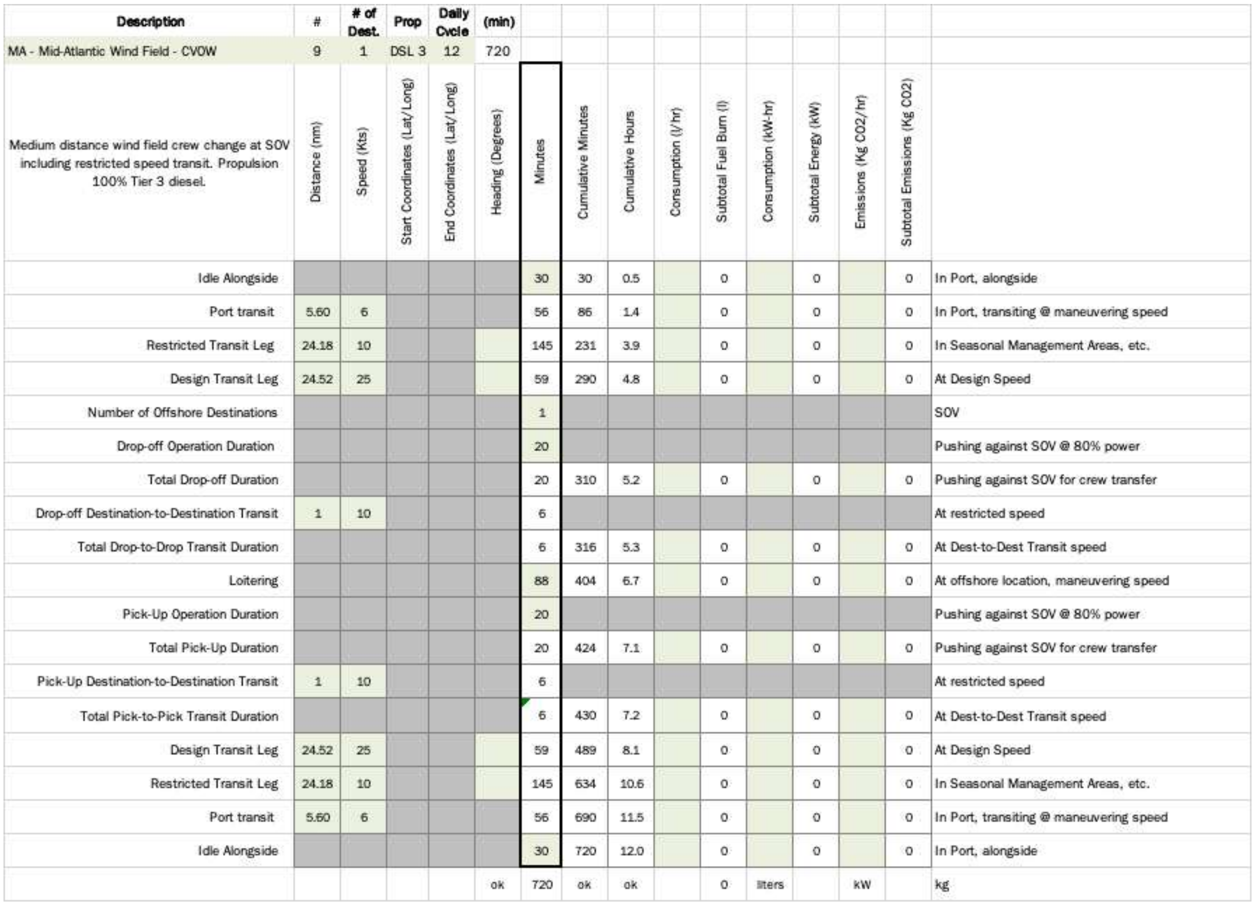
Tier 3 Diesel	*Propulsion 100% Tier 3 diesel.*
Parallel Hybrid Electric	*Propulsion by Parallel Hybrid Electric (PHEV) platform. Idling, port transit and loitering all assumed at 100% electric propulsion. Shore power overnight charging assumed.*
Enhanced Parallel Hybrid Electric	*Propulsion by Enhanced Parallel Hybrid Electric (EPHEV) platform. This platform assumes substantial improvements in energy storage technology and high voltage electrical system upgrades over PHEV. Idling, port transit, restricted speed transits and loitering all assumed at 100% electric propulsion. Shore power overnight charging assumed.*
Fully Electric	*Propulsion by 100% electric platform. Idling, port transit, restricted and full speed transits, loitering and in-field activities all assumed at 100% electric propulsion. Shore power overnight charging availability assumed and offshore charging availability assumed.*

Source: BOT

4.2.3.3 Emissions and Consumption Estimates in Calm Water and in Sea State Conditions

In order to test our second hypothesis that increasingly electrified platforms would be more cost effective and with a lower carbon footprint than traditionally diesel-powered vessels, we needed to calculate total energy costs and emissions for each run in the simulation model. These results would be estimates of energy consumption and emissions for a vessel not just in calm water, but in various sea state conditions. Additionally, the estimates would need to be developed for each propulsion platform. With these estimates as inputs, outputs from the simulation model would allow cost and emissions comparisons across platforms in the same region and for propulsion platforms in different regions. In further development of the Operating Profiles in Table 5 and Appendix 4, we determined what variables we would need for the simulation model, namely, diesel consumption, electric consumption, and emissions as illustrated in the additional green columns in Table 7. The white columns with zeroes represent the desired outputs, or values we sought to determine through this phase of the research. These values would be calculated by the simulation model for each run. (Note that while heading is a desired output in Table 7, this value was assumed to be 0 degrees, or worst-case scenario in head seas for this research. We suggest as follow-on work in Section 7.1.2 to explore using multiple headings to further condition consumption and emissions results.)

Table 7 - Development of MAR Operating Profile to Determine Energy Usage and Emissions



Description	#	# of Dest.	Prop	Daily Cycle	(min)										
MA - Mid-Atlantic Wind Field - CVOW	9	1	DSL 3	12	720										
Medium distance wind field crew change at SOV including restricted speed transit. Propulsion 100% Tier 3 diesel.	Distance (nm)	Speed (Kts)	Start Coordinates (Lat/Long)	End Coordinates (Lat/Long)	Heading (Degrees)	Minutes	Cumulative Minutes	Cumulative Hours	Consumption (l/hr)	Subtotal Fuel Burn (l)	Consumption (kW-hr)	Subtotal Energy (kW)	Emissions (Kg CO2/hr)	Subtotal Emissions (Kg CO2)	
Idle Alongside						30	30	0.5		0		0		0	In Port, alongside
Port transit	5.60	6				56	86	1.4		0		0		0	In Port, transiting @ maneuvering speed
Restricted Transit Leg	24.18	10				145	231	3.9		0		0		0	In Seasonal Management Areas, etc.
Design Transit Leg	24.52	25				59	290	4.8		0		0		0	At Design Speed
Number of Offshore Destinations						1									SOV
Drop-off Operation Duration						20									Pushing against SOV @ 80% power
Total Drop-off Duration						20	310	5.2		0		0		0	Pushing against SOV for crew transfer
Drop-off Destination-to-Destination Transit	1	10				6									At restricted speed
Total Drop-to-Drop Transit Duration						6	316	5.3		0		0		0	At Dest-to-Dest Transit speed
Loitering						88	404	6.7		0		0		0	At offshore location, maneuvering speed
Pick-Up Operation Duration						20									Pushing against SOV @ 80% power
Total Pick-Up Duration						20	424	7.1		0		0		0	Pushing against SOV for crew transfer
Pick-Up Destination-to-Destination Transit	1	10				6									At restricted speed
Total Pick-to-Pick Transit Duration						6	430	7.2		0		0		0	At Dest-to-Dest Transit speed
Design Transit Leg	24.52	25				59	489	8.1		0		0		0	At Design Speed
Restricted Transit Leg	24.18	10				145	634	10.6		0		0		0	In Seasonal Management Areas, etc.
Port transit	5.60	6				56	690	11.5		0		0		0	In Port, transiting @ maneuvering speed
Idle Alongside						30	720	12.0		0		0		0	In Port, alongside
					ok	720	ok	ok		0	liters		kW		kg

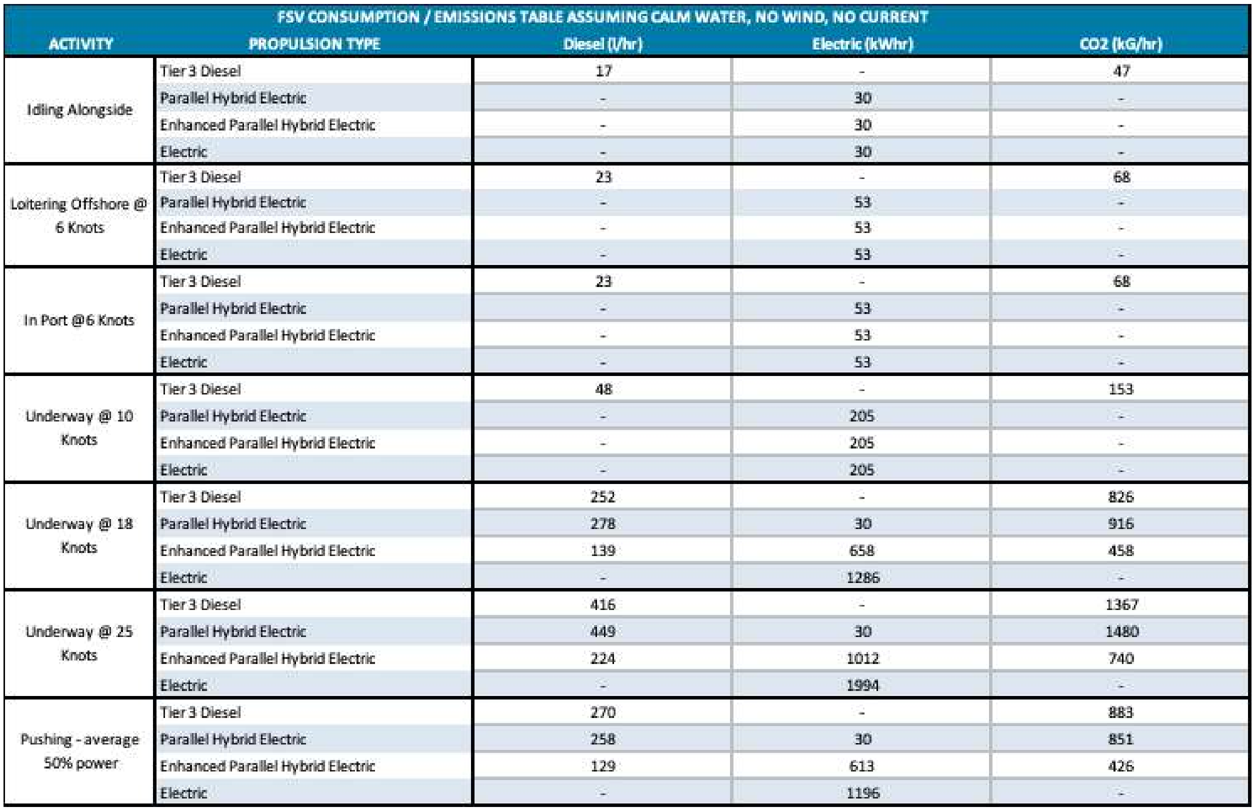
Source: BOT

In order to provide energy consumption and emission estimates at various sea states, we chose the Delphi approach, discussed in more detail in Section 5.2.1, where Incat Crowther provided estimates of these values based on their industry expertise in both calm water and in sea state conditions, specifically, significant wave height.

First, a calm water table, under which Operating Profiles are commonly evaluated, was developed as a baseline in Table 8. The engineers then produced estimates in 0.5-meter seas (Table 9), 1.2-meter seas (Table 10) and 1.75-meter seas (not pictured).

Note that in tables 8 through 10, some values are not applicable because purely diesel engines would not consume electricity and fully electric propulsion systems would not consume diesel. Further, an assumption is made in Table 8 that when electrified vessels are idling in port, loitering offshore at 6 kts, in port at 6 kts, or underway at 10 kts, only electric propulsion would be used, meaning diesel fuel would not be consumed and CO_2 would not be emitted. These assumptions were applied to the logic of the model. However, when accounting for present-day technology and the lack of charging availability offshore, it is only practical to assume that when underway at 10 knots, the vessel must consume diesel fuel and, in turn, emit CO_2, as seen in Tables 25 and 26.

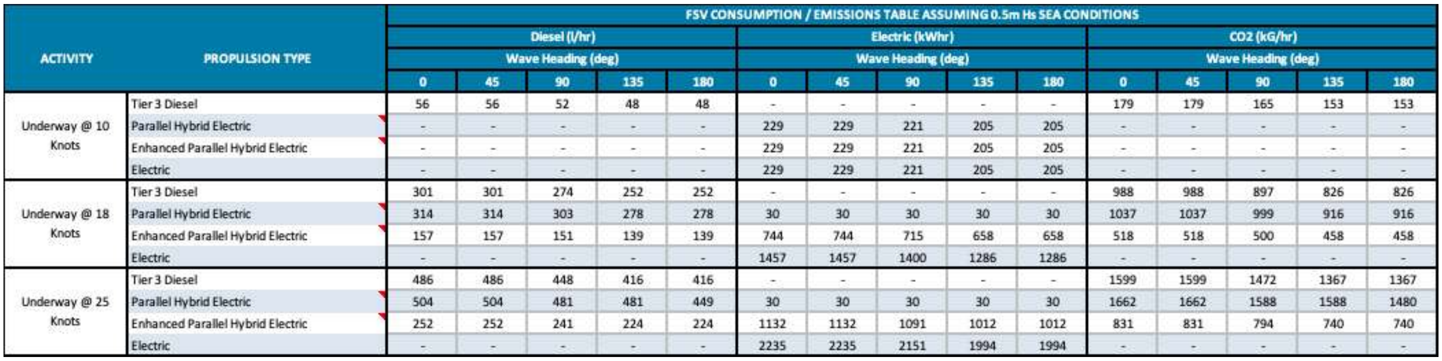
Table 8 - Consumption and Emissions Estimates in Calm Water Conditions



FSV CONSUMPTION / EMISSIONS TABLE ASSUMING CALM WATER, NO WIND, NO CURRENT				
ACTIVITY	PROPULSION TYPE	Diesel (l/hr)	Electric (kWhr)	CO2 (kG/hr)
Idling Alongside	Tier 3 Diesel	17	-	47
	Parallel Hybrid Electric	-	30	-
	Enhanced Parallel Hybrid Electric	-	30	-
	Electric	-	30	-
Loitering Offshore @ 6 Knots	Tier 3 Diesel	23	-	68
	Parallel Hybrid Electric	-	53	-
	Enhanced Parallel Hybrid Electric	-	53	-
	Electric	-	53	-
In Port @6 Knots	Tier 3 Diesel	23	-	68
	Parallel Hybrid Electric	-	53	-
	Enhanced Parallel Hybrid Electric	-	53	-
	Electric	-	53	-
Underway @ 10 Knots	Tier 3 Diesel	48	-	153
	Parallel Hybrid Electric	-	205	-
	Enhanced Parallel Hybrid Electric	-	205	-
	Electric	-	205	-
Underway @ 18 Knots	Tier 3 Diesel	252	-	826
	Parallel Hybrid Electric	278	30	916
	Enhanced Parallel Hybrid Electric	139	658	458
	Electric	-	1286	-
Underway @ 25 Knots	Tier 3 Diesel	416	-	1367
	Parallel Hybrid Electric	449	30	1480
	Enhanced Parallel Hybrid Electric	224	1012	740
	Electric	-	1994	-
Pushing - average 50% power	Tier 3 Diesel	270	-	883
	Parallel Hybrid Electric	258	30	851
	Enhanced Parallel Hybrid Electric	129	613	426
	Electric	-	1196	-

Source: Incat Crowther

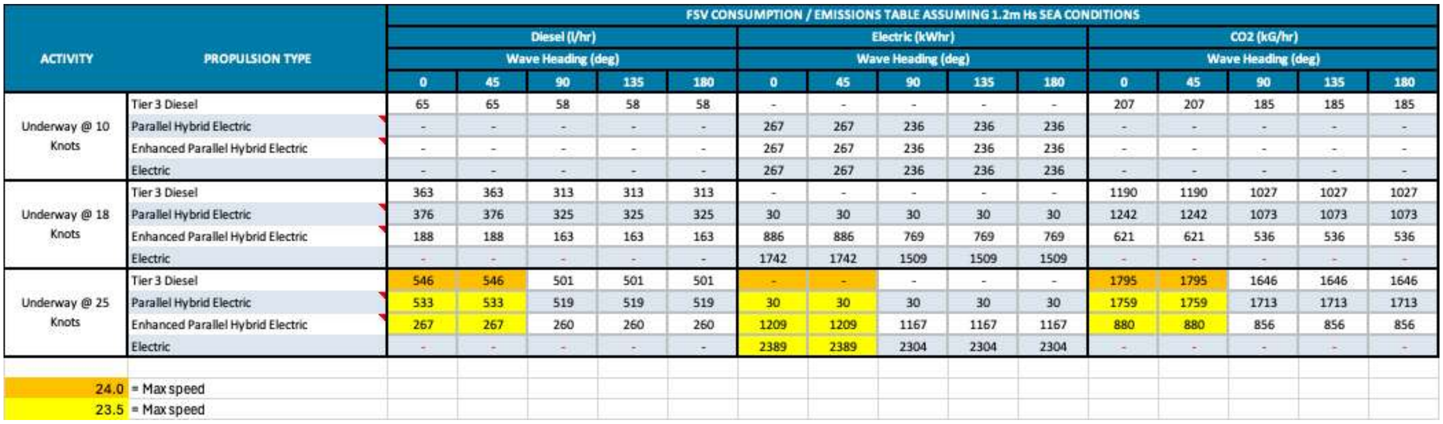
Table 9 - Consumption and Emissions Estimates in Sea State Conditions of 0.5 Meters



ACTIVITY	PROPULSION TYPE	FSV CONSUMPTION / EMISSIONS TABLE ASSUMING 0.5m Hs SEA CONDITIONS														
		Diesel (l/hr)					Electric (kWhr)					CO2 (kG/hr)				
		Wave Heading (deg)					Wave Heading (deg)					Wave Heading (deg)				
		0	45	90	135	180	0	45	90	135	180	0	45	90	135	180
Underway @ 10 Knots	Tier 3 Diesel	56	56	52	48	48	-	-	-	-	-	179	179	165	153	153
	Parallel Hybrid Electric	-	-	-	-	-	229	229	221	205	205	-	-	-	-	-
	Enhanced Parallel Hybrid Electric	-	-	-	-	-	229	229	221	205	205	-	-	-	-	-
	Electric	-	-	-	-	-	229	229	221	205	205	-	-	-	-	-
Underway @ 18 Knots	Tier 3 Diesel	301	301	274	252	252	-	-	-	-	-	988	988	897	826	826
	Parallel Hybrid Electric	314	314	303	278	278	30	30	30	30	30	1037	1037	999	916	916
	Enhanced Parallel Hybrid Electric	157	157	151	139	139	744	744	715	658	658	518	518	500	458	458
	Electric	-	-	-	-	-	1457	1457	1400	1286	1286	-	-	-	-	-
Underway @ 25 Knots	Tier 3 Diesel	486	486	448	416	416	-	-	-	-	-	1599	1599	1472	1367	1367
	Parallel Hybrid Electric	504	504	481	481	449	30	30	30	30	30	1662	1662	1588	1588	1480
	Enhanced Parallel Hybrid Electric	252	252	241	224	224	1132	1132	1091	1012	1012	831	831	794	740	740
	Electric	-	-	-	-	-	2235	2235	2151	1994	1994	-	-	-	-	-

Source: Incat Crowther

Table 10 - Consumption and Emissions Estimates in Sea State Conditions of 1.2 Meters



ACTIVITY	PROPULSION TYPE	FSV CONSUMPTION / EMISSIONS TABLE ASSUMING 1.2m Hs SEA CONDITIONS														
		Diesel (l/hr)					Electric (kWhr)					CO2 (kG/hr)				
		Wave Heading (deg)					Wave Heading (deg)					Wave Heading (deg)				
		0	45	90	135	180	0	45	90	135	180	0	45	90	135	180
Underway @ 10 Knots	Tier 3 Diesel	65	65	58	58	58	-	-	-	-	-	207	207	185	185	185
	Parallel Hybrid Electric	-	-	-	-	-	267	267	236	236	236	-	-	-	-	-
	Enhanced Parallel Hybrid Electric	-	-	-	-	-	267	267	236	236	236	-	-	-	-	-
	Electric	-	-	-	-	-	267	267	236	236	236	-	-	-	-	-
Underway @ 18 Knots	Tier 3 Diesel	363	363	313	313	313	-	-	-	-	-	1190	1190	1027	1027	1027
	Parallel Hybrid Electric	376	376	325	325	325	30	30	30	30	30	1242	1242	1073	1073	1073
	Enhanced Parallel Hybrid Electric	188	188	163	163	163	886	886	769	769	769	621	621	536	536	536
	Electric	-	-	-	-	-	1742	1742	1509	1509	1509	-	-	-	-	-
Underway @ 25 Knots	Tier 3 Diesel	546	546	501	501	501	-	-	-	-	-	1795	1795	1646	1646	1646
	Parallel Hybrid Electric	533	533	519	519	519	30	30	30	30	30	1759	1759	1713	1713	1713
	Enhanced Parallel Hybrid Electric	267	267	260	260	260	1209	1209	1167	1167	1167	880	880	856	856	856
	Electric	-	-	-	-	-	2389	2389	2304	2304	2304	-	-	-	-	-

24.0 = Max speed
23.5 = Max speed

Source: Incat Crowther

When comparing Tables 8 through 10, it is clear that consumption and emissions values increase as sea state conditions worsen. Note that in Table 10, the bigger waves at 1.2m significant wave height result in worse performance by the propulsion system. In these cases, 25 knot speeds are unachievable; therefore, maximum speed is listed.

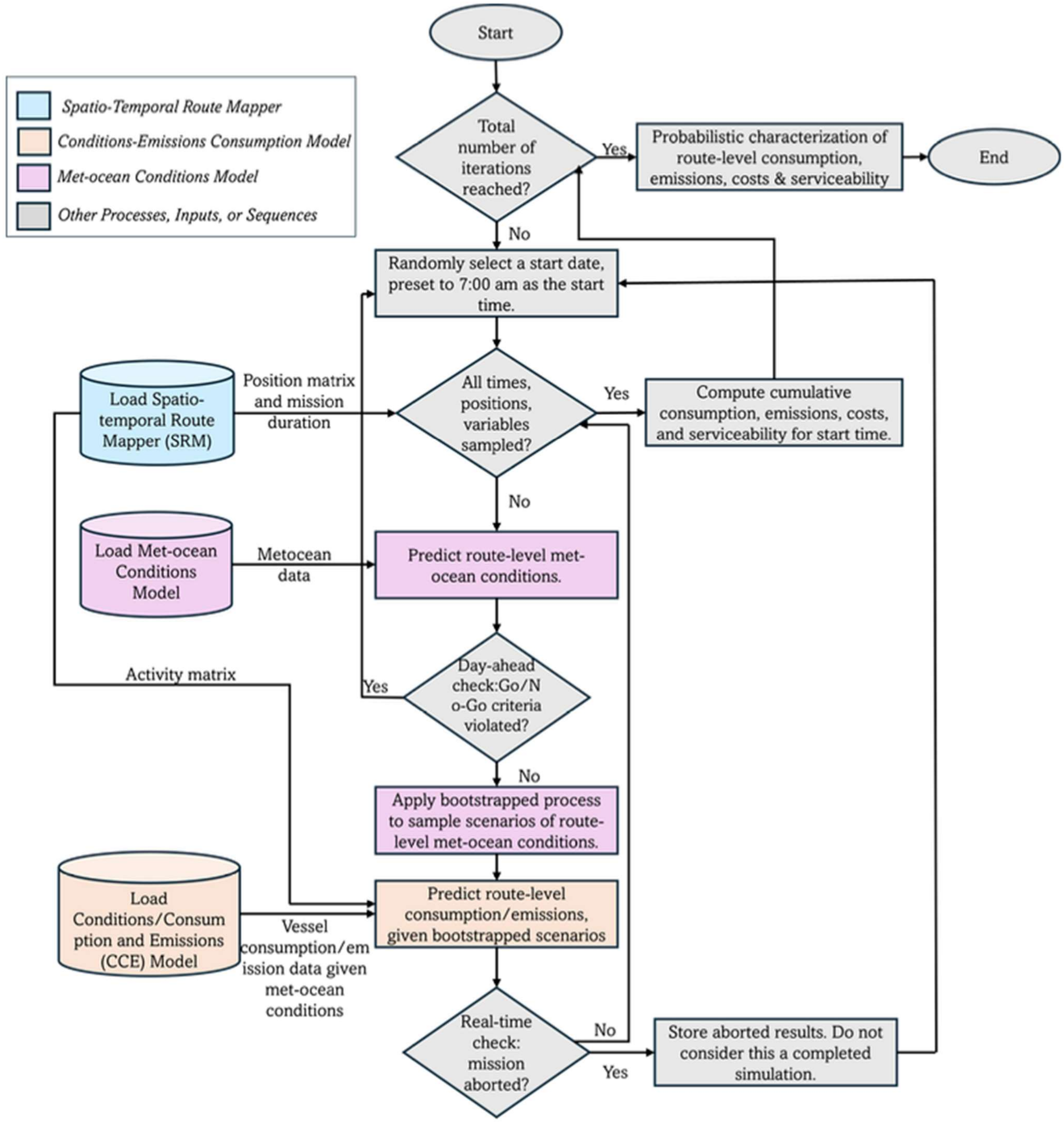
These templates were constructed to inform on how Operating Profiles and relevant outputs were to be coded into the spatio-temporal route mapper (SRM) and the conditions-consumption-emissions (CCE) model discussed in Sections 4.2.4.2 and 4.2.4.3.

4.2.4 Model Description and Function

The simulation framework comprises three components: (1) The met-ocean model (MTM), evolved from the initial sea state modeling activities conducted in the study. The MTM purpose is to realistically assess weather and sea states. It is a time series model to estimate the met-ocean conditions experienced by a vessel along its full route (from port to site and back); (2) The spatio-temporal route mapper (SRM), which is a mapping algorithm to determine the expected vessel position and activity at each hourly interval based on route-level operational profile information; and (3) the conditions-consumption-emissions (CCE) model, which is a suite of statistical models linking vessel activities and met-ocean conditions to fuel consumption and emissions for different propulsion systems. The CCE model is based on a Delphi approach to the data comprising fuel consumptions and emissions for the FSV at various speeds in various sea states (including calm water). Further work as identified in Sections 5.2 and 7.1.2 would improve model quality by substituting empirical observations for the Delphi data while adding wave period and a relative wave heading variable to condition the consumptions and emissions further.

4.2.4.1 Logic Flow Chart

Figure 18 - Simulation Model Flow Chart



Source: Petersen et al., 2025b

4.2.4.2 Met-Ocean Conditions Model (MTM)

The goal of the met-ocean conditions model (MTM) is to predict the met-ocean conditions at any location and time visited by the vessel along its full route (from port to asset and back). As shown in equation (1) from Petersen et al., 2025b, the MTM is a time series regression model, which regresses the observational data on lagged numerical model predictors and seasonal effects:

$$
\begin{aligned}
x_{i,t,m} = \theta_0 &+ \theta_1 \tilde{x}_{i,t,m} + \theta_2 \tilde{x}_{i,t-1,m} + \theta_3 \tilde{x}_{i,t-24,m} \\
&+ \sum_{k=1}^{K} \alpha_k s_{k,t} + \sum_{k=1}^{K} \beta_k c_{k,t} + \sum_{k=1}^{K} \psi_k s'_{k,t} + \sum_{k=1}^{K} \omega_k c'_{k,t} + \epsilon_{it}, \\
&\qquad \forall i \in \{1, \ldots, I\}, \quad \forall m \in \{1, \ldots, M\} \quad (1)
\end{aligned}
$$

In equation (1), $x_{i,t,m}$ is the observed buoy value for met-ocean variable m at location i and time t, whereas $\tilde{x}_{i,t,m}$ is the co-located numerical model output. The parameters θ_0, θ_1, θ_2, and θ_3 are regression coefficients for the intercept, the numerical model output and its lagged values at $t - 1$ and $t - 24$ hours, respectively. The parameters $\{\alpha_k, \beta_k\}$ and $\{\psi_k, \omega_k\}$ are coefficients for the Fourier basis terms capturing seasonal periodicity. Finally, ϵ_{it} is a zero-mean Gaussian error term with variance η. For a full discussion of this formulation, see Petersen, et al. 2025b.

4.2.4.3 Spatio-Temporal Route Mapper (SRM)

The spatio-temporal route mapper (SRM) is a mapping algorithm which determines the location and activity of the vessel at each hourly interval of its journey. The SRM takes as input the route-specific operational profile, which lists the sequence of activities carried out by the vessel along a route, their associated distances, vessel speeds, and expected durations. The SRM then processes this operational information to output two quantities: a position matrix and an activity matrix.

The position matrix encodes the expected position of the vessel at each hourly interval along the route. This information enables us to sample the met-ocean conditions at these specific locations and times using the MTM described in Section 4.2.4.2. Each entry of the position matrix is a binary value indicating whether the vessel occupies a position at a specific hour. Because operational profiles are listed based on activities that vary in durations and vessel speeds, they do not provide information on where the vessel is expected to be at every hour.

The SRM estimates the hourly position of the vessel by linear interpolation of where the vessel was in the previous hour and where it will be by the end of the current activity. This is encoded in the SRM to denote the estimated vessel position through the linear interpolation.

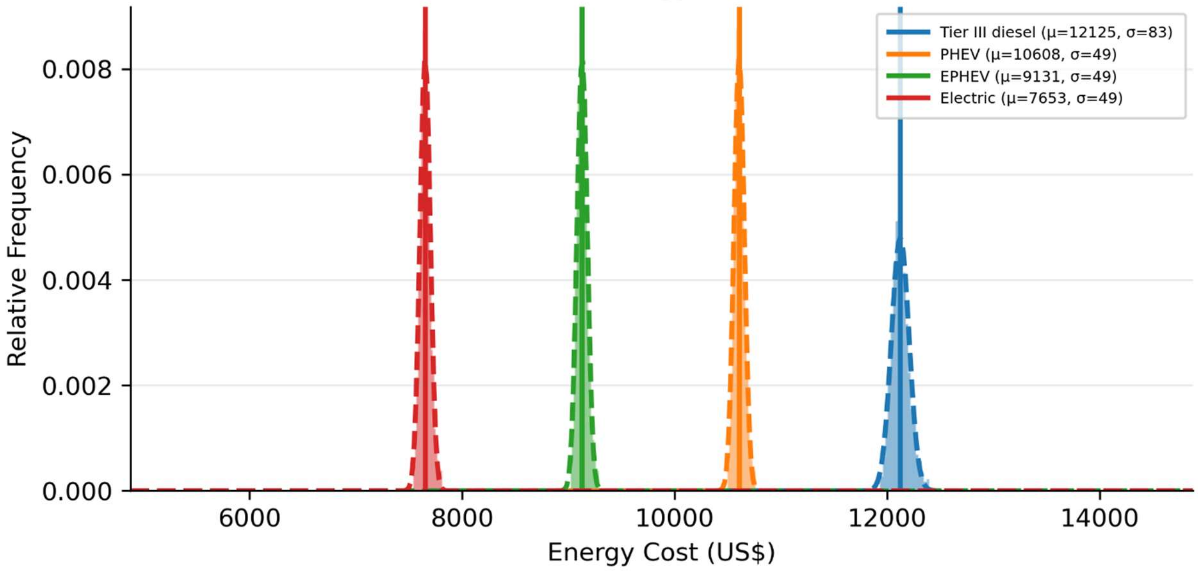
4.2.4.3 Conditions-Consumption-Emissions (CCE) Model

The goal of the conditions-consumption-emissions (CCE) model is to relate met-ocean conditions and activities to vessel consumptions and emissions. A distinct model is trained for each response (three in total: diesel consumption, electric consumption, or CO_2 emissions), propulsion system (four in total), and activity type (seven in total).

This model is seeded with a matrix of energy consumptions and emissions production for the operating profile activities conducted in varying sea states by the four different propulsion platforms. This data was derived using a Delphi approach based on the engineering experience of Incat Crowther in Tables 8 through 10.

4.2.5 Comparative Total Energy Costs by Region

Figure 19 - NECL Total Energy Cost by Propulsion Type (Full Year Sea State)



Source: Rutgers University

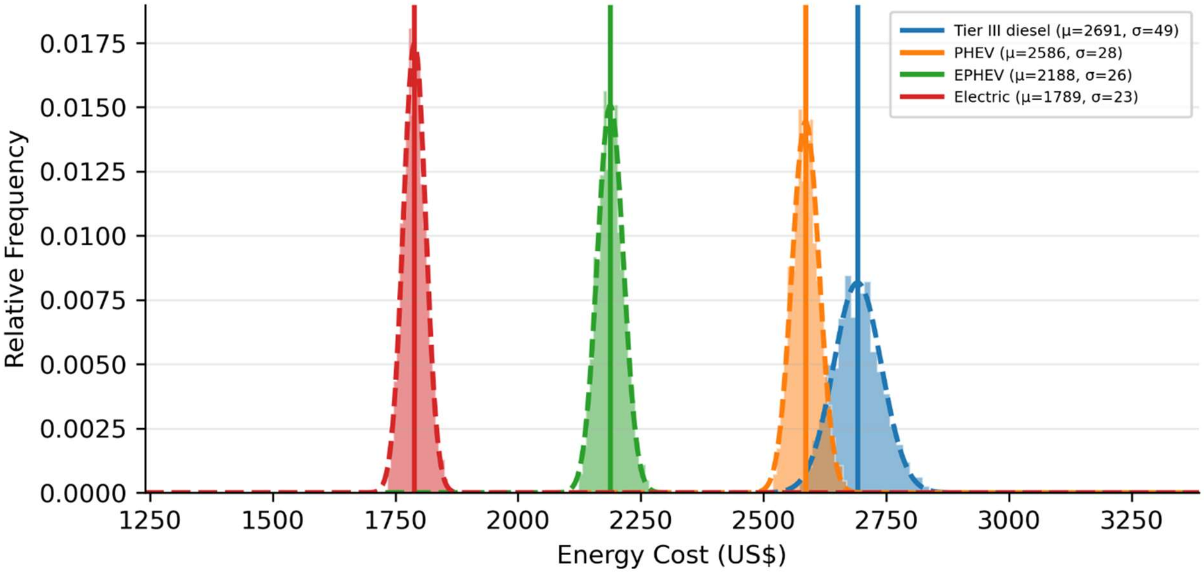
In this section, we compare total energy costs, comprised of diesel fuel at US$ 1.06/liter and electricity usage at US$ 0.16/kWh, across the four propulsion platforms. Further analysis is conducted in 4.3.1.

Energy costs displayed in Figure 19 for PHEV and EPHEV platforms in the NECL are almost entirely comprised of electricity costs since this deployment is conducted entirely at 10 knots or less, the assumed speeds where operation is electric. Only pushing at the offshore site requires conventional diesel power. Additionally, this deployment is the only one of the five studied with a multiple day engagement offshore. A 108-hour deployment consists of transit to the offshore site, three days offshore delivering technicians and gear, and transit back on the fifth day.

The figure clearly demonstrates that increasing electrification corresponds to decreasing total energy costs (from US$ 12,125 per trip to US$ 7,653 per trip).

This deployment would require a method of recharging offshore such as alongside a Service Operation Vessel (SOV) for all three electrified platforms.

Figure 20 - NYB Total Energy Cost by Propulsion Type (Full Year Sea State)

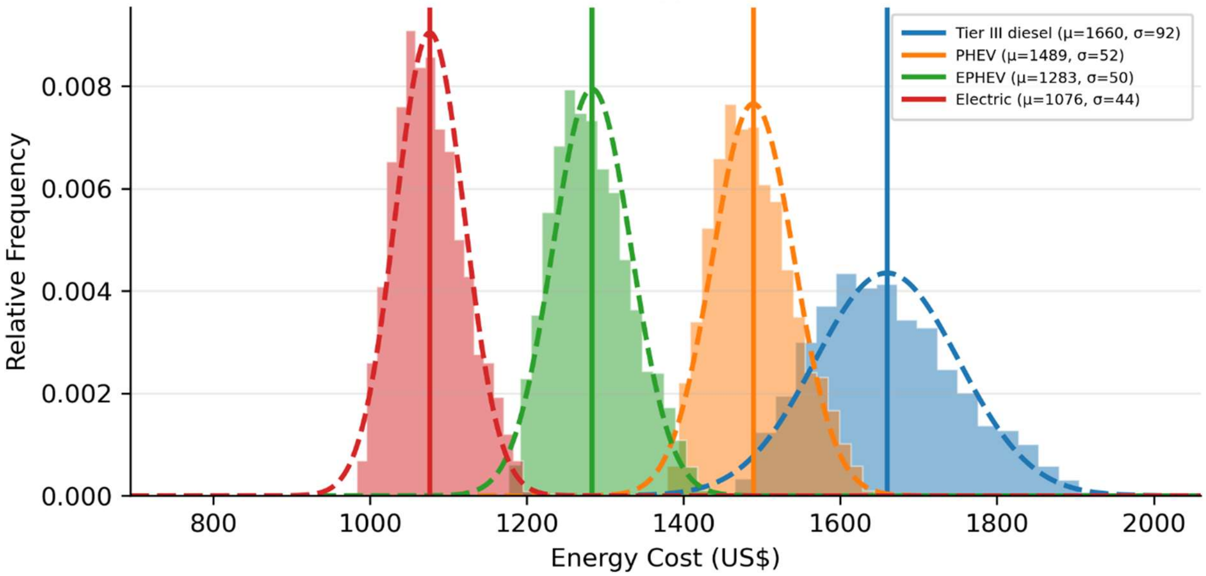


Source: Rutgers University

Noticeable in Figure 20 for NYB total energy cost is the relatively small savings from PHEV over diesel propulsion. This is due to the 15 nm leg conducted at 25 knots which represents 86% of the one-way voyage length and a larger share of total energy being provided by the diesel engines, as compared to the 10-knot transit of 2.175 nm (12%), making the PHEV platform less cost effective on this routing. The EPHEV, with additional electric motors, is able to supply some high speed transit from the motors, increasing the energy efficiency and reducing the cost of this platform.

Another observation from Figure 20 for NYB energy consumption is the relatively large variation in the Tier 3 diesel platform cost distribution (with a standard deviation almost twice that of the PHEV). This is a result of the participation of diesel propulsion in the ~ 10 knot transit segments of the voyage – for the electrified platforms this segment is assumed to be driven by electric motor. As the consumption contribution from the slower transit is added to each run result in the simulation, it will tend to skew the distribution to the left and broaden the range of the distribution since the added consumption for ~ 10 knots is below the average for the entire voyage. This can also be seen in Figure 21 for MAR energy consumption distribution.

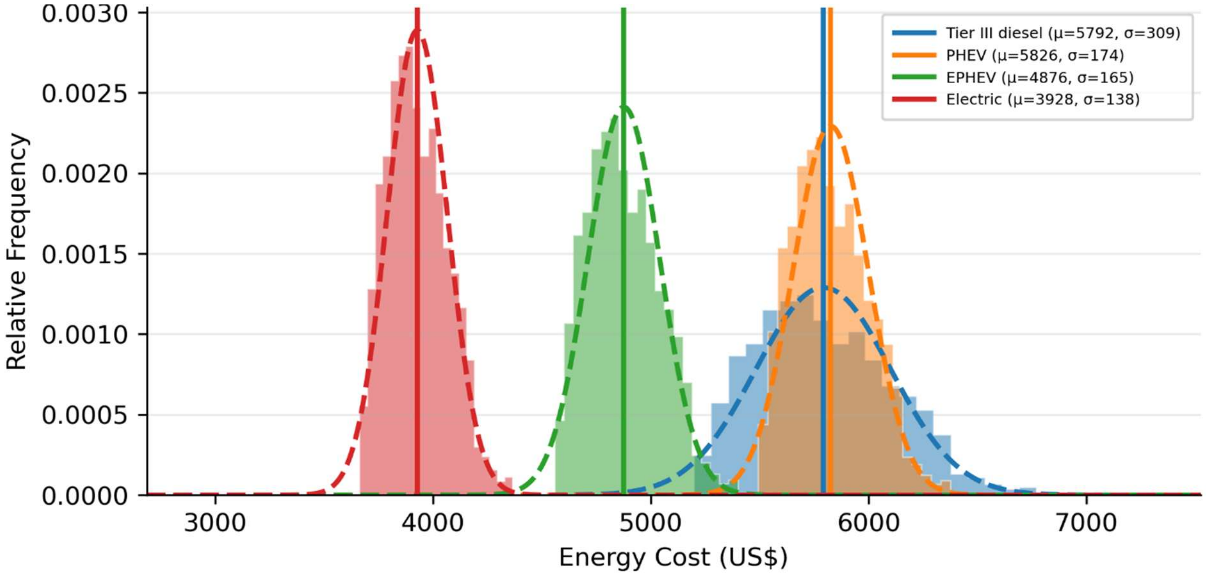
Figure 21 - MAR Total Energy Cost by Propulsion Type (Full Year Sea State)



Source: Rutgers University

The energy cost spread between the propulsion platforms is more evenly spaced for the MAR deployment with uniform increases in energy efficiency. Unlike the NYB routing, the MAR routing is balanced between 10 knot operation and high speed 25 knot operations, each at just over 24 nm. The increased variation of the diesel platform is evident.

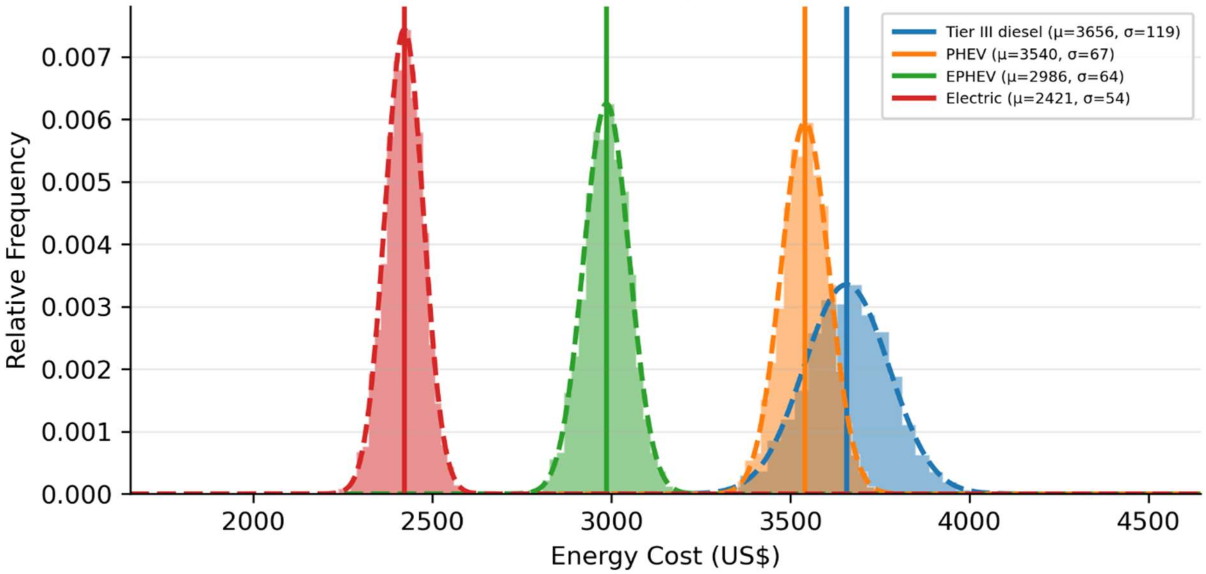
Figure 22 - GULF Total Energy Cost by Propulsion Type (Full Year Sea State)



Source: Rutgers University

On the GULF routing in Figure 22, the vast majority of the voyage time is spent at high speed, 108 nm distance versus 3.5 nm at 10 knots or under. This drives the efficiency of the PHEV hybrid down due to the prolonged run under diesel power, on par with a full diesel platform's efficiency levels.

Figure 23 - USWC Total Energy Cost by Propulsion Type (Full Year Sea State)



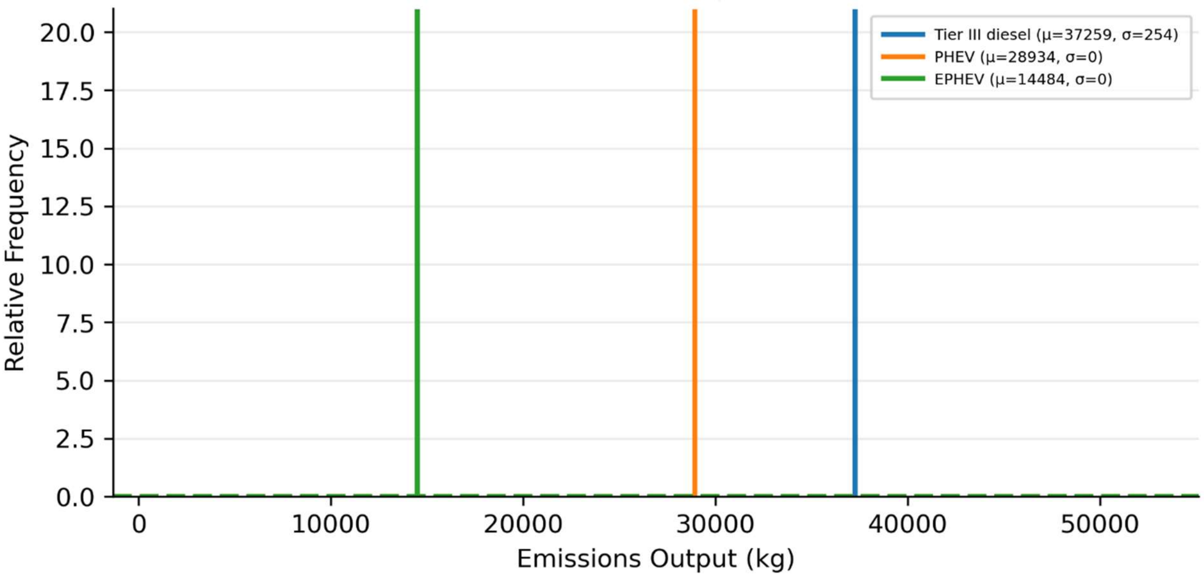
Source: Rutgers University

Again, on the USWC routing (Figure 23), the high speed distance represents the majority of the voyage which drives the efficiency of the PHEV towards the full diesel configuration, while the better equipped EPHEV is still able to generate meaningful savings on this route. While this result demonstrates the theoretical attractiveness of electrification on these routes, feasibility based on ESD technology may limit practical application.

4.2.6 Comparative Total Emissions by Region

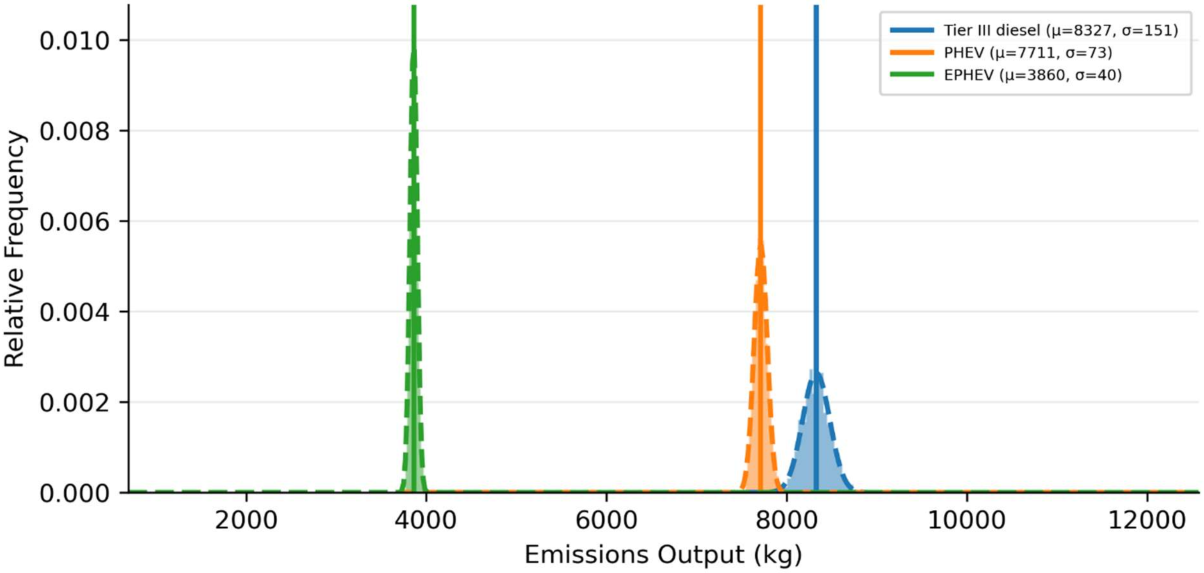
Figure 24 - NECL Total Emissions by Propulsion Type (Full Year Sea State)

This deployment is conducted entirely at 10 knots or less. The only emissions are generated by pushing at the offshore site, which is assumed a fixed consumption per occurrence and therefore with no distribution



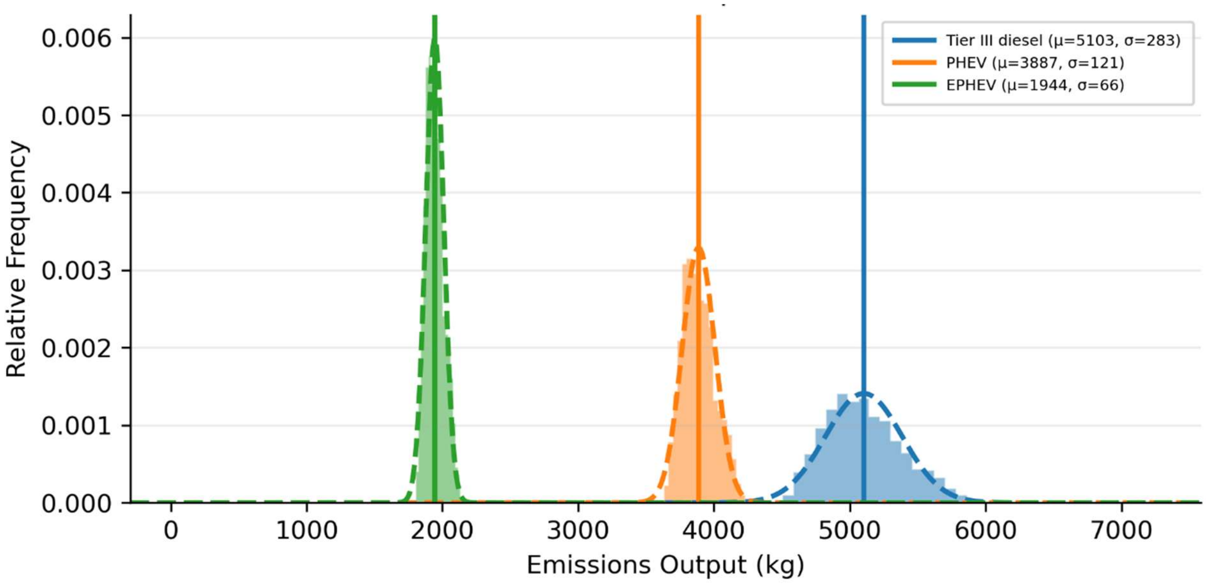
Source: Rutgers University

Figure 25 - NYB Total Emissions by Propulsion Type (Full Year Sea State)



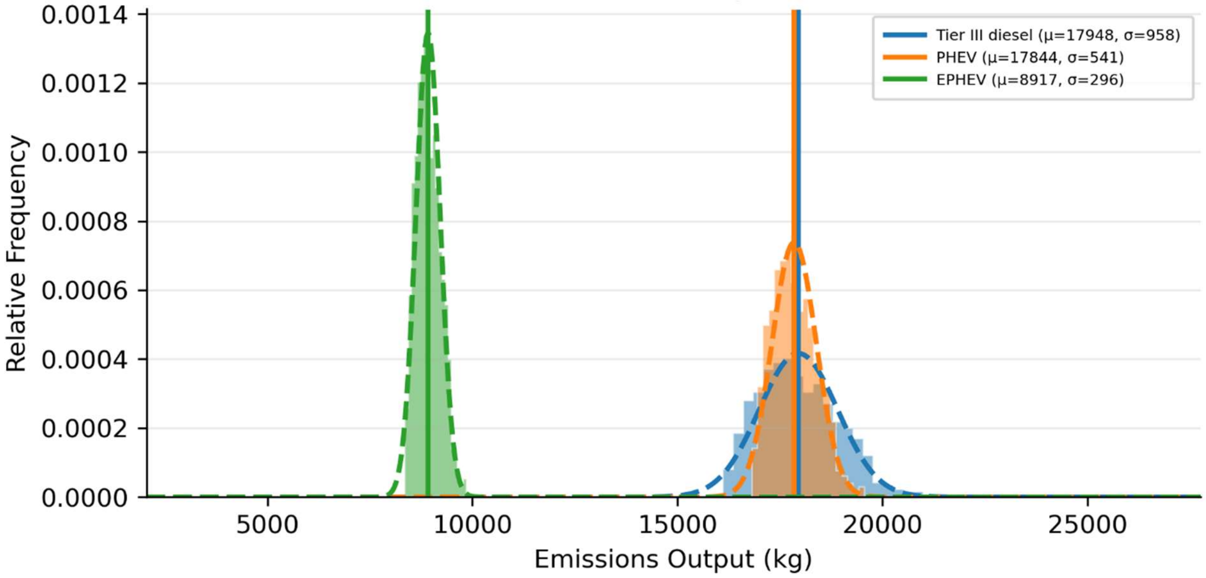
Source: Rutgers University

Figure 26 - MAR Total Emissions by Propulsion Type (Full Year Sea State)



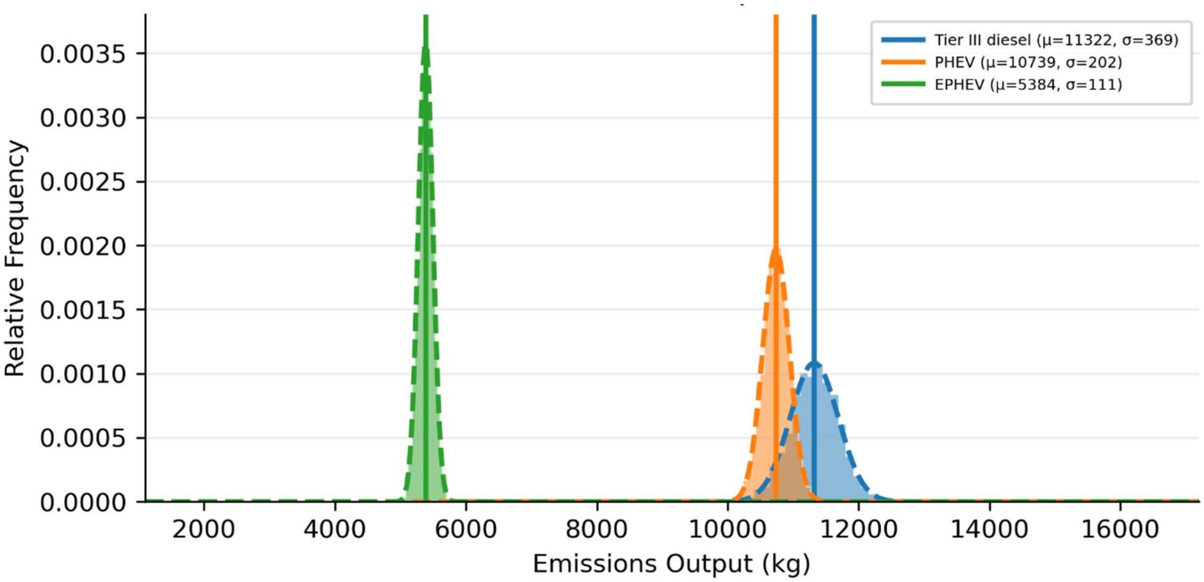
Source: Rutgers University

Figure 27 - GULF Total Emissions by Propulsion Type (Full Year Sea State)



Source: Rutgers University

Figure 28 - USWC Total Emissions by Propulsion Type (Full Year Sea State)



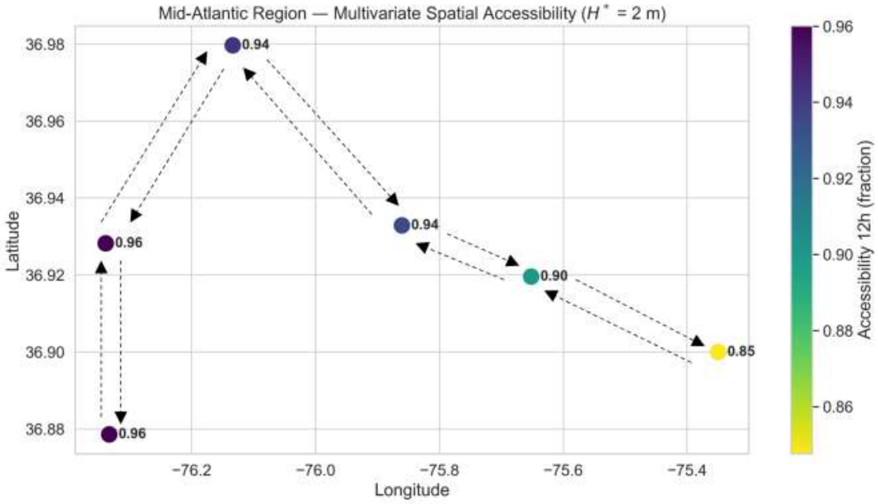
Source: Rutgers University

The emissions distributions in this section apply to only those platforms with a diesel energy component. These are the Tier 3 diesel platform, the PHEV configuration and the EPHEV configuration. The electric FSV is not shown as it produces no emissions along its operating profile. The emissions distributions of the voyages in all the regions follows closely the results of the energy consumptions in Section 4.2.5.

4.2.7 Approachability, Accessibility, and Serviceability

The existing concepts used to measure mission likelihood of completion for an FSV to complete its offshore mission (for example, transferring a technician at the turbine or offshore station) are approachability and accessibility. Approachability is defined as the fraction of time that met-ocean conditions are below their prescribed safety limits, and accessibility measures met-ocean conditions at a specific location (Petersen et al., 2025a). As the project team was working through early stages of research to account for the environmental conditions as described in Section 3.2.2.5, it became obvious that there was no method for measuring likelihood of mission completion when taking into account the entire operational route of a vessel for the whole duration of its mission.

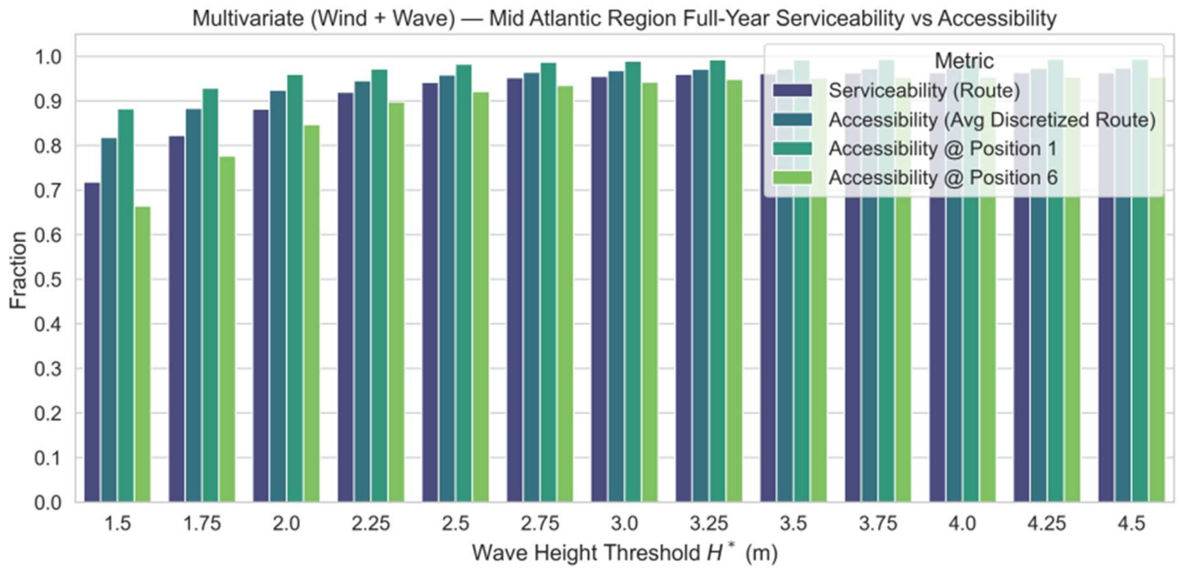
Figure 29 - Mid-Atlantic Region – Multivariate Spatial Accessibility (H* = 2m)



Source: Petersen et al., 2025a

Figure 29 shows accessibility along the vessel voyage transiting to and from the MAR according to latitudinal and longitudinal coordinates, with the bottom left corner representing the port and the lower right corner representing the offshore site. (The original representation of the charted route is seen in Figure 15.) Notice the decrease in accessibility as the vessel travels to the farthest point offshore, representing the harsher conditions it experiences.

Figure 30 - Multivariate (Wind and Wave) – Mid Atlantic Region Full-Year Serviceability vs. Accessibility



Source: Petersen et al., 2025a

Rutgers used the outputs from the Met-Ocean Conditions Model described in Section 4.2.4.2 to evaluate and compare these metrics of serviceability and accessibility (Petersen et al., 2025a). Taking into account both wind and wave conditions, Figure 30 shows accessibility in port (Position 1);

accessibility at a central point in the offshore site (Position 6); an accessibility average; and the serviceability score. At 2-meter wave height, the accessibility reading is at 0.85 annually, whereas serviceability is higher at approximately 0.88. Note that when comparing accessibility and serviceability in Figure 30, accessibility is typically a lower value, meaning that a vessel operator or project coordinator focusing solely on accessibility at the site would lead to overly conservative logistical decisions and loss of workdays since it represents a lower likelihood of mission completion (Petersen et al. 2025a). Unlike approachability, which is limited to one point in time, and accessibility, which is limited to one spatial location, the new concept of serviceability developed by this team and implemented into the simulation model accounts for dynamic spatial and temporal progression along the vessel route, therefore showing a more accurate representation of the likelihood of mission completion. Relying on the accessibility score means fewer days at sea and resulting project delays, while using the more accurate serviceability score is of greater utility to operators servicing offshore oil and gas installations and other offshore infrastructure: It identifies the likely percentage of completed missions throughout the construction and O&M phases based on weather and sea state conditions present.

When offshore project managers and vessel operators are preparing for a mission, environmental conditions are assessed to determine whether the work should go ahead as scheduled. However, even with the best planning and most up to date projections of sea state conditions, there are scenarios where the vessel leaves port but experiences harsh and unsafe conditions at sea and is forced to turn around, resulting in a failed mission. These are illustrated in the bottom of Figure 18 and referred to aborted missions. Despite the voyage being cut short, consumption of diesel fuel and electricity have occurred across all propulsion types, and CO_2 has been emitted in all cases except the fully electric platform. Since failed missions still have consumption and emissions consequences, those must be accounted for in the simulation model. Therefore, the results are stored and costs accounted for. These costs are then distributed into the final calculations of diesel and electric energy consumed and resulting emissions across all missions - both successful and failed.

4.3 Propulsion Solutions to Inform on Optimal Vessel Design

In this study our focus was on electrification as an alternative energy source for propulsion of an offshore service vessel, specifically a 32-meter, high speed aluminum catamaran Fast Service Vessel (FSV). We analyzed the total energy consumption and emissions output for four different propulsion platforms deployed on five different service routes and mission profiles in five different regions offshore the US coast. Each of the five missions' operating profiles were different in terms of the duration of time spent and distance traveled idling in port; maneuvering in port (6-knots); under slow speed transit (10-knots); on high speed transit legs (25-knots); and working or loitering offshore at the job site. Each deployment was in a different offshore region with different set of sea states and weather conditions simulated. The purpose of this exercise was to examine the performance of the four platforms in terms of total energy consumption and emissions output during the missions as defined by the specific operating profiles. From this examination we observed comparative energy consumption and emissions output performance to inform on optimal vessel design. The outcomes of this analysis are summarized in Sections 4.3.1 – Simulation Analysis and 4.3.2 – Validation of First BOT Hypothesis.

4.3.1 Simulation Analysis

In Sections 4.2.5 and 4.2.6, simulation results for total energy consumption and emissions output are illustrated, comparing the distributions for each of these variables on the same graph for each region. The results in general are as expected – as the level of propulsion platform electrification increases, the total energy cost and total emissions declines. Recall we assumed a fixed rate for diesel fuel at US$ 1.06/liter and electricity at US$ 0.16/kWh. As these rates change relative to one another, the results displayed in the graphs will vary.

Noticeable from the figures is the relatively small improvement in energy costs and emissions reduction achieved by the PHEV platform over the diesel platform, in some regions like the GULF and USWC savings are effectively zero. This is due to the large percentage of the time spent on the voyage in energy intense, high speed operation. This highlights the challenge with the FSV vessel type and its typical deployment. High speed transit is an extremely energy intensive activity and both these routes are comprised mainly of long distance, high speed transit legs. The GULF operating profile contains two 108 nautical mile (nm) transits to/from the offshore site at high speed while the USWC route has two 48 nautical mile transits at high speed. The other routes have nominal high speed legs (NYB-15 nm, MAR-24 nm, NECL-0 nm).

In Table 11 the mean total energy costs are summarized for each propulsion type in each region on a per trip basis and a per year basis assuming 300 days per year with the monetary benefit of the electrified platforms over diesel included.

Table 11 - Mean Total Energy Cost by Region and Propulsion Platform per Trip (US$)

		TIER 3	PHEV	EPHEV	ELECTRIC
Per Trip	NECL	12,125	10,608	9,131	7,653
	NYB	2,691	2,586	2,188	1,789
	MAR	1,656	1,487	1,282	1,075
	GULF	5,792	5,826	4,876	3,928
	USWC	3,656	3,540	2,986	2,421
		TIER 3	PHEV	EPHEV	ELECTRIC
Per Year	NECL	727,500	636,507	547,849	459,191
	NYB	807,419	775,681	656,334	536,659
	MAR	496,908	446,173	384,462	322,487
	GULF	1,737,600	1,747,800	1,462,800	1,178,400
	USWC	1,096,800	1,062,000	895,800	726,300
			PHEV	EPHEV	ELECTRIC
Annual Benefit Over Diesel	NECL		90,993	179,651	268,310
	NYB		31,738	151,085	270,760
	MAR		50,736	112,447	174,422
	GULF		(10,200)	274,800	559,200
	USWC		34,800	201,000	370,500

Source: Rutgers University

As seen in Table 11, the greatest benefit of electrification comes from the most difficult voyages as identified above, the GULF and USWC deployment. However, technology limits (ESD) likely prevent electrification for these deployments for some time to come. Note that in the table, the total benefit of the PHEV platform over diesel in the GULF deployment is negative – this is a consequence of the probabilistic nature of the result and the use of the mean of the distribution of energy cost as a proxy for total energy consumption. Because of the characteristics of the voyage PHEV total energy costs can be considered about the same as the Tier 3 diesel configuration.

Table 12 - Mean Total Emissions By Region and Propulsion Platform (kg CO_2)

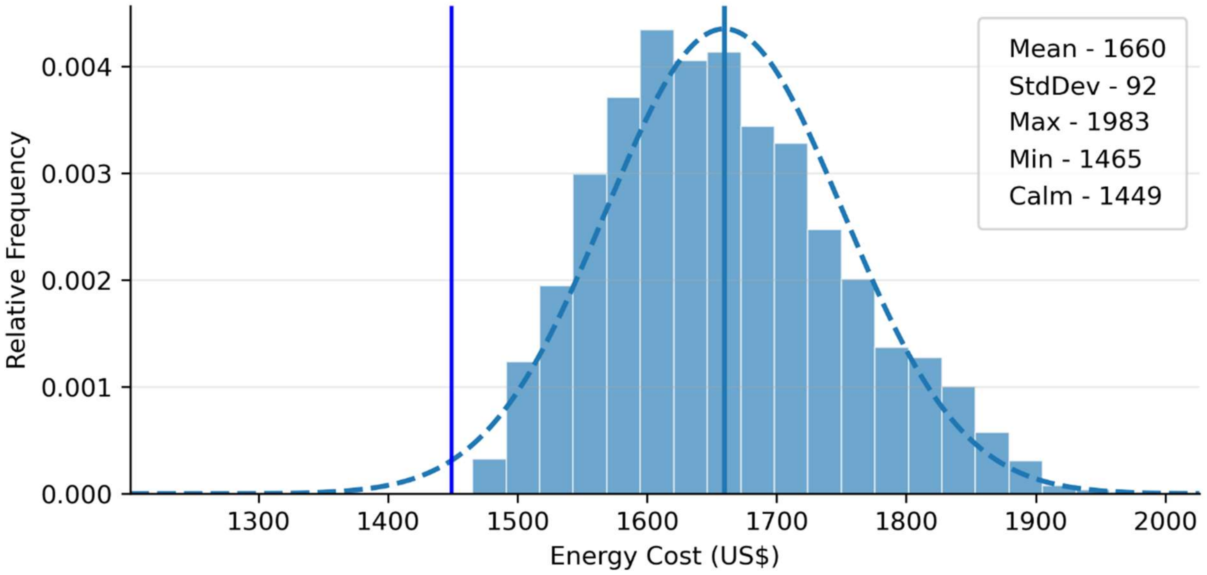
		TIER 3	PHEV	EPHEV	ELECTRIC
Per Trip	NECL	37,259	28,934	14,484	0
	NYB	8,327	7,711	3,860	0
	MAR	5,093	3,881	1,941	0
	GULF	17,948	17,844	8,971	0
	USWC	11,322	10,739	5,384	0
		TIER 3	PHEV	EPHEV	ELECTRIC
Per Year	NECL	2,235,536	1,736,040	869,040	0
	NYB	2,498,218	2,313,404	1,157,961	0
	MAR	1,527,862	1,164,319	582,303	0
	GULF	5,384,400	5,353,200	2,691,300	0
	USWC	3,396,600	3,221,700	1,615,200	0
		TIER 3	PHEV	EPHEV	ELECTRIC
Benefit Over Diesel	NECL		499,496	1,366,496	2,235,536
	NYB		184,814	1,340,257	2,498,218
	MAR		363,543	945,559	1,527,862
	GULF		31,200	2,693,100	5,384,400
	USWC		174,900	1,781,400	3,396,600

Source: Rutgers University

Emissions output (Table 12) follows the same pattern where deployments with the greatest high speed transits see the greatest emissions reductions through electrification.

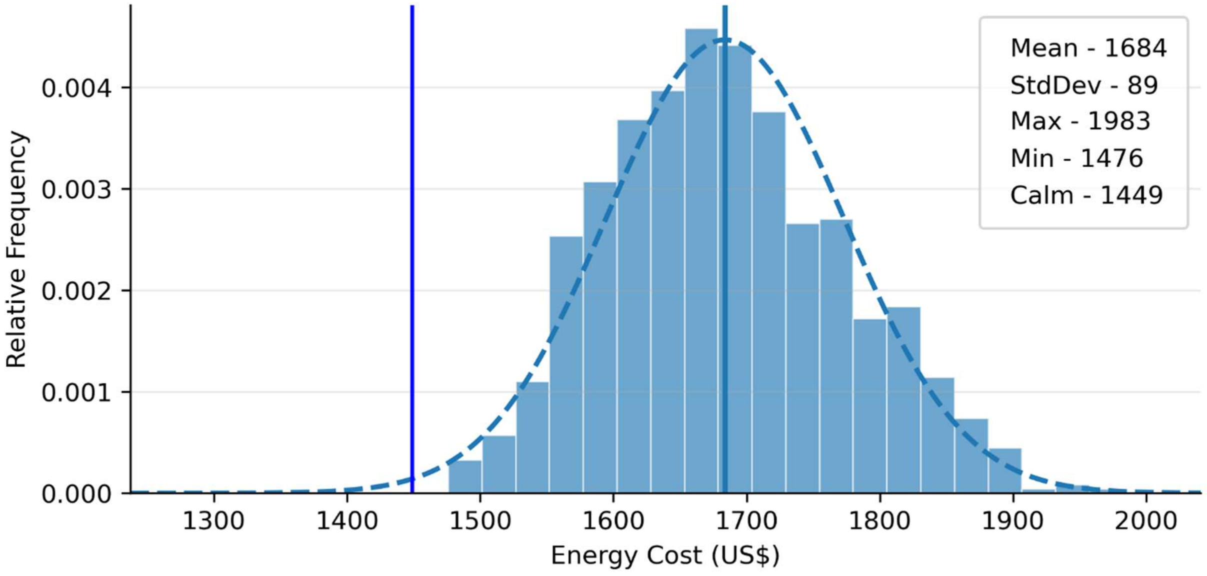
A review of seasonal consumption figures reveals no surprises - MAR full year, winter and summer seasonal diesel consumptions are illustrated in Figures 31 through 33. As expected, winter seasonal simulation results indicate the highest consumption levels, summer season the lowest with full year results falling in between. Appendix 3 illustrates Tier 3 diesel platform season results across regions. Using winter seasonal results to inform on vessel propulsion system design will be the prudent approach to the specification of a new vessel.

Figure 31 - Total Diesel Consumption distribution – MAR (Full Year Season)



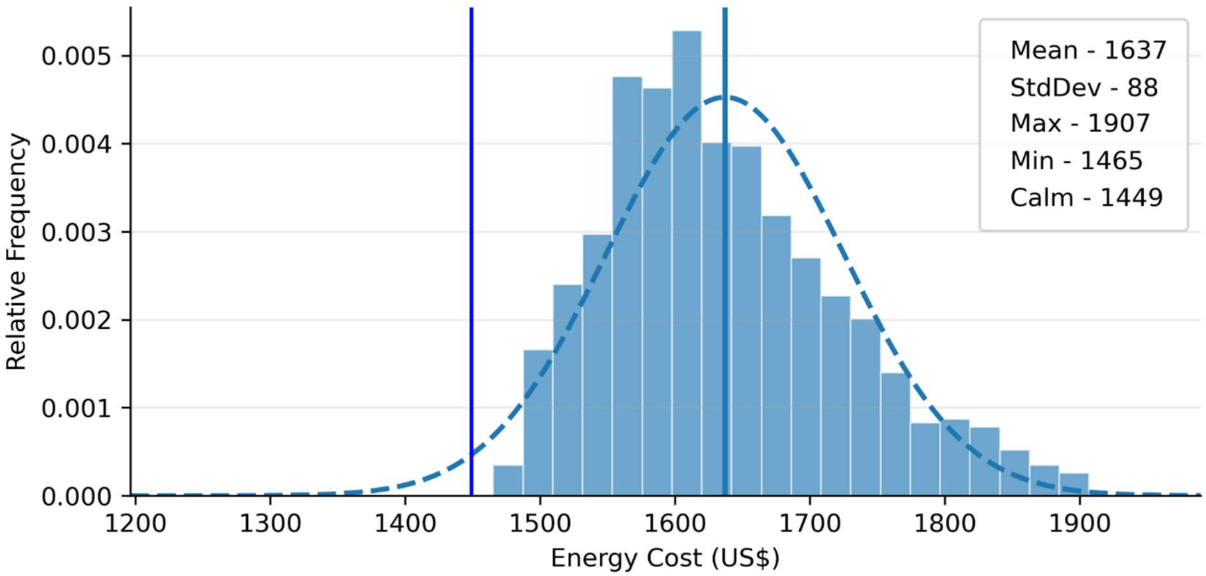
Source: Rutgers University

Figure 32 - Total Diesel Consumption Distribution – MAR (Winter)



Source: Rutgers University

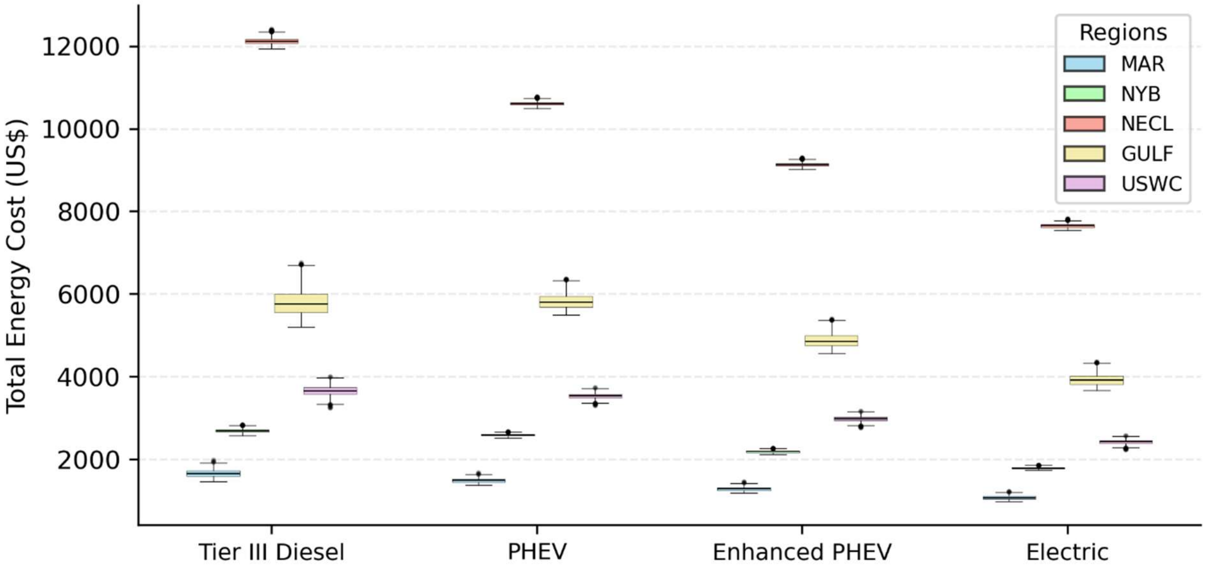
Figure 33 - Total Diesel Consumption distribution – MAR (Summer)



Source: Rutgers University

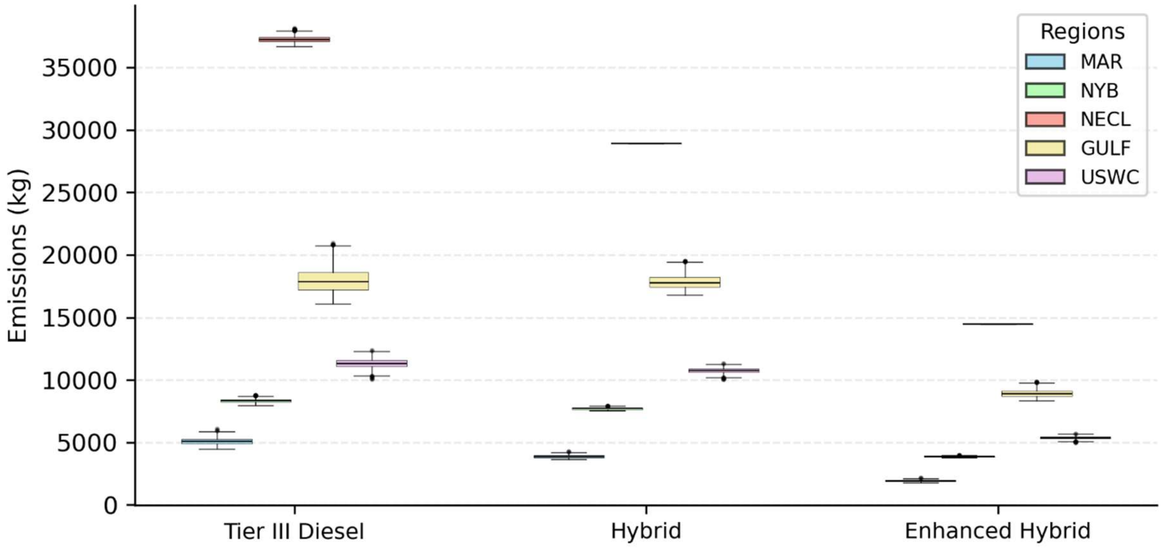
Figures 34 and 35 display distributions for total energy cost and emissions for each propulsion platform across five regional deployments. From these figures it is evident that energy costs decline as electrification increases (left to right on the graph). We can also surmise that the deployments with a large majority of the trip represented by high speed, high energy intense transits (GULF, USWC) benefit the most from electrification on a theoretical basis at the energy pricing for diesel fuel and electricity used in the study. Energy storage density improvement trajectories will determine when actual deployments are feasible.

Figure 34 - Total Energy Cost Across Vessel Types & Regions



Source: Rutgers

Figure 35 - Total Emissions Across Vessel Types & Regions



Source: Rutgers

4.3.2 Validation of First BOT Hypothesis

In Section 2.2 we advised our first hypothesis considered in the study was that consideration of dynamic sea state and weather conditions would yield more meaningful design parameters for high speed aluminum catamaran offshore support vessels. The four figures in Section 4.3.1 illustrate the difference in energy consumptions from a calm water evaluation as compared to a dynamic sea state for an FSV deployment in the MAR. Additional figures in the appendix illustrate this difference in the other regions studied.

We conducted a statistical significance test with a 95% confidence level of dynamic sea state results versus calm water results for total energy costs for the four different propulsion platforms to prove or disprove our hypothesis. The results of this test are summarized in Table 13. For every propulsion platform, there is a statistically significant difference between total energy cost based on the dynamic environmental conditions modeled in the simulation as compared to the calm water total energy costs, as shown by the p-value results of approximately 2%, below a 5% significance level in Table 13.

Table 13 - Total Energy Cost for Four FSC propulsion Platforms Calm vs. Dynamic Sea States (US$)

		Model Results			
Vessel	Calm Water Value	Mean Hs	Std Dev	z-score[1]	p-value[2]
Tier 3 Diesel	1449	1660	92	2.29	(0.0218)
PHEV	1364	1483	52	2.29	(0.0221)
EPHEV	1153	1266	49	2.31	(0.0211)
Electric	950	1048	43	2.28	(0.0227)

Source: Rutgers University

4.3.3 Current Marine Electrification State-of-Play

4.3.3.1 Existing Electrified Platforms Similar to an FSV

To date, there are numerous examples of hybrid electric platforms either in the stages of advanced design and implementation or on the water servicing current offshore energy and other projects. A particularly large concentration of these vessels is located around the European continent and far east supporting offshore wind and similar energy projects. There are a few underlying factors to this result driven by the fact that these areas maintain a more established offshore wind and renewable energy industry to where there have been numerous ports and shoreside facilities developed to support offshore sites with advancements made to infrastructure both ashore and at sea. Unlike ships trading between continents via ocean transits to varying ports, the offshore energy industry provides vessel owners and operators more visibility about what the vessels will be doing when they leave port. Offshore site locations are known and therefore so are the distances to the offshore sites and transit times. Schedules are often governed by 12- or 24-hour shifts to where the vessel is deployed accordingly to change out offshore personnel and fuel/charge for the next days' operations.

This allows operators to better understand their vessel energy consumption requirements for the voyage ahead and in turn can better design and introduce electrification and hybrid power systems to their vessels. Examples of technology currently in use include the following along with various partnerships formed between vessel operators and their propulsion and marine engine manufacturers to develop advanced hybrid and electric platforms able to support the vessels mission profile.

4.3.3.1.1 Hybrid Ready Designs (HYRD) – US Based

Five hybrid ready 30-meter crew transfer vessels have been designed by Incat Crowther and are currently servicing the US offshore wind industry owned and operated by way of a joint venture between Windea and Hornblower called WINDEA CTV LLC (WINDEA, 2024). "Hybrid ready" is

---

[1] A z-score measures how many standard deviations a specific data point is above or below the mean.

[2] A p-value (probability value) is a statistical measure ranging from 0 to 1 that helps determine if research results are statistically significant. It calculates the probability of obtaining evidence at least as extreme as the observed results, assuming the null hypothesis is true. A smaller p-value (<0.05 at 95% confidence level) indicates stronger evidence against the null hypothesis, suggesting results are likely not due to chance.

commonly used to describe a vessel with spaces to accommodate hybrid systems and equipment at a future date.

Three 27-meter and two 29-meter hybrid ready crew transfer vessels have been designed by BMT and are currently servicing the US offshore wind industry owned and operated by Windserve Marine. These vessels, all launched between 2023 and 2025, join the companies' original and first built CTV - the 20-meter Windserve Odyssey delivered in 2020, not incorporating hybrid or future proof planning at the time (BMT, 2025).

Four hybrid ready 30-meter crew transfer vessels have been designed by European CTV operator Northern Offshore Services (NOS) and are currently servicing the US offshore wind industry under NOS' recently established Jones Act operating arm American Offshore Services (AOS, n.d.).

4.3.3.1.2 Parallel Hybrid Electric Vessel (PHEV)

As of 2021, MHO-Co of Denmark have built and currently operate two Parallel Hybrid Electric Crew Transfer vessels – M/V's MHO-ASGARD & MHO-APOLLO, both designed by Incat Crowther. The vessels' power and propulsion packages consist of four Volvo IPS 30 propulsors driven by a series of (2) Volvo D13 diesel engines inboard working alongside (2) Danfoss Editron electric motors outboard. These e-motors are supported by a series of (5) Volvo D8 Generators and a 284 kWh battery package. The parallel system allows the electric motor and combustion engine to work in tandem to optimize performance and fuel efficiency providing for operation on electric motors alone for low-speed/zero-emission operation (up to ~8 hours) or using the diesel engines for higher speed transit and power demand. These vessels were designed specifically for work in the North Sea and surrounding areas (MHO-Co, 2023).

WINDEA ONE is the world's first Crew Transfer Vessel to utilize Volvo Penta's latest parallel hybrid system together with IPS propulsion and being able to operate in an all-electric mode for up to six hours by way of integrating Volvo's battery and electric motor integration. This vessel, launched in 2023 will be servicing the offshore wind industry of Germany and is propelled by a suite for four IPS 30 drives powered by four Volvo Penta D113 main engines producing 690 HP at 2,2500 RPM (Incat Crowther, 2023; Incat Crowther, n.d.).

As of March 2023, LD Tide, the joint venture company formed between Louis Dreyfus Armateurs and Tidal Transit welcomed its third and final CTV to their marine spread servicing France's Saint-Nazaire offshore wind project supporting the efforts of EDF Renewables and General Electric. The CTV CAPTL'VENT joined the sister vessels INNO'VENT and MOTL'VENT where two of the three vessels contain a hybrid electric propulsion package with one operating as hybrid-ready and able to accept a machinery package upgrade to hybrid propulsion some time in the future (Foxwell, 2023). The initial vessel of this series was the first crew transfer vessel to be designed and manufactured in France by MAURIC, a French naval architect based in Nantes and built by the French builder OCEA with a yard location in Les Sables d'Olonne. Hybrid vessels include both battery systems as well as afoil technology geared to reduce fuel consumption and improve performance combining for a reduction of CO2 emissions by approximately 15% (Foxwell, 2023; LD Armateurs, 2022).

4.3.3.1.3 Serial Hybrid Electric Vessel (SHEV)

In 2024, MHO-Co of Denmark commissioned and launched a pair of state-of-the-art Serial Hybrid Electric Crew Transfer Vessels – M/V's MHO-BALDER & MHO-BOREAS. The vessels build on the company's success in advancing the hybrid vessel designs of their M/V's MHO-ASGARD & MHO-APOLLO where they have been designed to handle high speed transit while offering low-emission or zero-emission idling and maneuvering, reducing fuel consumption and CO2 emissions while also enabling zero emission operation for up to eight hours while in fully electric mode.

The vessels' power and propulsion packages consist of four Volvo IPS 30 propulsors driven by a series of (8) Volvo D8 diesel generators accompanied by (8) Danfoss power packs driving (4) Danfoss Editron electric motors. The e-motors and propulsors are supported by a suite of (4) Dolphin 4 x 94kWh batteries with a designed working life expectancy of 10 years. These vessels of 36m in length have been deployed to offshore energy sites in and around the North Sea (MHO-Co., 2022).

4.3.3.1.4 Fully Electric Vessel

Understood to be the world's first fully electric crew transfer vessel, the M/V E-GINNY, has been converted to a fully electric platform via an all-electric retrofit commenced in 2024 by the vessel's owner Tidal Transit. The vessel, which was expected to be trialed in 2026, will be equipped with a quad Volvo IPS system powered by 3.45MWh Corvus Batteries. The vessel will support offshore wind energy projects in Europe and is being used to further advance the state of offshore and onshore charging stations that will allow the vessel to charge directly from the offshore wind turbines themselves (Tidal Transit, 2026).

4.3.3.1.5 Offshore Charging Technologies

To capture the inherent benefits of electrified offshore service vessels, accessible offshore charging systems are critical. Like vessel development, offshore charging system infrastructure development is primarily made up of ideas, tests and trials at present. However, some pilot projects such as Parkwind's 8-megawatt charging station in the Belgian North Sea as well as Oasis Marine's buoy charging system have been established.

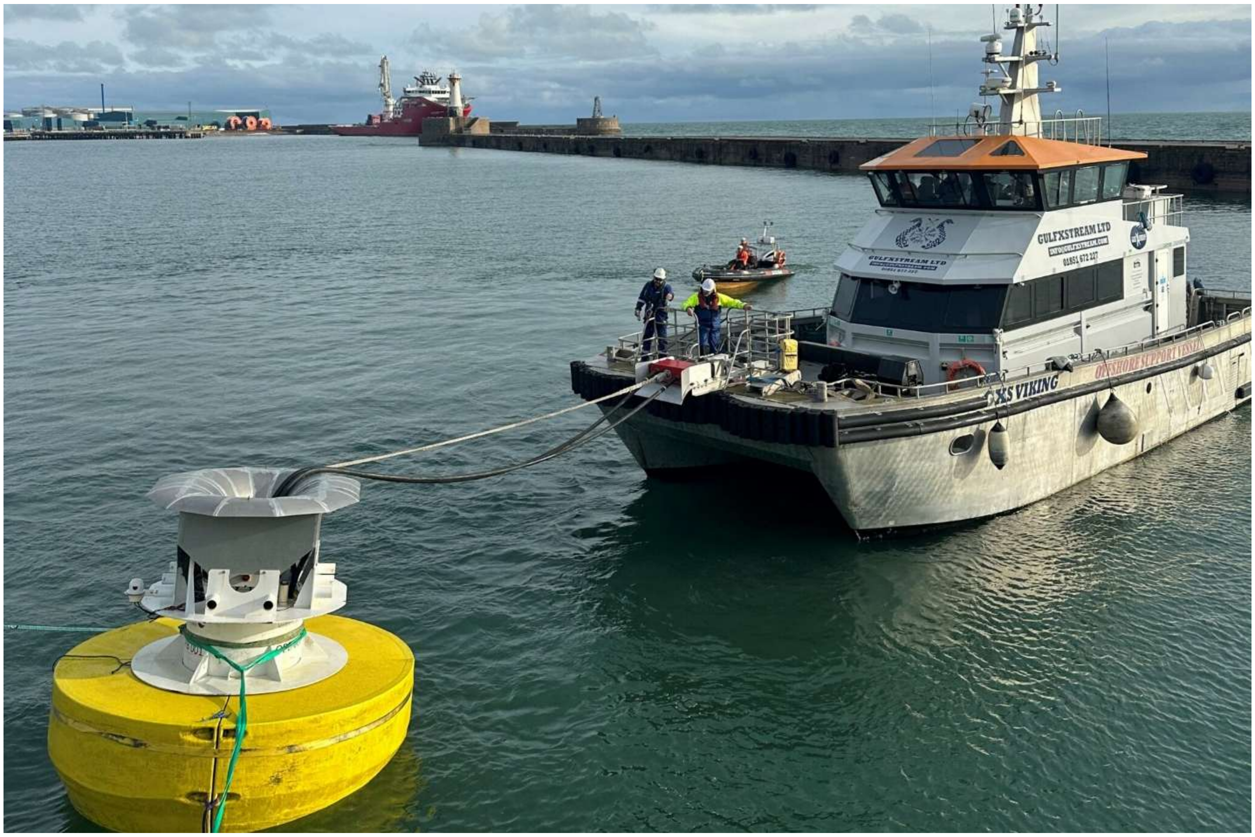
In 2024, the Parkwind offshore wind project commissioned a wind powered electric charging station connected to the offshore wind field's offshore substation capable of providing at its maximum output a total of 8 MW of charge to various offshore vessels working on the project from crew transfer vessels to service operations vessels which are outfitted with hybrid and/or electric power systems (Puttkamer, 2024).

Figure 36 - Parkwind CTV Charging Trial

Source: Puttkamer, 2025; Parkwind

Also in 2024, the UK based firm Oasis Marine, commissioned and tested their project called the Oasis Power Buoy which serves as a mooring and charging station for crew transfer vessels capable of working in offshore energy project settings. The success of this achievement paves the way for electrified vessels working in the offshore energy industries while also reducing maritime related emissions by expanding vessel charging capabilities beyond port and harbor settings. To date, successful testing of both the charging and mooring elements of this buoy system have been completed with positive results. As of 2025, Oasis Marine embarked on a study with ScottishPower to further understand the feasibility of offshore charging in this manner. Study findings suggest that the electrification of offshore operations was technically feasible, with the potential for reduced energy consumption and a reduction in emissions (Oasis Marine, 2024; Oasis Marine, 2025).

Figure 37 – Charging at the Sea Buoy



Source: Oasis Marine, 2025

In use to varying degrees, although not on a commercially viable scale thus far, these charging projects have been primarily focused around offshore wind energy projects.

4.3.3.2 Electrified Vessels in the US

In the research of electrified vessels of all types in the US, we notice that the most suitable applications are those with predetermined routes that operate near shore and have frequent charging availability. For example, ferries favor electrification because they shuttle between ports and can rapidly charge while passengers are embarking and disembarking. Two of the notable electrified ferries in 2025 are the newbuild Harbor Charger, providing lower-emission service to Governor's Island in New York Harbor, and the retrofit Wenatchee, operated by Washington State Ferry and providing service between Bainbridge Island and Seattle. Ferries are also notable as early adopters of electrification with examples in Hornblower's Alcatraz Clipper and Alcatraz Flyer, refit to hybrid electric propulsion in 2011 and 2012, respectively (Baker, 2024).

We have identified several dozen commercial vessels with electrified propulsion either operating, under construction, or planned in the US, ranging from small patrol boats to large ferries and research vessels. Overall categories are shown in Table 14 with further details are found in Appendix 2.

Table 14 - Electrified Vessels in the US – Operating, Under Construction, or Planned
Note: The Planned and Retrofit columns may overlap as some existing vessels are planned upgrades.

	Operating	Under Construction	Planned	**Total identified:**	New Build	Retrofit
Ferries	9	3	44	**56**	33	23
Service operation vessel	1	0	0	**1**	1	0
Lightering support vessel	0	1	0	**1**	0	1
Research vessels	4	4	0	**8**	8	0
Ocean sampling vessel	0	0	1	**1**	1	0
Tug and tow boats	3	0	10	**13+**	10	3
Tour boats	3	1	0	**4**	4	0
Fishing boats	1	0	2	**3**	0	3
Patrol boats	0	0	2	**2**	2	0
Other workboats	1	TBD	TBD	**1**	1	0

Source: BOT

Ferries represent large numbers of electrified vessels in all categories of operating, under construction, and planned. Ferries are good candidates for electrification because of their predicable routes and voyage times with downtime for charging in between each mission. This may also be due to their location in dense port communities and compliance with state entities such as the California Air Resources Board.

In contrast with ferries that have existing charging infrastructure onshore (and predictable charging times in between voyages), offshore vessels such as FSVs modeled in this paper would not readily have access to charging once they leave shore. Given the present state of ESD limits and capability of onshore but not offshore charging, vessels would prioritize full zero-emission battery usage when traveling in port or idling, and in 10-knot restricted speed zones in coastal areas. For large research vessels with electrified propulsion, use of the batteries will likely be prioritized in port and during slow transits, the latter where research work can be carried out under conditions of less noise and vibration.

It is often the case that newbuild vessels, as well as retrofits, have received funding from federal, state, and other sources to pursue electrification and promote lower emissions, especially in dense port communities in major cities. However, some owners are noticing the benefits of investment in electrification and are independently funding without government and other incentives or subsidies. This is seen in the case of eight ship assist tugboats being developed between Arc Boats and Curtin Maritime that will serve the West Coast, with a $160 million private investment (Hayden, 2025c). The team emphasizes cost competitiveness with the diesel counterpart vessels, highlighting similar acquisition costs for hybrid versus diesel propulsion, and further saving in fuel, maintenance and compliance in the long term when using electrified propulsion systems (Hayden, 2025c). This example aligns with our second hypothesis that electrified vessels can be more cost effective and with a lower carbon footprint than diesel counterparts.

4.3.4 Summary of Findings & Observations to Inform on Optimal Vessel Design

Total energy costs and emissions production vary greatly across the different regions and vessel deployments evaluated in the study.

The energy consumption and emissions figures calculated point to a clear trend of increasing energy efficiency, lower energy costs and reduced emissions with increasing electrification of the propulsion system, on less energy-intense deployments.

Industry experience to date related to electrification of propulsion systems indicates that there is significant and growing activity towards the construction and modification of vessels to increase electrification. This activity applies in the majority to transport situations in near-coastal areas and in harbors where transits are shorter, speeds are lower, and regular access to charging is available.

Vessel deployments with long high speed legs representing a larger proportion of the operating profile tend to reduce the efficiency of the electrified platforms because a majority of the energy required comes from the diesel engines. Regions and vessel deployments with shorter high speed legs show the greatest efficiency gains from electrification.

In this study, even with the benign weather conditions in the US Gulf, the long, the high speed transit legs drive efficiency of hybrid platforms down. Knowing that energy storage density is a factor in electrification, a look at the total power required for a long high speed transit such as the GULF region or even the USWC reveals a factor of 5x and 2x respectively for the additional power requirements over the MAR site, for example.

Based on examination of the five regions and routes in this study, and the energy consumptions and costs associated with each, it is evident that the routes with longer high speed transits and representing a greater proportion of consumption and cost, are less favored for electrification. Indeed, certain voyages may remain infeasible well into the future, beyond the 10-year timeframe assumed in this study. In the case of the regions evaluated in this study, the GULF and USWC likely fall into this category.

FSV deployments with shorter duration high speed legs represent high potential applications of propulsion system electrification from an energy efficiency standpoint with added benefits of significantly reducing emissions output on these deployments. This would represent an expansion of currently considered deployments. In this study, the NECL, NYB and MAR are representative of these operating profiles.

4.4 Propulsion Electrification Design Concept in Cadence with Technology Advancements

4.4.1 Summary

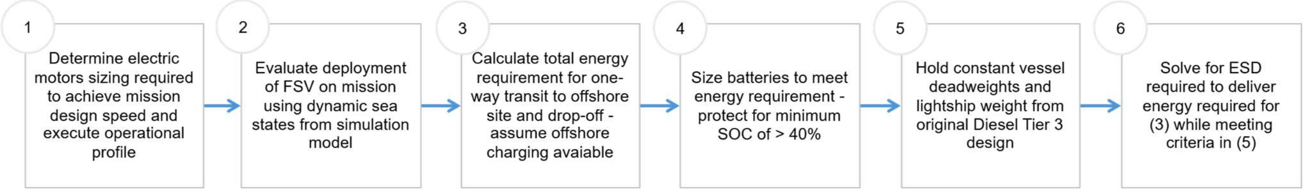
The third objective of this study was to propose a hybrid electric propulsion systems design concept that could be built today with currently available equipment and evolve into a fully electric configuration in cadence with technological advancements over a 10-year period. The challenge in this case was to devise a vessel design and step-by-step evolution from diesel-driven to fully electric in a cost effective and increasingly beneficial manner. Recognizing that minimizing capital costs during this evolution highlighted the path forward, the objective is to use the same vessel over the period of 10-years, updating only the relevant propulsion components necessary in a step-by-step fashion for the systems evolution towards electrification. In this way, the cost of expensive new vessels for each stage in the electrification evolution can be avoided, dramatically enhancing the attractiveness of full electrification over time. Our hypothesis was that evolution from diesel propulsion to fully electric propulsion can be effectively achieved using one vessel platform.

The key to this approach was to look forward in time to the future configuration of a fully electric FSV. The fact that current energy storage density (ESD - the amount of energy carried per unit of weight) technology does not presently support feasible offshore deployments of fully electrified high speed aluminum catamaran service vessels produced parallel efforts to 1) Determine the ESD requirements for a fully electrified FSV; and 2) Assess expected commercially available ESD's in 10-years' time through research on current ESD developments for various chemistries and trajectories for ESD in the future.

4.4.2 Determine the ESD Requirements for a Fully Electric FSV

BOT's vessel designer Incat Crowther carried out the analysis on BOTs FSV design to "future proof" the vessel for repeated iterations of increasingly electrified propulsion platforms. Starting with a conceptual design for a fully electric propulsion FSV ten years from now based on the parameters of the current BOT vessel design, the FSV is deployed on the Mid-Atlantic study region (MAR) operational profile using simulation results for consumption requirements for the mission. With these inputs, we solve for the ESD parameters required for a feasible electric vessel based on the mission requirements of the MAR deployment. The following figure illustrates the general process steps followed:

Figure 38 - Determining ESD Requirements that Support Fully Electric FSV



Source: BOT

4.4.2.1 Propulsion Parameters

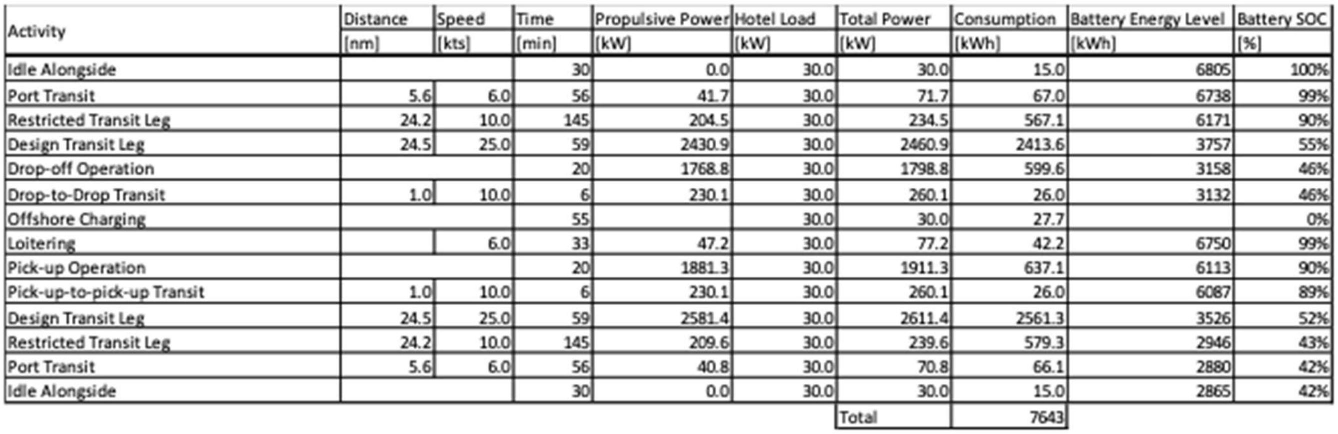
The determination of the powering requirement for the propulsion system of a vessel (Step 1 in Figure 38) follows a well-developed engineering approach used by BOT's vessel designer Incat Crowther based on hydrodynamic investigations including hull type, weight, speed requirements, and resistance calculations. The overall arrangement of a twin-hull catamaran provided a framework for equipment selection. In the current FSV design powered by diesel engines, regulatory and spatial requirements determined an overall configuration of four engines, two in each hull, driving four propeller shafts. A total powering requirement of 2,500 kW was specified. Incat Crowther then carried out the design engineering to establish the number and sizing of the electric motors used to drive the future FSV using the spatial assumptions for the current design. Four 625 kW AC motors were indicated.

4.4.2.2 Performance and Energy Consumption

Using the operational profile for the Mid-Atlantic Route (MAR) (Table 5) along with the results of the simulation model in terms of energy consumptions and emissions in a dynamic sea state, total energy consumptions were calculated on a round-trip basis for each month of the year. The propulsive power consumed varies by month reflective of the variation in sea states produced by the simulation modeling. It is assumed that after arriving offshore and delivering equipment and technicians, the vessel uses offshore charging facilities to restore battery capacity for the remainder of the day's operation. Existing suppliers of offshore charging facilities are currently developing facilities with a minimum 2MW power supply with some up to 8MW. In this study, 4MW is used as the assumed power supply as it is an achievable capacity which will be widespread in 10 years' time and offers enough power for the vessel to fully recharge its batteries.

Once the batteries are full, the remainder of the time is spent loitering offshore at the site until the time to collect technicians and equipment and return to shore (Steps 2 and 3 in Figure 38). A summary of monthly calculations is illustrated in Tables 15 and 16 for January and June, demonstrating the highest and lowest consumption conditions.

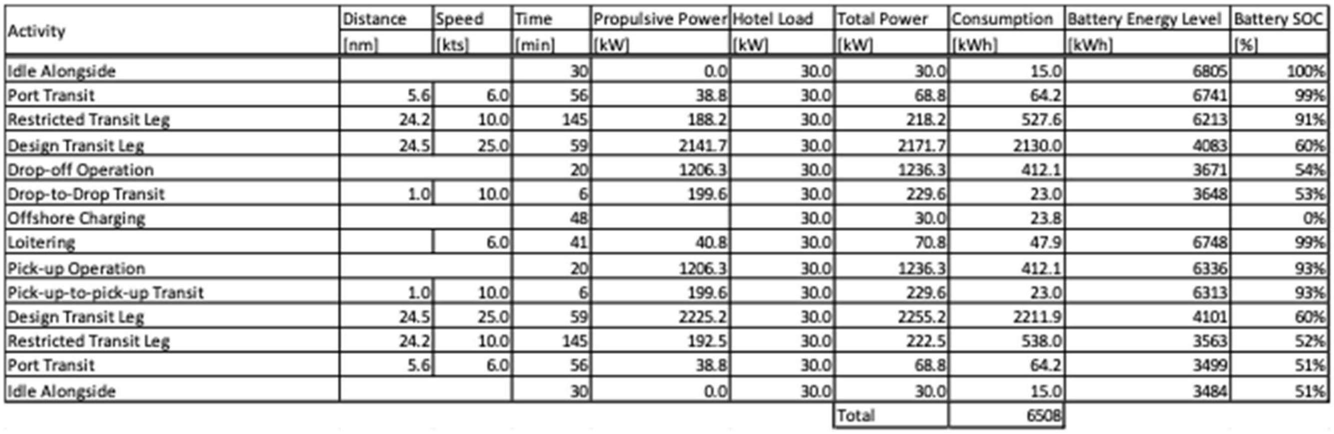
Table 15 - Energy Consumption, Fully Electric – January



Activity	Distance	Speed	Time	Propulsive Power	Hotel Load	Total Power	Consumption	Battery Energy Level	Battery SOC
	[nm]	[kts]	[min]	[kW]	[kW]	[kW]	[kWh]	[kWh]	[%]
Idle Alongside			30	0.0	30.0	30.0	15.0	6805	100%
Port Transit	5.6	6.0	56	41.7	30.0	71.7	67.0	6738	99%
Restricted Transit Leg	24.2	10.0	145	204.5	30.0	234.5	567.1	6171	90%
Design Transit Leg	24.5	25.0	59	2430.9	30.0	2460.9	2413.6	3757	55%
Drop-off Operation			20	1768.8	30.0	1798.8	599.6	3158	46%
Drop-to-Drop Transit	1.0	10.0	6	230.1	30.0	260.1	26.0	3132	46%
Offshore Charging			55		30.0	30.0	27.7		0%
Loitering		6.0	33	47.2	30.0	77.2	42.2	6750	99%
Pick-up Operation			20	1881.3	30.0	1911.3	637.1	6113	90%
Pick-up-to-pick-up Transit	1.0	10.0	6	230.1	30.0	260.1	26.0	6087	89%
Design Transit Leg	24.5	25.0	59	2581.4	30.0	2611.4	2561.3	3526	52%
Restricted Transit Leg	24.2	10.0	145	209.6	30.0	239.6	579.3	2946	43%
Port Transit	5.6	6.0	56	40.8	30.0	70.8	66.1	2880	42%
Idle Alongside			30	0.0	30.0	30.0	15.0	2865	42%
						Total	7643		

Source: Incat Crowther

Table 16 - Energy Consumption, Fully Electric – June

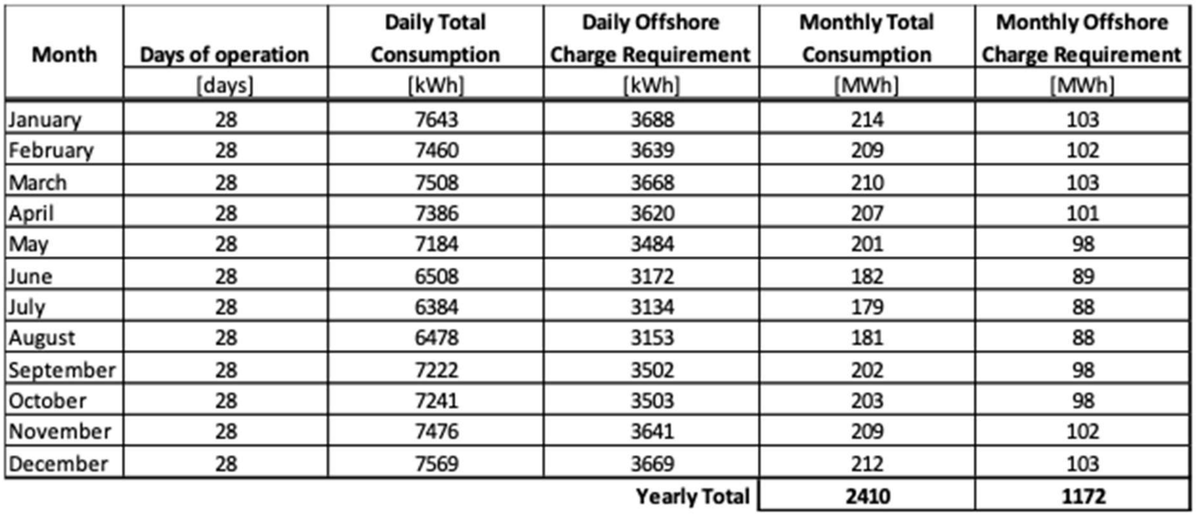


Activity	Distance	Speed	Time	Propulsive Power	Hotel Load	Total Power	Consumption	Battery Energy Level	Battery SOC
	[nm]	[kts]	[min]	[kW]	[kW]	[kW]	[kWh]	[kWh]	[%]
Idle Alongside			30	0.0	30.0	30.0	15.0	6805	100%
Port Transit	5.6	6.0	56	38.8	30.0	68.8	64.2	6741	99%
Restricted Transit Leg	24.2	10.0	145	188.2	30.0	218.2	527.6	6213	91%
Design Transit Leg	24.5	25.0	59	2141.7	30.0	2171.7	2130.0	4083	60%
Drop-off Operation			20	1206.3	30.0	1236.3	412.1	3671	54%
Drop-to-Drop Transit	1.0	10.0	6	199.6	30.0	229.6	23.0	3648	53%
Offshore Charging			48		30.0	30.0	23.8		0%
Loitering		6.0	41	40.8	30.0	70.8	47.9	6748	99%
Pick-up Operation			20	1206.3	30.0	1236.3	412.1	6336	93%
Pick-up-to-pick-up Transit	1.0	10.0	6	199.6	30.0	229.6	23.0	6313	93%
Design Transit Leg	24.5	25.0	59	2225.2	30.0	2255.2	2211.9	4101	60%
Restricted Transit Leg	24.2	10.0	145	192.5	30.0	222.5	538.0	3563	52%
Port Transit	5.6	6.0	56	38.8	30.0	68.8	64.2	3499	51%
Idle Alongside			30	0.0	30.0	30.0	15.0	3484	51%
						Total	6508		

Source: Incat Crowther

These tables present the average daily electrical power and consumptions for each activity in the operating profile for January and June voyages in the Mid-Atlantic region deployment. Also included is the prevailing battery energy level at the conclusion of each activity and the State of Charge (SOC) in percentage terms. The SOC should not fall below 40% - doing this regularly will significantly reduce battery health and lifespan. Note from the tables that at the conclusion of transit to the offshore site and dropping off technicians and gear, the battery energy levels show 3,132 kWh and 3,648 kWh remaining for the January and June results. From the monthly data, an annual summary is compiled in Table 17.

Table 17 - Energy Consumption, Fully Electric – Full Year
(assumes vessel operations 28 days per month)

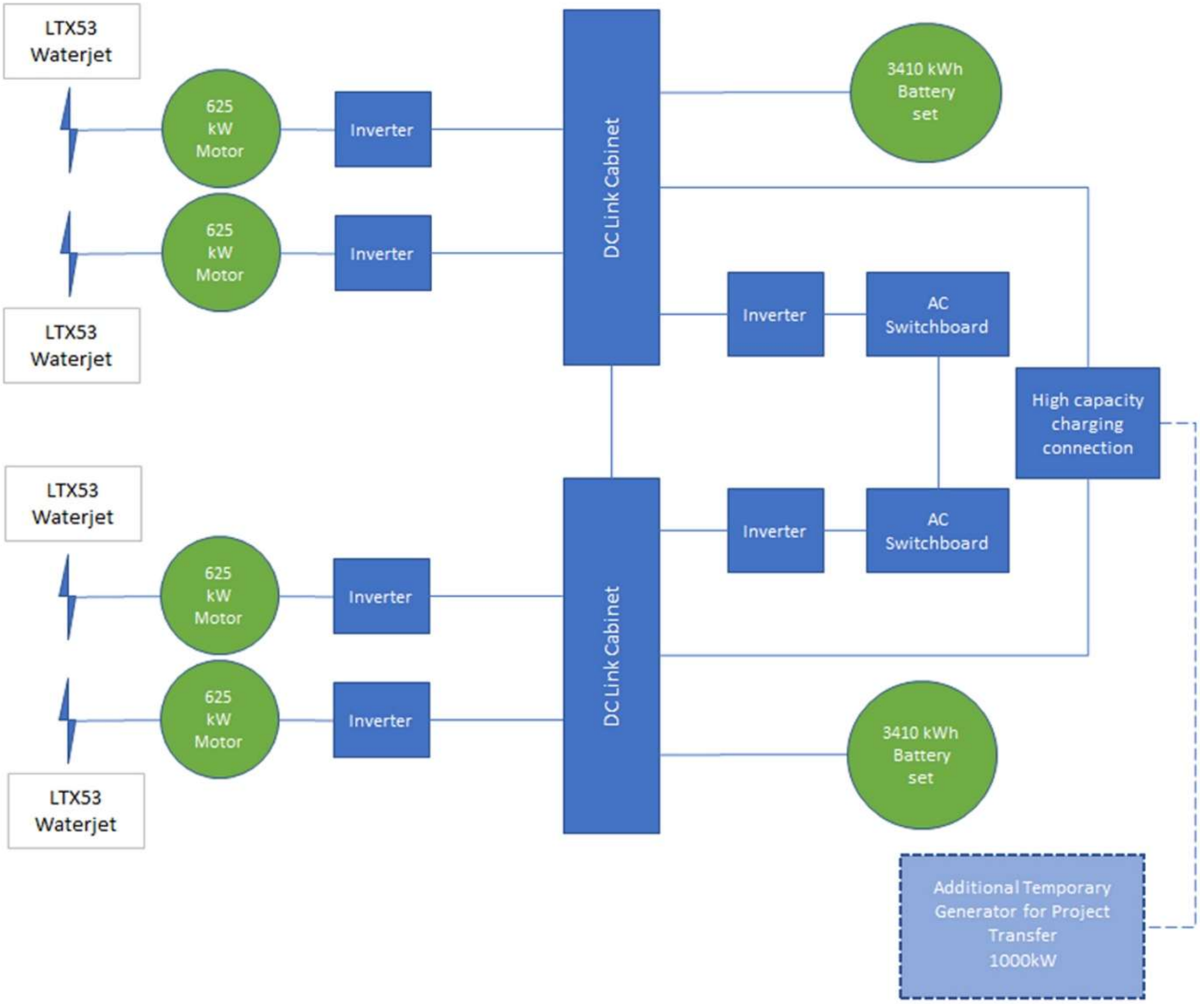


Month	Days of operation	Daily Total Consumption	Daily Offshore Charge Requirement	Monthly Total Consumption	Monthly Offshore Charge Requirement
	[days]	[kWh]	[kWh]	[MWh]	[MWh]
January	28	7643	3688	214	103
February	28	7460	3639	209	102
March	28	7508	3668	210	103
April	28	7386	3620	207	101
May	28	7184	3484	201	98
June	28	6508	3172	182	89
July	28	6384	3134	179	88
August	28	6478	3153	181	88
September	28	7222	3502	202	98
October	28	7241	3503	203	98
November	28	7476	3641	209	102
December	28	7569	3669	212	103
			Yearly Total	**2410**	**1172**

Source: Incat Crowther

4.4.2.3 System Design and Equipment Description

Figure 39 - Fully Electric FSV Propulsion System Concept Design



Source: Incat Crowther

For effective offshore deployments, BOT FSVs are designed with waterjet drives, two per catamaran hull, four in total, connected to propulsion power by four direct drive shafts. In place of waterjets, controllable-pitch propellers or Volvo IPS drives could be employed, depending on mission requirements. A fully electric FSV propulsion platform will be comprised of four 625 kW alternating-current (AC) electric motors, each driving a shaft. The electric motors are connected to inverters that change direct current (DC) from the batteries to AC for the motors. These motors are sized to provide the design speed for the FSV required by the mission. A DC electrical link cabinet (switchboard) is located in each hull port and starboard through which energy from battery sets located in the port and starboard hulls is supplied.

The battery sets are each rated at 3,410 kWh each for a total of 6,820 kWh capacity. Recall from Table 15 that the January average daily total remaining battery level at the end of the transit and drop off at the offshore site is 3,132 kWh, 46% SOC. The sizing of the batteries aligns with the power requirements for the deployment in January (highest energy consumption) as described in Section 4.5.2.2 (Step 4 in Figure 38).

The DC switchboard also routes energy through AC inverters in each hull to two AC switchboards that distribute domestic (hotel) power throughout the vessel. Additionally, a high-capacity charging line is connected to the DC link cabinet for fast charging of the batteries at sea or in port.

An ancillary circuit is included in the electrical system design to connect a 1000 kW portable generator temporarily housed on deck that can provide charging for the batteries for the case of vessel repositioning between distant deployments or when charging is unavailable.

Table 18 - Propulsion Components for Fully Electric FSV

Component	Quantity	Remarks
Hamilton LTX 53 Water Jet Drives	4	Can be substituted with twin CPP or quad Volvo IPS drives for greater efficiency
625 kW AC Electric Motor	4	Scania e-Motor or similar
DC to AC Inverter	4	For electric motors
DC Link Switchboard	2	One in each hull
DC to AC Inverter	2	To convert from DC bus to AC for domestic accommodation / hotel loads
AC Switchboards	2	For domestic accommodation / hotel loads
3410 kWh Battery	2	One in each hull
High Capacity Charging Connection (4000kW)	1	Wired into both DC Links, provides connection to shore fast charging stations and to offshore fast charging stations
Temporary Containerized 1000 kW Generator	1	For discretionary use to reposition vessel or other non-mission deployments & emergencies

Source: Incat Crowther

4.4.2.4 Vessel Weights

As indicated in Step 5 in Figure 38, the total vessel weight of the future FSV is held constant (or nearly so) to the current diesel powered version initially designed. Table 19 is a comparison of the vessel particulars for the fully diesel FSV as compared to the fully electric platform. The full diesel platform has the capacity for carrying more cargo but in general, the maximum deadweight is rarely utilized in operation.

Table 19 - Tier 3 Diesel / Electric FSV Particulars

	Diesel	Electric	
Overall Length	32.0	32.0	m
Waterline Length	31.4	31.4	m
Beam	10.0	10.0	m
Main Engines	4 x Scania DI16 588kW	n/a	
E-Motors	n/a	4 x 625kW Scania E-machine	kW
Main Propulsion	4 x Hamilton LTX53 Waterjets	4 x Hamilton LTX53 Waterjets	
Battery Capacity	n/a	6820 (2 x 3410 P/S)	kWh
Battery Weight	n/a	15.0	tonnes
Battery Energy Density	n/a	454.0	Wh/kg
Lightship Displacement	100.5	115.0	tonnes
Typical Departure Deadweight	20.5	8.0	tonnes
Total Typical Departure Displacement	121	123.0	tonnes

Source: Incat Crowther

4.4.2.5 Observations and Findings

Starting from the required energy storage capacity for the batteries of ~ 6,300 kWh, and holding the vessel's weight calculation constant, solving for the ESD required for a feasible solution yields 454 Wh/kg (Step 6 in Figure 38).

Future ESD requirements were found using current vessel weights for a conventionally powered FSV with four Tier 3 diesel engines and replacing these with four electric motors capable of meeting mission requirements, batteries and all necessary system components while maintaining the vessel weights of the conventional configuration.

If the ESD available in 10 years is only 50% of the 454 Wh/kg value the additional displacement of the vessel would be approximately 10 tonnes, increasing power requirements by 20%. For an average day in January, the SOC would drop below 30% which would be highly detrimental to the battery health and lifespan. Fifty percent less ESD would be an infeasible solution that would not meet mission requirements.

This exercise was approximate – the deadweight difference was arrived at iteratively and represents a slight advantage for the diesel platform in terms of cargo carrying capacity over a fully electric vessel.

If transit speeds were reduced from 25 knots to 20 knots, less energy would be required, allowing for heavier batteries. The amount of time spent offshore would reduce but still fall within the operations profile assumptions for the deployment.

Alternative propulsion drives such as controllable-pitch propellers (CPP) or Volvo IPS drives are more energy efficient than waterjets. This would allow for a lower battery capacity requirement, allowing feasible operation with batteries of lower ESD while still meeting weights restrictions.

Table 20 - Propulsion Type Energy Consumptions

Propulsion Type	Energy Consumption – January [kWh]	Energy Consumption - June [kWh]	Average Reduction [%]
Quad Hamilton LTX53	7643	6508	-
Quad Volvo IPS	7187	6113	6.0
Twin CPP	7342	6154	4.7

Source: Incat Crowther

4.4.3 Forecast for Marine Electrification

4.4.3.1 Historical ESD

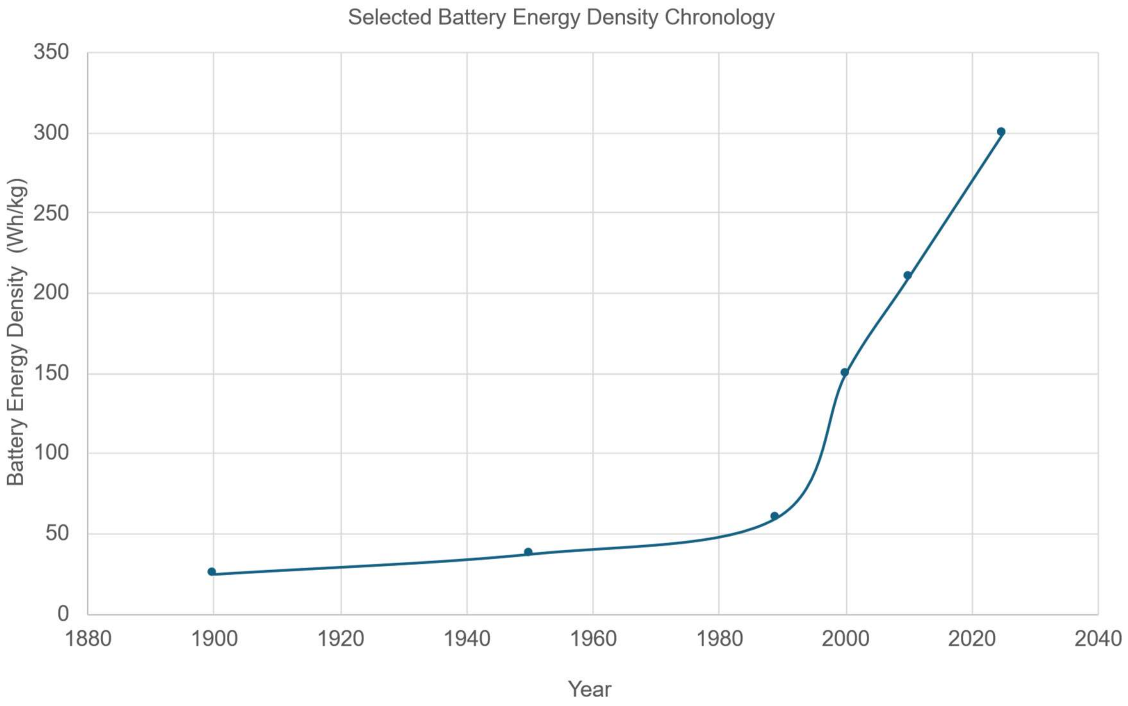
For marine applications, especially smaller high speed utility craft, the key success factor for electrification is ESD but the challenges are significant. Higher speeds drive up energy consumption requiring more energy storage to meet mission requirements. In the previous section, we found that more energy storage increases weight significantly, which in turn requires more energy in order to meet mission requirements.

Many references cite historical and forecasted growth of energy storage density. These can be used to develop credible estimates of future ESD. For this study we surveyed several sources for estimated commercially available ESD values in 10 years' time.

In a 2023 paper from RMI, Walter et al. summarize the historical growth of the energy storage market from the 1900s: Batteries have been around for over 200 years having only recently emerged as a key technology in the global energy system. The authors explain that for most of their history, batteries were simply too heavy to be practical in sectors that could otherwise have readily used them, such as transport (2023). In 1900, over one-third of cars in the United States were battery powered, but their limited range due to battery weight could not compete against internal combustion engine (ICE), so battery cars rapidly faded away (Walter et al., 2023, *citing* Richardson, 2018).

The development of battery ESD stagnated for over half a century until the 1970s and 1980s, when innovation in the United States and Japan picked up (Walter et al., 2023, *citing* Reddy et al, 2020). In the 1990s, lithium-ion batteries (LIBs) entered the market, and rapid innovation in ESD and cost declines in the decade that followed enabled novel applications in electronics, such as battery use in cell phones and laptops (Walter et al., 2023). The RMI report then explains that as ESD rose, battery applications for transportation became useful and ESD has kept rising ever further, with new applications for heavy trucks and even aviation applications (2023). This is illustrated in Figure 40 showing selected years and then-current energy storage densities.

Figure 40 - Evolution of Battery Energy Density



Source: Adapted from Pattanayak, T. & Mavris, D., 2025

Walter et al. explain that since 1993, top-tier energy density has increased by 7% for every doubling of battery deployment, growing even faster from 2012 at 18%. The innovation potential of batteries is in part driven by the wide range of elements that can make up a battery: Batteries can be made from many different chemical compositions, which means the chemical properties of lithium, sodium, nickel, cobalt, manganese, and many other minerals can be used to improve the technology (Walter et al., 2023). This explains why battery innovation has so much potential: the solution space is vast, and investigations are in an adolescent stage (Walter et al., 2023).

Historically, as innovation accelerated and battery uptake rose, battery costs declined, closely following Wright's law over the past three decades — as production grew, economies of scale and R&D learning drove down cost (Walter et al., 2023) (internal citations omitted). The learning rate for battery costs since the first introduction of the lithium-ion battery in 1991 has been 19%, meaning that battery prices fell by 19% for every doubling of battery deployment (Walter et al, 2023). The battery cell learning rate has increased over time, and over the past two decades, the learning rate was 29% (Walter et al, 2023). As batteries dropped in cost, this did not just improve the economics of existing battery technology — it also enabled competitive market entry in new sectors that were unlocked by rising ESD (Walter et al, 2023).

With more attractive batteries through improvements in ESD and cost, market uptake further accelerated with electronics driving early uptake and battery demand growing at an average annual rate of 33% for nearly three decades (Walter et al, 2023). As saturation was reached in these, the early use sectors and growth started to ease to 20% per year, and batteries became a viable technology in the transport market in the 2010s (Walter et al, 2023). This led to a resurgence of market growth (Walter et al, 2023). Since 2014, battery demand has been growing at an annual average of 41%, doubling every two years (Walter et al, 2023).

As the global battery market scaled up, it reinforced the rise in ESD and fall in cost, furthering momentum in ESD improvements with the accelerated growth. The result was a rapid, exponential increase of battery demand, unhindered by manufacturing supply that responded to the demand signal and outpaced it - demand grew by a factor of 24, yet battery manufacturing capacity went up by a factor of 42 (Walter et al., 2023). With this strongly positive growth trajectory, ample capital became available from investment markets (Walter et al., 2023, *citing* Bloch et al., 2019).

4.4.3.2 Future ESD

With continued investment and growth in the battery market and continued spending on R&D, ESD will keep rising. Walter et. al. formulate a projection for energy density going forward in 2030 of ~600 to 800 Wh/kg, based on past improvement rates of the battery energy density of the top tier leaders with a focus on new applications and markets for batteries (2023).

Other bottom-up expert assessments of future battery ESD appear to confirm the feasibility of these ESD projections. Already in 2023, there were lab-scale battery cells with energy densities that exceed 700 Wh/kg, and these technologies are on their way toward commercialization (Walter et al., 2023) (internal citations omitted). Argonne National Labs even states a potential of 1,200 Wh/kg if some breakthroughs are made sooner than expected (Walter et al., 2023, *citing* Harmon, 2023). These batteries still have a long road to the market, but lab results show that there is ample reason to believe top-tier cell density can rise well above 600 and towards 800 Wh/kg by 2030 (Walter et al., 2023).

The Fraunhoffer Institute in the publication Alternative Battery Technologies Roadmap 2030+ reviews the status of electric storage solutions across several chemistries. There are many other alternative battery technologies that are still being developed or are about to enter the market. Alternatives to LIBs are listed in Table 21.

Table 21 - Alternative Battery Technologies

METAL ION (Me-io	METAL SULFUR (Me-S)
▪ Sodium-ion batteries (SIBs) ▪ Sodium-ion saltwater batteries (SIBs Salt) ▪ Magnesium-ion batteries (MIBs) ▪ Zinc-ion batteries (ZIBs) ▪ Aluminum-ion batteries (AIBs)	▪ Lithium-sulfur (Li-S) ▪ Sodium-sulfur room temperature (Na-S RT) ▪ Sodium-sulfur high temperature (Na-S HT)
METAL LEFT(Me-air)	Redox flow batteries (RFBs)
▪ Lithium-air (Li-air) ▪ Zinc-air (Zn-air)	Non-Vanadium based (Zn, Na, Mg)

Source: Stephan & Thielmann, 2023

While alternative chemistries provide a broad field for investigation, development and deployment, and ensure continued performance levels in ESD going forward over the long term, the authors note that in the coming decade Lithium-Ion (LIB) batteries will likely continue to be the only other scaled technology than lead-acid (PbA) batteries (2023).

In their work they provide assessments for current ESD availability for several cell chemistries as well as their projection in 2035.

Table 22 - ESD Cell-Level Assessments - Current and 2035

	Short Term / 2025	Long-Term Vision 2035
Lithium-ion	200–300 Wh/kg	320–360 Wh/kg
Metal-ion	30–35 Wh/kg	550 Wh/kg

Source: Stephan & Thielmann, 2023

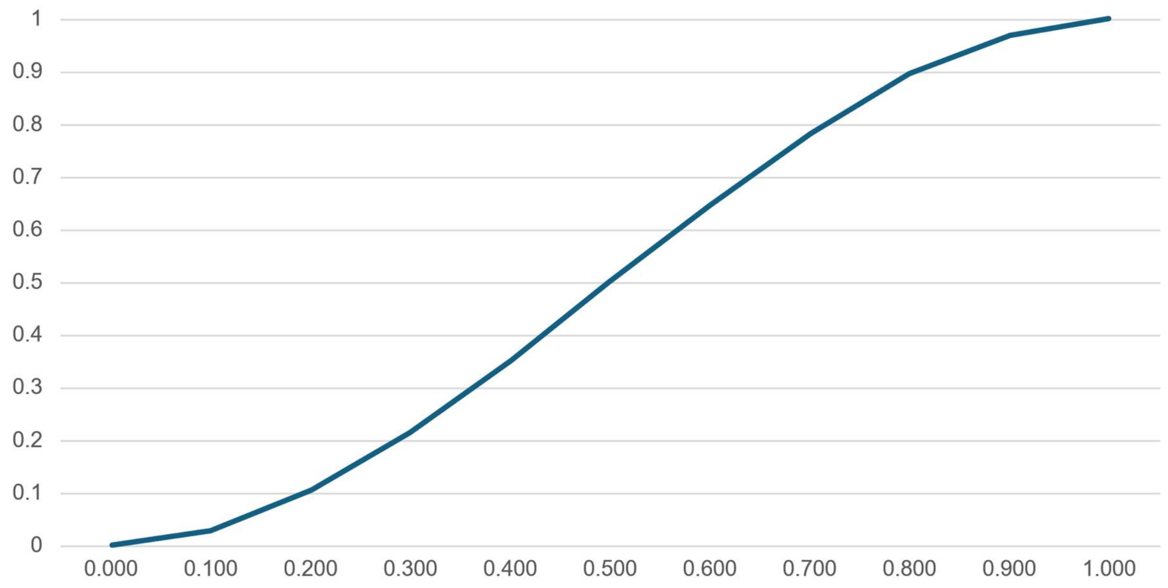
4.4.3.2.1 Modeling ESD Growth

Market growth, efficiency increases, unit cost trajectories over time and other phenomena can be modeled using a specific form of the generalized logistic function called a Richards Curve. Originated by F. J. Richards in 1959, he proposed it as a more flexible S-shaped (sigmoidal) curve to model asymmetrical biological growth with capacity or environmental constraints, with a parameter for asymmetry, allowing it to encompass other common growth functions as special cases for applications in biology, forestry, and epidemiology. Widely used in ecology (population modeling), forestry (tree growth), medicine, and even in forecasting epidemics (like COVID-19), it serves as a versatile tool when the exact growth pattern is unknown.

Sigmoidal growth, or S-shaped growth, describes a pattern where growth starts slowly, accelerates rapidly (exponentially), then slows down as it approaches a maximum limit (carrying capacity), eventually plateauing or stabilizing, seen in populations, biological development, and even learning. It has three main phases: an initial slow lag/exponential phase, a rapid middle section with the fastest growth (inflection point), and a final asymptotic/plateau phase where growth stops or levels off due to resource limits or environmental resistance. Normalized, the plot of sigmoidal growth is a cumulative distribution function whose end value is 1.0.

The specific form of this function used frequently in the evaluation of ESD growth is called the Boltzmann Sigmoid where the inflection point exists at 50% of the cumulative value. An example is illustrated in Figure 41.

Figure 41 - Boltzmann Sigmoid



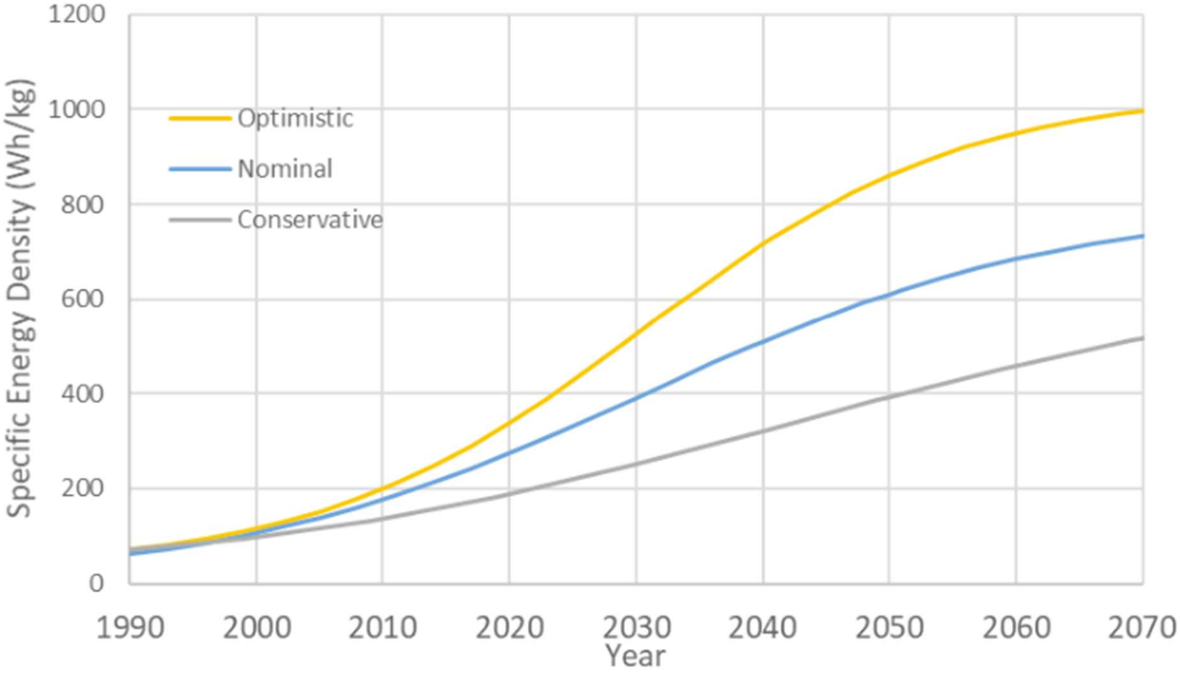
Source: BOT

Tiede, et al, employ a methodology using the Boltzmann Sigmoid to project commercial ESD's for various chemistries out to 2050 when looking at the feasibility of electrified aircraft. Their projections are developed based on examining historical commercial SOA (safe operating area) trends as well as practical limitations of future chemistries (2022). Feasible projections of future specific energy values help to inform on the length and duration of the pathway to electrification. An S-curve projection of cell energy densities was combined with a packing factor multiplier to project battery pack level specific energies in 2030, 2040, and 2050 (Tiede et al., 2022). A packing factor multiplier accounts for the additional weight of the structure required to house the battery cells.

Figure 42 presents the cell level energy densities for 2030, 2040, and 2050 from this work. Conservative, nominal, and aggressive rates of technological advancement are shown to capture the uncertainty of projecting future progress.

Corresponding to Figure 42, Table 23 estimates nominal cell level specific energies for rechargeable batteries of 489 Wh/kg by 2030, 638 Wh/kg by 2040, and 764 Wh/kg by 2050. Pack-level estimates are lower, reflecting the efficiency of storage design. However, the estimations show nominal estimates of energy density at pack levels of 391 Wh/kg in 2030, 510 Wh/kg in 2040 and 611 Wh/kg in 2050.

Figure 42 - Forecast ESD 2030-2040-2050



Source: Tiede et al., 2022

Table 23 - Forecast ESD 2030-2040-2050

(Wh/kg)	2030			2040			2050		
	C	N	A	C	N	A	C	N	A
Cell Level Energy Density	359	489	584	459	638	795	561	764	957
Pack Level Energy Density	251	391	525	321	510	715	393	611	861
C = Conservative N + Nominal A = Aggressive									

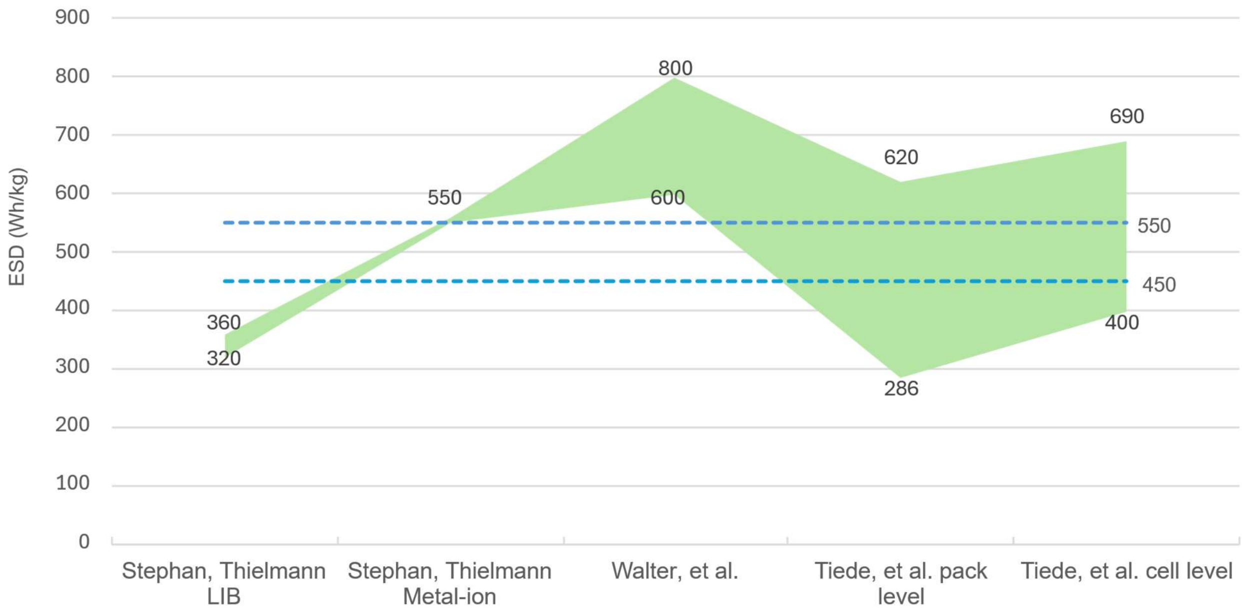
Source: Tiede et al., 2022

4.4.3.3 ESD Estimate 2035

Walter et. al. note in their 2023 work that despite the clear exponential trend batteries have been on for decades, experts keep underestimating the pace of change. A systematic underestimation of the improvement potential of energy density and costs led to battery uptake outlooks that were far too pessimistic, a trend that persists today. They point to a clear repeating pattern: Initially, experts estimate that low energy density will confine batteries to a niche role in a sector; Then, as battery-powered technology continues its ascent, expert outlooks change, acknowledging a significant role for batteries in the sector, except for a final niche that needs even higher energy density. Later, the narrative shifts again, with experts predicting a complete takeover by battery-powered technology (Walter, et al., 2023).

Considering these references in the context of systemic underestimation bias, we believe commercially available ESD's in the 2035 timeframe may be reasonably approximated in the range of 450-550 Wh/kg for pack level ESD as illustrated in Figure 43. Note that in Section 4.5.2.3 the required ESD in 2035 for feasible FSV operation was found to be 454 Wh/kg.

Figure 43 – Estimation of Commercially Available ESD in 2035 (- - - -)



Source: BOT

The investigations carried out in Sections 4.5.2 and 4.5.3 demonstrate that it is reasonable to expect ESD 10 years from now in the range of 450-550 Wh/kg, while the ESD required to make a fully electric FSV is 450 Wh/kg. This supports the claim that a fully electric FSV can be achieved within 10 years' time, a fundamental part of proving our third hypothesis that evolution from diesel propulsion to fully electric propulsion can be achieved cost effectively using one vessel platform.

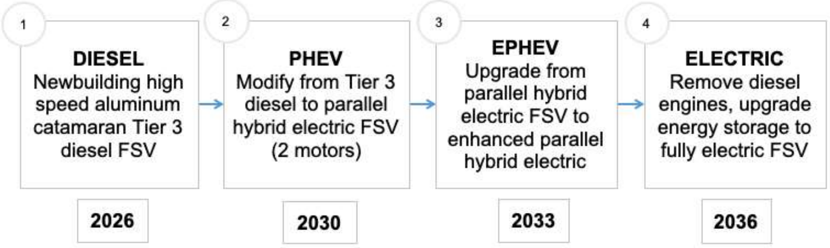
4.4.4 Roadmap to Fully Electric from Fully Diesel Assumptions

4.4.4.1 – Step-by-Step Implementation

Having identified the configuration and conceptual specifications of a fully electric FSV 10 years from now using a vessel configuration based on an FSV powered by four Tier 3 diesel engines built in the current timeframe, a feasible implementation plan from fully diesel powered to fully electric powered is necessary. A logical approach recognizes that the move towards electrification is dependent on equipment technology - specifically energy storage technology – and is a step-by-step process, employing new propulsion systems and installing them on board, while replacing irrelevant or obsolete components and adding components that contribute to further electrification at each step in concert with the availability of technology, especially ESD improvements.

A phased approach with propulsion platform evolution through four stages in suggested. It begins with Tier 3 diesel propulsion today, then a parallel-hybrid electric propulsion vessel (PHEV) in a few years, followed by a modification to a more enhanced parallel-hybrid electric vessel (EPHEV), then to fully electric propulsion system installation including removal of the original diesel engines within a 10-year period from delivery of the first vessel configuration, planned to occur in the next few years.

Figure 44 - Phased Electrification Approach



Component	#	#	#	#	Remarks
Hamilton LTX 53 Water Jet Drives	4	4	4	4	Can be substituted with twin CPP or quad Volvo IPS drives
Tier 3 Diesel Engines	4	4	2	0	Scania DI16082M-588kW@2100 RPM
AC Electric Motor	0	2 x 230 kW	2 x 625 kW	4 x 625 kW	Scania e-Motor or similar
DC to AC Inverter	0	2	4	4	For electric motors
DC Link Switchboard	0	2	2	2	One in each hull
DC to AC Inverter	0	2	2	2	To convert from DC bus to AC for domestic accommodation / hotel loads
AC Switchboards	2	2	2	2	For domestic accommodation / hotel loads
2 x Battery Packs @ kWh each	0	490	~ 1000	3410	One in each hull
High Capacity Charging Connection	0	1	1	1	Wired into both DC Links, provides connection to onshore fast charging stations and to offshore fast charging stations
Temporary Containerized 1000 kW Generator	0	0	0	1	For discretionary & emergency use to reposition vessel or other non-mission deployments

Source: BOT

To note, fast charging of the batteries shoreside was a requirement of the PHEV and later platform versions and that for EPHEV and fully electric platforms offshore charging would further be required.

The step-by-step approach supports the use of the same vessel throughout the transition across four stages of propulsion to fully electric operations. Additional capital costs for different vessel platforms are avoided, reducing the execution cost of this approach dramatically. Propulsion system component replacement or upgrade is selectively chosen to increase capabilities under electric operation while minimizing incremental capital expense.

4.4.4.2 Tier 3 Diesel FSV

Using the results of Sections 4.4.2 and 4.4.3, we established that a fully electric FSV is possible in 10 years' time using the same vessel design, therefore a 10-year implementation timeline is assumed. We recognize that if the opportunity exists (driven by availability of additional capital), it may be possible to build a PHEV initially, starting with a PHEV instead of a fully diesel driven vessel as the newbuild configuration and noting that current battery technology solutions have specifications of 250-300 Wh/kg.

For the purposes of this report, we assume the initial configuration is a Tier 3 diesel driven vessel, with vessel particulars as described in Table 24.

4.4.4.3 Initial Parallel Hybrid Electric Vessel (PHEV) Propulsion System Design

The vessel particulars for the PHEV platform are described in Table 24. Two of the four Scania diesel engines of the Tier 3 diesel platform have Scania e-motors coupled to them and battery packs, one per hull are incorporated, for zero-emission operation on certain segments of the operational profile. If the initial newbuilding configuration is a fully diesel driven FSV, we anticipate modification to parallel hybrid electric around 2030. Ideally, the newbuilding configuration would be a PHEV propulsion package, eliminating one of the steps in the electrification evolution.

Table 24 - Tier 3 Diesel and PHEV FSV Particulars

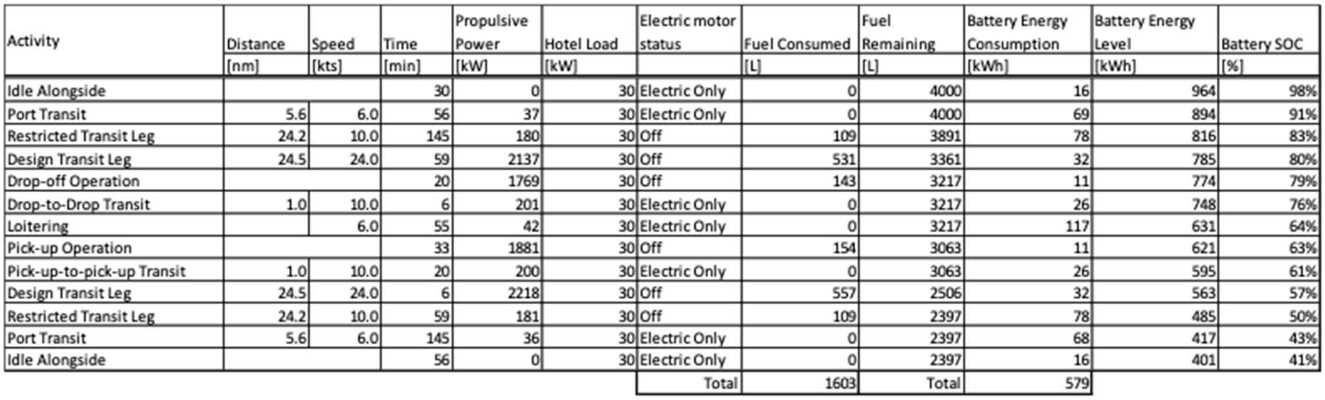
	Diesel	PHEV	
Overall Length	32.0	32.0	m
Waterline Length	31.4	31.4	m
Beam	10.0	10.0	m
Main Engines	4 x Scania DI16 588kW	4 x Scania DI16 588kW	
E-Motors	n/a	2 x 230kW Scania E-machine	
Main Propulsion	4 x Hamilton LTX53 Waterjets	4 x Hamilton LTX53 Waterjets	
Battery Capacity	n/a	980 (10x98kWh)	kWh
Battery Weight	n/a	6.7	tonnes
Battery Energy Density	n/a	147.0	Wh/kg
Lightship Displacement	100.5	109.7	tonnes
Typical Departure Deadweight	11.3	11.3	tonnes
Total Typical Departure Displacement	111.8	121.0	tonnes

Source: Incat Crowther

4.4.4.3.1 PHEV Performance and Energy Consumption

Incat Crowther carried out the design engineering to establish the number and sizing of the electric motors and battery storage used to supplement the current diesel platform. Operationally, we anticipate the ability to operate in zero-emissions (battery-powered and motor-driven) mode alongside in port, while maneuvering in port and offshore on-site loitering while waiting to collect technicians for the trip back to shore. The operational profile for the Mid-Atlantic Route (MAR) (Table 5) is again assumed. A similar investigation was undertaken to that of the fully electric platform using the results of the simulation model in terms of energy consumptions and emissions in a dynamic sea state. Total energy consumptions were calculated on a round-trip basis for each month of the year. The propulsive power consumed varies by month reflective of the variation in sea states produced by the simulation modeling. A summary of monthly calculations for the PHEV is illustrated in Tables 25 and 26 for January and June, demonstrating the highest and lowest consumption conditions.

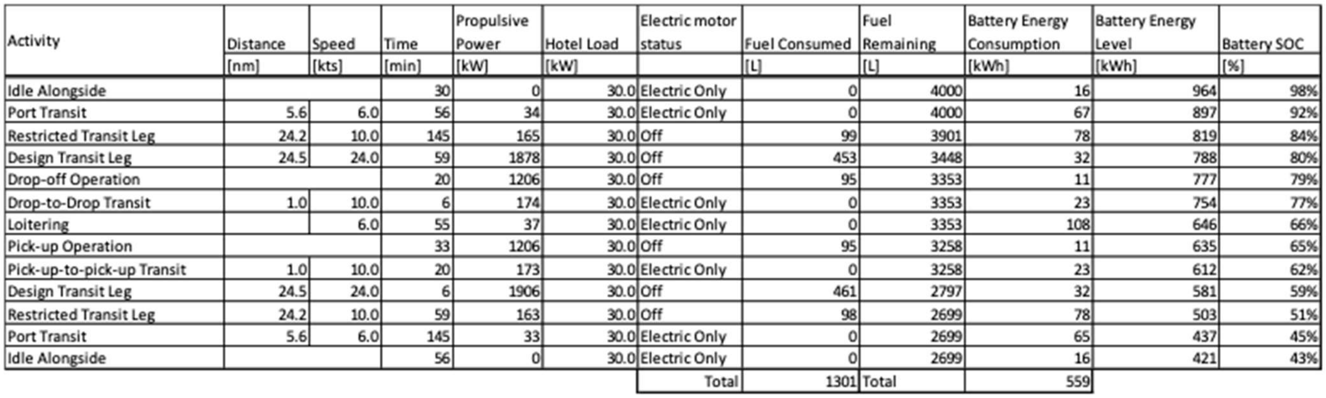
Table 25 - Energy Consumption, PHEV – January



Activity	Distance	Speed	Time	Propulsive Power	Hotel Load	Electric motor status	Fuel Consumed	Fuel Remaining	Battery Energy Consumption	Battery Energy Level	Battery SOC
	[nm]	[kts]	[min]	[kW]	[kW]		[L]	[L]	[kWh]	[kWh]	[%]
Idle Alongside			30	0	30	Electric Only	0	4000	16	964	98%
Port Transit	5.6	6.0	56	37	30	Electric Only	0	4000	69	894	91%
Restricted Transit Leg	24.2	10.0	145	180	30	Off	109	3891	78	816	83%
Design Transit Leg	24.5	24.0	59	2137	30	Off	531	3361	32	785	80%
Drop-off Operation			20	1769	30	Off	143	3217	11	774	79%
Drop-to-Drop Transit	1.0	10.0	6	201	30	Electric Only	0	3217	26	748	76%
Loitering		6.0	55	42	30	Electric Only	0	3217	117	631	64%
Pick-up Operation			33	1881	30	Off	154	3063	11	621	63%
Pick-up-to-pick-up Transit	1.0	10.0	20	200	30	Electric Only	0	3063	26	595	61%
Design Transit Leg	24.5	24.0	6	2218	30	Off	557	2506	32	563	57%
Restricted Transit Leg	24.2	10.0	59	181	30	Off	109	2397	78	485	50%
Port Transit	5.6	6.0	145	36	30	Electric Only	0	2397	68	417	43%
Idle Alongside			56	0	30	Electric Only	0	2397	16	401	41%
						Total	1603	Total	579		

Source: Incat Crowther

Table 26 - Energy Consumption, PHEV – June

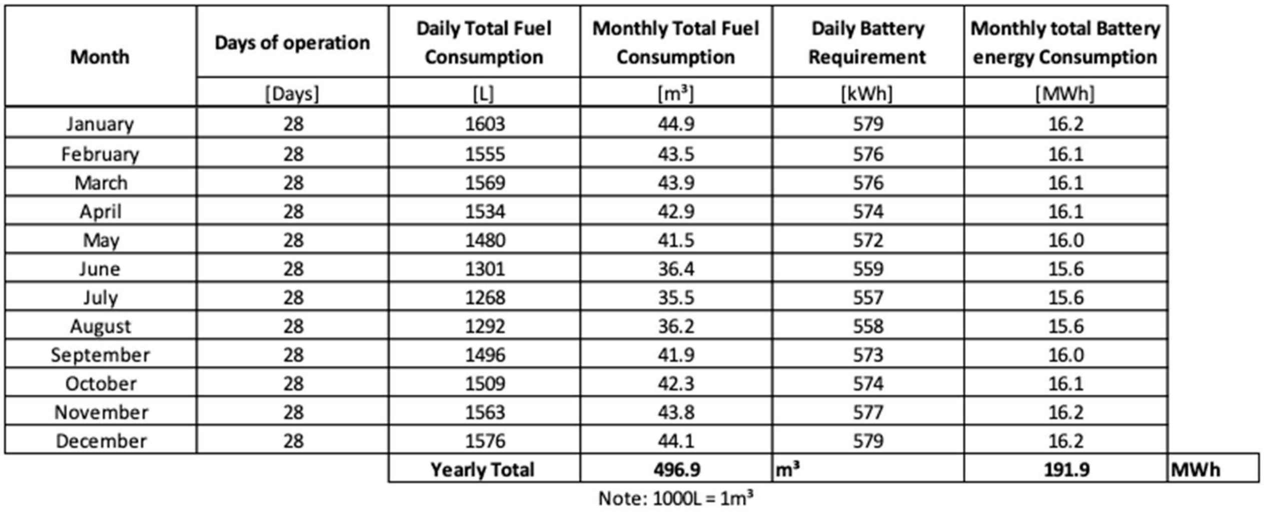


Activity	Distance	Speed	Time	Propulsive Power	Hotel Load	Electric motor status	Fuel Consumed	Fuel Remaining	Battery Energy Consumption	Battery Energy Level	Battery SOC
	[nm]	[kts]	[min]	[kW]	[kW]		[L]	[L]	[kWh]	[kWh]	[%]
Idle Alongside			30	0	30.0	Electric Only	0	4000	16	964	98%
Port Transit	5.6	6.0	56	34	30.0	Electric Only	0	4000	67	897	92%
Restricted Transit Leg	24.2	10.0	145	165	30.0	Off	99	3901	78	819	84%
Design Transit Leg	24.5	24.0	59	1878	30.0	Off	453	3448	32	788	80%
Drop-off Operation			20	1206	30.0	Off	95	3353	11	777	79%
Drop-to-Drop Transit	1.0	10.0	6	174	30.0	Electric Only	0	3353	23	754	77%
Loitering		6.0	55	37	30.0	Electric Only	0	3353	108	646	66%
Pick-up Operation			33	1206	30.0	Off	95	3258	11	635	65%
Pick-up-to-pick-up Transit	1.0	10.0	20	173	30.0	Electric Only	0	3258	23	612	62%
Design Transit Leg	24.5	24.0	6	1906	30.0	Off	461	2797	32	581	59%
Restricted Transit Leg	24.2	10.0	59	163	30.0	Off	98	2699	78	503	51%
Port Transit	5.6	6.0	145	33	30.0	Electric Only	0	2699	65	437	45%
Idle Alongside			56	0	30.0	Electric Only	0	2699	16	421	43%
						Total	1301	Total	559		

Source: Incat Crowther

These tables present the average daily electrical power and consumptions for each activity in the operating profile for January and June voyages in the Mid-Atlantic region deployment. Also included is the prevailing battery energy level at the conclusion of each activity and the State of Charge (SOC) in percentage terms. The SOC should not fall below 40% - doing this regularly will significantly reduce battery health and lifespan. From the monthly data, an annual summary is compiled in Table 27.

Table 27 - Energy Consumption, PHEV – Full Year
(assumes vessel operations 28 days per month)



Month	Days of operation	Daily Total Fuel Consumption	Monthly Total Fuel Consumption	Daily Battery Requirement	Monthly total Battery energy Consumption	
	[Days]	[L]	[m³]	[kWh]	[MWh]	
January	28	1603	44.9	579	16.2	
February	28	1555	43.5	576	16.1	
March	28	1569	43.9	576	16.1	
April	28	1534	42.9	574	16.1	
May	28	1480	41.5	572	16.0	
June	28	1301	36.4	559	15.6	
July	28	1268	35.5	557	15.6	
August	28	1292	36.2	558	15.6	
September	28	1496	41.9	573	16.0	
October	28	1509	42.3	574	16.1	
November	28	1563	43.8	577	16.2	
December	28	1576	44.1	579	16.2	
		Yearly Total	**496.9**	**m³**	**191.9**	**MWh**

Note: 1000L = 1m³

Source: Incat Crowther

4.4.4.3.2 PHEV System Design and Equipment Description

A DC electrical link cabinet (switchboard) is located in each side of the vessel (Port and Starboard). The batteries are equally split between the Port and Starboard DC link. Energy for the Port hybrid propulsion system is drawn from the Port DC link (Starboard similar).

A generator is also installed to provide an alternative means of supplying the hotel load, connected to the starboard DC cabinet, this assumes that it is accepted by class to use the batteries as the main source of power for the hotel load and the generator as a backup.

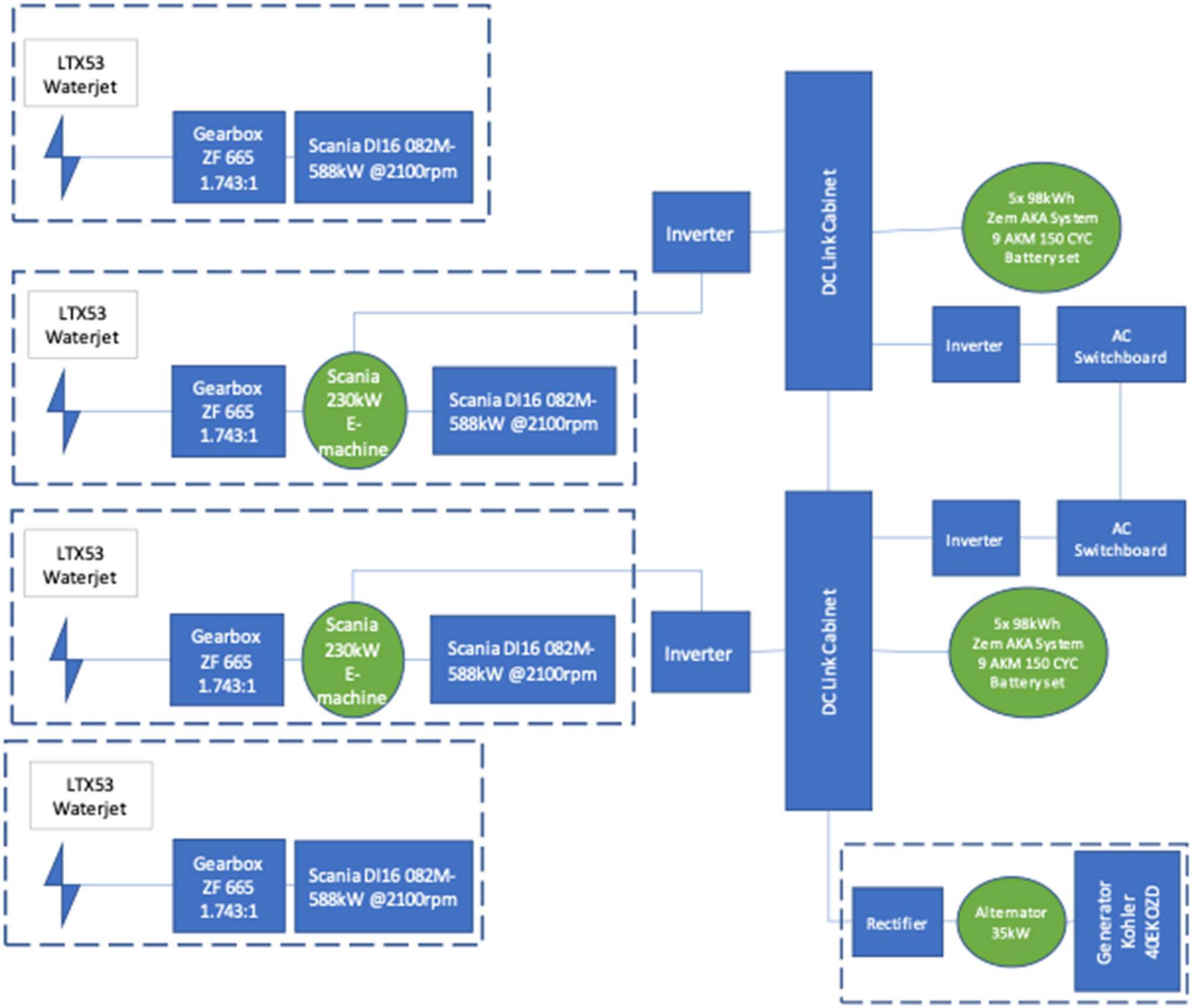
The AC switchboards are connected to the DC links. Domestic AC power is then distributed throughout the vessel in a normal fashion.

A crossover between the Port and Starboard DC link is provided to provide flexibility and redundancy.

A battery capacity of 980kWh is selected using the assumed 10 x 98kWh Zem AKASystem 9 AKM batteries (x5 in each hull). On a typical day in winter, the minimum State of Charge (SOC) is 41%, while in summer months this increase to 43%. Battery life is related to the number of cycles, and the SOC of each cycle, with a cycle defined as 1 discharging period and 1 charging period. It is common that if discharging to less than 40% regularly, the number of cycles in a battery lifetime reduces; if discharging to 30% the lifetime could be less than 50% of the quoted lifetime. However, as battery technology improves the minimum SOC recommended is likely to decrease.

The following single line diagram shows the high-level arrangement of the power supply and propulsion equipment.

Figure 45 - PHEV Propulsion System Diagram



Source: Incat Crowther

Table 28 - Propulsion Components for PHEV FSV

Component	Quantity	Remarks
Hamilton LTX 53 Water Jet Drives	4	Can be substituted with twin CPP or quad Volvo IPS drives
ZF 665 Gearbox	4	1.743:1 ratio
Scania DI16 082M	4	588kW @ 2100 rpm
230 kW AC Electric Motor	2	Scania e-Machine, mounted to engine, one per hull
DC to AC Inverter	2	For electric motors
DC Link Switchboard	2	One in each hull
DC to AC Inverter	2	To convert from DC bus to AC for domestic accommodation / hotel loads
AC Switchboards	2	For domestic accommodation / hotel loads
Battery Set	10	98 kWh Zem AKM 150 CYC - 5 in each hull
Charging Connection	1	Wired into both DC Links, provides connection to shore stations for overnight battery charging
35kW Kohler 40EKOZD Generator	1	Back up for hotel load, connected to starboard DC cabinet
Rectifier	1	

Source: Incat Crowther

4.4.4.3.3 PHEV Findings and Observations

The current electric motor PHEV operational profile enables the vessel to save fuel and emissions during certain portions of the voyage. On an annual basis, the cost savings is estimated to be about US$ 50,400 at the assumed diesel pricing of US$ 1.06 per litre. This is in comparison to a similar vessel without batteries or the additional electric equipment associated with the hybrid system, and with all propulsion power from diesel engines and hotel load provided by diesel generators.

The current installed battery capacity is only sufficient for in-port idle and transit and slow speed loitering & transfer at the wind field, but includes providing energy for hotel loads during these periods as well. To provide assistance during the transit operations, greater capacity is required. Double the battery capacity is required for the E-motors to provide their full capability during the slow speed transit (10 knots).

No offshore charging is considered in the MAR profile. At the end of each day the vessel's batteries will need charging overnight. With a 4,000 litres fuel capacity it is expected that refuelling will be required every 2 or 3 days depending on the time of year.

Using the main engines with motors on the driveline in a power take off mode will provide the capability to recharge the batteries while at sea. There are added mechanical losses in the engine and motor in generating the electrical power from main engines and increased fuel consumption. This is not an efficient method of increasing the battery endurance recommended; however, where the vessel is berthing in a strict zero emissions port or in emergency scenarios where there is not sufficient battery power, this method of recharging the batteries at sea is possible.

4.4.4.3.4 PHEV ROM Capital Cost

Based on a rough, order-of-magnitude (ROM) cost analysis carried out by Incat Crowther, the incremental cost of the PHEV platform over the Tier 3 diesel platform is estimated to be approximately US$ 1.75 million in addition to a vessel cost of US$ 14.5 million, resulting in a US$ 16.25 million total cost for a PHEV FSV. The key items contributing to the increase in cost are: Electric motors, hybrid control systems, batteries, additional large diameter electrical cables and additional/larger transformers.

The cost above for a parallel hybrid vessel includes 980kWh of battery capacity as prescribed earlier in this report. Comparing pricing trends of the last 4 years, an estimate of US$ 400 per kWh has been used for the cost of the batteries.

Over the last 5 years the battery energy density has increased from approximately 100 Wh/kg to 140-170 Wh/kg, with 147 Wh/kg being used in this report for the commercial availability of batteries. Predictions in the increase of energy density follow an exponential trend. It has previously been explored in this report that the required energy density for a feasible fully electric vessel is ~ 450 Wh/kg. With the predicted trend an approximate timeline for a fully electric FSV is approaching 10 years, however with other improvements in propulsion efficiency this may be reduced, only needing to reach 250-350 Wh/kg.

4.4.4.4 Enhanced Parallel Hybrid Electric Vessel (EPHEV)

The EPHEV propulsion platform advances installed equipment capability and capacity as technology progresses over time. We anticipate a modification to EPHEV from PHEV around 2033 with incremental equipment improvements to the electrical components as highlighted in Table 29. Two of the diesel engines, one per hull, are removed, and electric motors in each hull are upgraded to 625kW. The reduction in weight from removal of two engines provides margin for additional batteries. Battery configuration and capacity for the EPHEV is dependent on the improvement in ESD technology over time, as discussed in Section 4.4.3.

Table 29 - Propulsion Components for PHEV to EPHEV FSV

Component	PHEV	EPHEV	Remarks
Hamilton LTX 53 Water Jet Drives	4	4	Can be substituted with twin CPP or quad Volvo IPS drives
ZF 665 Gearbox	4	4	1.743:1 ratio
Scania DI16 082M	4	2	588kW @ 2100 rpm, 2 removed in EPHEV
AC Electric Motor	2 x 230kW	2 x 625kW	Scania e-Machine, mounted to engine, one per hull, upgraded in EPHEV
DC to AC Inverter	2	4	For electric motors
DC Link Switchboard	2	2	One in each hull
DC to AC Inverter	2	2	To convert from DC bus to AC for domestic accommodation / hotel loads
AC Switchboards	2	2	For domestic accommodation / hotel loads
Battery Set	980	~2,000	Wh/kg – EPHEV ESD assumed then-current technology
Charging Connection	1	1 High Capacity	Wired into both DC Links, provides connection to shore stations for overnight battery charging
35kW Kohler 40EKOZD Generator	1	1	Back up for hotel load, connected to starboard DC cabinet
Rectifier	1	1	

Source: Incat Crowther

4.5 Comparative Economic Analysis of Electrified Platforms

This study produced estimates of total energy costs for each propulsion platform on each regional deployment exposed to historically experienced weather and sea states for each region. Table 30 illustrates the results from the simulation model described in Section 4.2 showing total energy costs simulation results for each regional deployment for each propulsion platform.

This section uses the findings from the lower energy-intense routes in the US east coast regions (NECL, NYB, MAR) to assess the advantages of electrification of FSVs deployed in regional weather and sea state conditions. Higher energy-intense routes with long transits at full speed (25 knots) are poor candidates for electrification based on current and projected energy storage technologies. The results in Table 30 are further conditioned to reflect more realistic results on an annualized basis with assumptions of average utilization of the vessel over the course of the year. Utilization should take into account non-operational weather days where the conditions do not support offshore operations, as well as planned vessel maintenance and off-hire periods related to repairs. For the purposes of evaluating economic attractiveness deriving from energy savings via electrification, 300 operational days per year is a conservative annual deployment to use in calculating annual energy consumptions (~82% utilization). In addition to accounting for utilization, actual savings may be reduced further considering operational limitations such as SOC that limit the duration of activities under electric power.

Table 30 - Mean Total Energy Cost by Region and Propulsion Platform per Trip

US$		TIER 3	PHEV	EPHEV	ELECTRIC
Per Trip	NECL	12,125	10,608	9,131	7,653
	NYB	2,691	2,586	2,188	1,789
	MAR	1,656	1,487	1,282	1,075
	GULF	5,792	5,826	4,876	3,928
	USWC	3,656	3,540	2,986	2,421

US$		TIER 3	PHEV	EPHEV	ELECTRIC
Per Year	NECL	727,500	636,507	547,849	459,191
	NYB	807,419	775,681	656,334	536,659
	MAR	496,908	446,173	384,462	322,487
	GULF	1,737,600	1,747,800	1,462,800	1,178,400
	USWC	1,096,800	1,062,000	895,800	726,300

Source: Rutgers

The economic attractiveness of a hybrid or fully electric FSV as compared to a fully diesel FSV can be assessed at a high level by comparing the initial capital expenditures required for the hybrid and electric configurations to the energy cost savings generated from the electrified vessel as compared to the full diesel vessel during operational deployment. The capital expense estimated includes expenditures for equipment and materials (electric motors, batteries, cables, electronic control, etc.) as well as the labor and expenses associated with the layup and modification period alongside or in a shipyard.

4.5.1 Assumptions

A preliminary approach to this investigation is to examine the energy savings from the initial investment in hybridization. Recall from Section 4.4.4.3.4 the estimated incremental cost for the PHEV platform was US$ 1.75 million. In Table 12 in Section 4.3.1 the energy savings from less fuel burned in PHEV hybrid operation was between US$ 31,738 and US$ 90,993 annually, depending on the location on the US east coast. However, selecting an appropriate project period in years to calculate total energy cost savings is the challenge. Evaluating just the PHEV platform, the payback period (without discounting) would be between 20 and 50 years – but we assume additional electrification investments and savings within a 10-year timeframe. Clearly additional financial elements need to be considered however, the result does provide some useful information - on the basis of cost alone, a PHEV conversion is clearly uneconomic on its own and would not be pursued unless subsidies to offset a substantial amount of the capital cost could be applied or non-economic drivers such as emissions reduction were prioritized.

A fuller perspective on cost attractiveness of electrification would include the entire timeline and step-by-step implementation to fully electric operation illustrated in Table 31. This approach adds complexity to the analysis by assuming multiple capital investments over a 10-year period, upgrading to more electrified propulsion platforms, with several different energy savings profiles resulting after each platform modification. The cost assumptions in the table are ROM estimates with uncertainty increasing for the estimation of cost for future platform modifications. The calculations are evaluated with consideration of the time value of money using a discounted cash flow (DCF) approach. Table 32 1 summarizes the assumptions for this analysis.

Table 31 - DCF Analysis Assumptions – Fully Electric Evolution Assumptions

Element	Assumptions	Remarks
Tier 3 Diesel FSV Platform	US$ 14.50 million	Estimated Acquisition Price
PHEV FSV Platform	US$ 1.75 million	Incremental capital expense (PHEV modifications)
EPHEV FSV Platform	US$ 2.00 million	Incremental capital expense (EPHEV modifications)
Electric FSV Platform	US$ 1.25 million	Incremental capital expense (Fully Electric modifications)
Levering	US$ 0	Unlevered equity return analysis
Annual Energy Savings	US$	31,738-270,760, depending on electrified platform & region
Discount Rate	10%	Assumed cost of capital
Project Period	30 years	10-year electrification roadmap, the 20-year electric operation
Residual Value	10%	Of electrification capital expense, then current US$
Compounding	Annually	In arrears
Diesel Fuel Cost	US$ 1.06/liter	US EIA, 2025
Electricity Cost	US$ 0.16 kWh	US EIA, 2025

Source: BOT, Incat Crowther

In Table 31, capital spend for PHEV, EPHEV and electric conversion are ROM estimates from Incat Crowther based on diesel, hybrid electric and fully electric FSVs designed by Incat Crowther that have either been built or are being built. We assume equity returns only in the DCF cost benefit analysis – a levered case with debt will likely yield more attractive results. We assume energy savings in Table 12, Section 4.3.1, conditioned by utilization and operational considerations. A discount rate of nominally 10% is used to identify the opportunity cost of the investment and to calculate the net present value of the total cash flows from investment and energy savings. The project period is 30 years – 10 years for the implementation of a fully electric platform and 20 years thereafter in operation as a fully electric vessel. Residual equipment value is assumed to be 10% of the total capital invested in the modifications. Compounding is applied annually to simplify the analysis – monthly compounding will yield superior results. A copy of the financial model can be found in Appendix 5.

4.5.2 Results

On the surface, the results in Table 32 suggest slightly positive net present values (NPVs) for electrified deployments in the NECL and the NYB. A deployment in the MAR generates a slightly negative NPV. We can interpret this result as an indication that some electrification projects for FSVs on US east coast deployments are economically favored as compared to other investments of similar risk that generate a 10% unlevered return.

Table 32 - Discounted Cash Flow Analysis Results NECL-NYB-MAR

US$ Million	NECL	NYB	MAR
Cash Flow Valuation - All Equity			
Capital Invested (PHEV, EPHEV, Electric)	5.0	5.0	5.0
PV of Capital Invested	2.7	2.7	2.7
Total Present Value Energy Savings	3.0	2.9	1.9
Hurdle Rate	10%	10%	10%
NPV	0.3	0.2	(0.8)
IRR	11.7%	11.1%	5.5%

Source: BOT

We solved for the internal rate of return (IRR) of the unlevered deployments in Table 32. Note that we discount our future investments in electrification modifications at a fixed 10% discount rate while discounting future positive cash flow at the rate required to yield a US$ 0 NPV. Doing so results in an IRR of 11.7% for the northeast cluster (NECL), an IRR of 11.1% in the NYB and an IRR of 5.5% for the MAR. These results would improve somewhat using debt leverage and compounding monthly.

4.5.2.1 Capital Cost Sensitivity

If we look a little deeper into this subject, we can evaluate the sensitivity to capital costs, energy costs and the value of the social costs of emissions in the DCF result.

In Table 33 we vary capital costs to determine the sensitivity of the DCF result, and hence overall attractiveness of electrification of FSVs using a 20 percent capital cost reduction. The results indicate substantially increased IRRs across the three deployments.

Table 33 - Discounted Cash Flow Analysis Results NECL-NYB-MAR – 20% Capital Cost Reduction

US$ Million	NECL	NYB	MAR
Cash Flow Valuation - All Equity			
Capital Invested (PHEV, EPHEV, Electric)	4.0	4.0	4.0
PV of Capital Invested	2.2	2.2	2.2
Total Present Value Energy Savings	3.0	2.7	3.8
IRR	15.8%	15.1%	8.4%

Source: BOT

Reduced capital requirements from design and/or technology improvements or through subsidy can improve the economic attractiveness of the FSV project significantly, increasing returns by 3-4%.

4.5.2.2 Incorporating Variation in Energy Costs

In Section 3.2.3.3 we established the energy costs used in the study as US$ 1.06/liter for diesel fuel and US$ 0.16/kWh. Energy rates exist in a dynamic market and fluctuate continuously in response to the competitive drivers existent in the associated market segments. In this study we do not attempt to forecast energy costs as there are numerous agencies worldwide who are much more experienced and equipped to do so. Here we reproduce expectations from the International Energy Agency (IEA) regarding future energy prices and then calculate the effect of a percentage change in energy price differences, leaving the reader to render an assessment of the benefit of electrification based on their own energy price appraisal. Table 34 is taken from the IEA publication "Global EV Outlook 2025 - Expanding Sales in Diverse Markets", published in July 2025.

Table 34 – Prices of diesel, electricity, and hydrogen, 2024 and 2030
Hydrogen prices are composed of the weighted levelized cost of productions and distribution, an assumed margin of 20%, and 10% tax. Underlying electricity prices are the same at both the depot and during enroute charging with the difference between them due exclusively to the differences in the infrastructure costs.

	Units	UNITED STATES		EUROPEAN UNION		CHINA	
Fuel	2024 US$	2024	2030	2024	2030	2024	2030
Diesel	US$/kWh	0.11	0.12	0.17	0.19	0.11	0.11
Diesel	US$/L	1.14	1.18	1.70	1.88	1.10	1.14
Electricity	US$/kWh	0.16	0.16	0.24	0.23	0.08	0.08
Hydrogen	US$/kWh	0.12	0.15	0.23	0.30	0.15	0.14
Hydrogen	US$/kg Hydrogen	3.88	4.87	7.84	9.88	4.86	4.83

Source: International Energy Agency, IEA, 2025

Tables 35 and 36 illustrate maximum effects of a +/- 10% change in diesel fuel prices and +/- 10% change in electricity prices.

Table 35 - Discounted Cash Flow Analysis Results NECL-NYB-MAR – More Expensive Diesel Cost, Less Expensive Electricity Cost - Diesel @ +10% = US$ 1.166/liter, Electric @ (10%) = US$ 0.144/kWh

US$ Million	NECL	NYB	MAR
Cash Flow Valuation - All Equity			
Capital Invested (PHEV, EPHEV, Electric)	5.0	5.0	5.0
PV of Capital Invested	2.7	2.7	2.7
Total Present Value Energy Savings	4.3	4.3	2.8
NPV	1.6	1.6	0.1
IRR	18.7%	18.9%	10.7%

Source: BOT

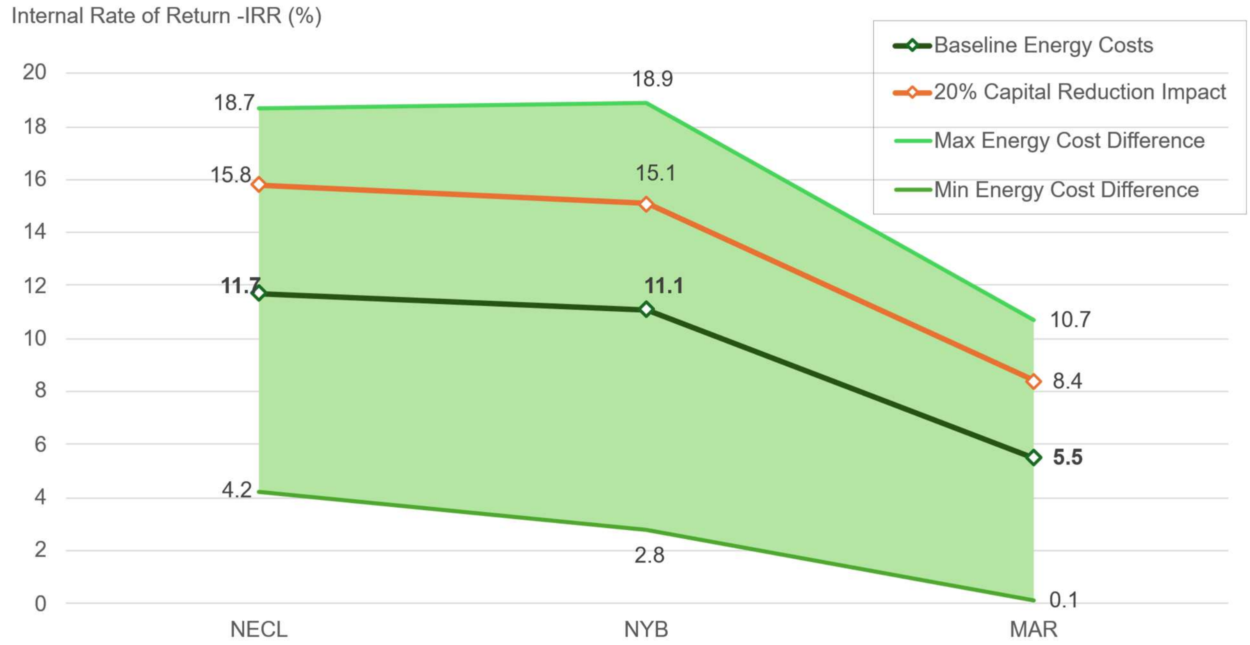
Table 36 - Discounted Cash Flow Analysis Results NECL-NYB-MAR – Less Expensive Diesel Cost, More Expensive Electricity Cost - Diesel @ (10%) = US$ 0.954/liter, Electric @ +10% – US$ 0.176/kWh

US$ Million	NECL	NYB	MAR
Cash Flow Valuation - All Equity			
Capital Invested (PHEV, EPHEV, Electric)	5.0	5.0	5.0
PV of Capital Invested	2.7	2.7	2.7
Total Present Value Energy Savings	1.7	1.5	1.0
IRR	4.2%	2.8%	0.1%

Source: BOT

A ten percent variation in energy costs results in an increase/decrease in the IRR of five to seven percentage points across the three regions. Figure 46 summarizes the effect of energy cost and capital cost variation on the unlevered project returns.

Figure 46 - IRR Range with Capital Cost and Energy Cost Variation
(20%) Capital Cost variation, +/1 10% Energy Cost Variation



Source: BOT

4.5.2.3 Incorporating the Social Cost of Emissions

Regarding emissions costs the literature refers to tangible cost estimates of emissions production from a social costs perspective to aid in total cost calculation including environmental impact. For example Meyer writes that the Social Cost of Carbon (SCC) is an estimate, in dollars, of the economic damages that result from emitting an additional ton of carbon dioxide into the atmosphere, a metric used to determine the economic value of one ton of greenhouse gas (GHG) emissions (2024). In May 2024, the US EPA released an updated SCC estimate that values GHG emissions at over US$ 190 per ton.

The goal of the metric is to encompass the broad variety of economic and societal impacts caused by GHG emissions and place a dollar value on those impacts. This allows policymakers to consider the monetary value of preventing GHG emissions in solid terms when considering the costs and benefits of proposed rules. The metric was created several years ago and has varied over the years with different interpretations of its composition and the value of its components. As a result, its value should be considered indicative, not definitive.

For the purpose of this study we carry out an exercise where we *solve* for the social cost of carbon emissions that is required to produce a 20% unlevered return on equity and leave to the reader the assessment of whether this social cost value is appropriate. A 20% unlevered return represents an attractive investment opportunity in marine logistics. This approach yields the results displayed in Table 37.

Table 37 - Discounted Cash Flow Analysis Results NECL-NYB-MAR – Solving for Social Cost of Emissions

US$ Million	NECL	NYB	MAR
Cash Flow Valuation - All Equity			
Capital Invested (PHEV, EPHEV, Electric)	5.0	5.0	5.0
PV of Capital Invested	2.7	2.7	1.7
Total Present Value Energy Savings	3.0	2.9	1.9
IRR	20%	20%	20%
Total Social Cost of Emissions Required for 20% IRR	US$ 62.73/mt	US$ 61.40/mt	US$ 155.20/mt

Source: BOT

Findings and observations from the results in Tables 31 through 37 are summarized in Section 4.5.2.

4.5.2 Findings and Observations

Using a traditional discounted cash flow (DCF) approach of evaluating the economic benefit of electrification of FSVs, the results suggest slightly positive net present values (NPVs) for electrified deployments in the NECL and the NYB regions while a deployment in the MAR generates a slightly negative NPV at a 10% hurdle rate.

Additional granularity in the results is achieved by solving for the internal rate of return (IRR) for each of these deployments. Doing so results in an IRR of 11.7% for the northeast cluster (NECL), an IRR of 11.1% in the NYB and an IRR of 5.5% for the MAR, illustrating the higher value proposition of electrification on the NECL and NYB deployments.

The economics are sensitive to the investments required: a 20 percent capital cost reduction, either through subsidy or technological advance can improve the economic attractiveness of the FSV project significantly, increasing returns by 3-4%.

The relative cost of different energy sources is an important economic driver of electrification - A ten percent variation in energy costs results in an increase/decrease in the IRR of five to seven percentage points across the three regions, a significant influence on project attractiveness.

When solving for the social cost of carbon emissions that is required to produce a 20% unlevered return on equity (a strong economic result) from electrification, the range of values is in line with past estimates of US$/kg.

5 Project Uncertainties and their Outcomes

5.1 Inclusion of Certain Sea State Variables

5.1.1 Significant Wave Height –Best Regression Model Results

As explained in 4.1.4, a regression model was created for three of the four sea state variables: significant wave height, wave period, and wind speed, enabling the team to probabilistically predict a distribution of true met-ocean behavior at various locations. While data from the buoys was collected and the regression model created to incorporate all the variables, the team decided throughout the course of the research to focus mainly on significant wave height. This was for two reasons: 1) significant wave height is the key determinant of power requirements and associated energy costs, and 2) this variable had the best regression model results while other elements experienced lower correlation coefficients, as seen in Table 2. Accounting only for significant wave height results in a quality simulation output as wave height relates the most closely with power consumption due to resistance the vessel will experience. However, incorporating the other variables may result in lower serviceability scores (but with less confidence).

Additionally, wave direction was analyzed, but with limitations. Without more advanced analysis under the Empirical or Theoretical approaches discussed in 5.2, the team determined that the most straightforward way to incorporate this into the model was to assume head seas, or worst-case conditions. The outcome of this is more conservative outputs for this element: under the worst-case scenario, the vessel will consume more energy and simulation results will show greater emissions and fuel and electric costs. Section 7.1.2 discusses follow-on work stemming from the inclusion of additional sea state variables, as well as the use of more in-depth methods of estimating energy consumption and emissions across vessel propulsion types.

5.2 Emissions & Consumption Data Sources

5.2.1 Considered 3 Approaches – Cost Benefit Analysis

The team evaluated different methods to estimate energy consumption and emissions for diesel propulsion, parallel-hybrid propulsion, advanced parallel-hybrid electric propulsion, and fully electric propulsion in different sea state conditions in order to populate the operating profiles. The team weighed the pros and cons such as cost, time, and usefulness of data (Table 38).

5.2.1.1 Delphi Approach

Methodology: Use industry expertise and discussions with vessel operators to best estimate the energy consumption and emissions values for a range of sea states. This offers qualitative added resistance in different sea states based on observation and experience. Results would show values at an assumed heading of zero degrees and in different wave heights.

5.2.1.2 Empirical Approach

Methodology: Use data from the operations of an existing vessel. This offers actual performance data for a similar 32-meter vessel based on recorded data and sea conditions. Steps include the collection, distillation, evaluation and analysis of empirical data for the creation of a table of energy consumption and emissions production estimates to simplify the calculation steps and facilitate the processing of a large number of operational profile cases.

5.2.1.3 Theoretical Approach

Methodology: Use computational fluid dynamics (CFD) calculations in regular waves in different directions using a seakeeping modeling tool and inputting the vessel's hull profile. Results would be a tabulation of quantitative added resistance in different sea states based on theoretical modeling, showing more specificity in energy demand based on the vessel's performance.

Table 38 - Comparison of approaches to consumption and emissions estimates

Method	Cost	Accessibility	Time involved	Accuracy
Delphi	$ - Up to 10k	Easiest to obtain	1 – 2 weeks	Estimated values
Empirical	$$ - Up to 30k	More involved with collection, distillation, etc.	8 - 10 weeks	Actual data
Theoretical (CFD)	$$$ to $$$$ 60k and up	Additional engineering expertise required	3 or more months	Industry recognized approach, but lacks real data

Source: BOT, Incat Crowther

5.2.1.4 Delphi Approach is Most Appropriate at this Stage

While the data resulting from the Delphi approach is limited, the other methods are costly and/or time consuming. Additionally, the Empirical Approach lacks relative heading of the vessel to the sea while the Theoretical Approach results in a base case with limited use; adding headings would dramatically increase cost from the baseline results.

Considering all the variables, the team decided that the Delphi approach is an appropriate level of specificity for this research project. While Delphi is most appropriate at this stage, it introduces an uncertainty by relying on quasi-subjective parameter values. A more robust, yet more economical than computational method, would be the collection and statistical analysis of empirical data to yield these results.

5.2.1.5 Pace of Technological Advancement

Another project uncertainty, as related to our second hypothesis that electrification of propulsion systems is more cost effective, is the pace of technological advancement. The historical and projected advancement of ESD is discussed in Section 4.4.3, and our findings show that the industry's projections most always undercast the market. However, projections may change as market saturation for electrification potential increases. Only time will determine where in the 10-year timeline assessed in this study storage density will land and when the optimal time to transition to the next evolution of electrified propulsion system will be.

[This page left blank for two-sided printing]

6 Conclusions & Recommendations

6.1 Conclusions

6.1.1 Realistic Environmental Conditions Model

An empirical/numerical statistical modeling approach produces realistic met-ocean datasets trained to given regions identified by the proximity of the buoys employed for data collection.

To realistically model met-ocean conditions, observational (buoy) data provides high-fidelity information about met-ocean conditions but using them restricts the evaluation to time periods when measurements are available, which is limited. Fairly long tracks of data are missing, resulting in misleading estimates due to the absence of important temporal features, such as season-to-season and year-to-year variations. Combining these observations with numerical model data which are fairly abundant helps to resolve the data missingness issues relative to observational data, but numerical models exhibit considerable biases that can increase estimation errors. A statistical framework was constructed to combine the high-fidelity buoy observations with the fairly abundant (but lower-fidelity) numerical model data, for improved estimates. The environmental conditions model was further improved to account for seasonal variability and significant auto-correlations through the inclusion of Fourier terms to capture monthly and yearly seasonalities with additional terms to capture autocorrelations diurnal seasonality. Ultimately, the model was incorporated into the MTM logic in the simulation model.

This approach met the goal of the formulation to calibrate the numerical model output and adjust for the remaining temporal variability that is not fully explained by the numerical model. The result is a modeling approach that produces realistic met-ocean datasets trained to given regions identified by the proximity of the buoys employed. Therefore, realistic energy consumption and emissions can be probabilistically modeled for FSVs in any offshore US region.

6.1.2 Regional Sea States

There are significant differences in sea spectra across regions with sea states varying from benign to severe – the models produced in this study allow for quantitative analysis of their comparative impact on the type and design of vessels deployed.

The five regions provided a good sampling of weather and sea states as well as voyage routing and operational profiles. Of the five areas considered in the study, the environmental conditions model indicates the USWC experiences the highest probability of the most consistent severe conditions with an H_s at 1.45 meters and low standard deviation of 0.39 meters. A right-skewed distribution indicates the preponderance of sea states is challenging for mid-to-smaller size vessels such as FSVs. On the other side of the severity range are the MAR and GULF areas, both with similar, relatively benign wave spectra results having an H_s of 0.83-0.84 meters. Left-skewed distributions indicate greater proportions of waves with heights towards the lesser size. In the northeast, both the NECL and NYB areas have significant wave heights around one meter on average. An important finding from these regional discussions is that location matters as the conditions offshore and hence performance results and input to vessel design parameters, vary considerably from harsh to benign from place to place.

6.1.3 Seasonal Sea States

Seasonal variation of sea states exhibits the same behavior across all regions: winter conditions are more severe than summer conditions.

Seasonal variation of sea states (full year; winter - November through April; and summer - May through October), exhibits the same behavior across all regions: While the overall shape of the distributions is preserved season to season, winter conditions are more severe than summer conditions. Seasonal variation is material in terms of sea spectra results with winter conditions more extreme than summer conditions offshore.

6.1.4 Simulation Model Results

The simulation model developed in the study produced energy consumption and emissions results for deployments in dynamic sea states useful as input parameters to the design process for FSV propulsion.

Using the Met-Ocean Model (MTM) results in combination with a Spatio-Temporal Route Mapper (SRM) algorithm and Conditions-Consumption-Emissions (CCE) routine, the simulation model was able to produce results for large numbers of runs, calculating energy consumption and emissions production for each run. The results reflected deployment of the vessels in a dynamic sea state according to the sequence of activities described by the operating profile for the specific regional voyage to and from the offshore site. The distribution of these results all showed central tendencies around a mean value representing the most probable consumption and emissions result for that voyage.

6.1.5 Deployment Criteria

Regional deployments with high speed transits representing large portions of the operational profile are not ideal candidates for electrification

For example, in considering comparative energy costs and emissions production for the four propulsion platforms, the NYB total energy cost results reveal the relatively small savings from PHEV over diesel propulsion. This is due to the 15 nm leg conducted at 25 knots which represents 86% of the one-way voyage length and a larger share of total energy being provided by the diesel engines, as compared to the 10-knot transit of 2.2 nm (12%), making the PHEV platform less cost effective on this routing. The EPHEV, with additional electric motors, is able to supply some high speed transit from the motors, increasing the energy efficiency and reducing the cost of this platform.

On the GULF routing, the vast majority of the voyage time is spent at high speed, 108 nm distance versus 3.5 nm at 10 knots or under. This drives the comparative efficiency of the PHEV hybrid down due to influence on cost of the prolonged run under diesel power, with results on par with a full diesel platform's efficiency levels. On the USWC routing, the high speed distance represents the majority of the voyage which drives the efficiency of the PHEV towards the full diesel configuration, while the better equipped EPHEV is still able to generate meaningful savings on this route. While this result demonstrates the theoretical attractiveness of electrification on these routes, feasibility based on ESD technology readiness may limit practical deployment of FSVs on these routes.

6.1.6 A New Parameter: Serviceability

Accessibility and Approachability are not sufficient to characterize regional deployments to offshore sites, a new measure – Serviceability - serves the purpose

It became obvious that there was no method for measuring likelihood of mission completion when taking into account the entire operational route of a vessel for the whole duration of its mission. Unlike approachability, which is limited to one point in time, and accessibility, which is limited to one spatial location, the new concept of serviceability developed throughout the course of this research accounts for dynamic spatial and temporal progression along the vessel route.

Serviceability is of greater utility to operators servicing offshore oil and gas installations and other offshore infrastructure: It identifies the likely percentage of completed missions throughout the construction and O&M phases based on weather and sea state conditions present.

6.1.7 Electrification Benefits

As the level of propulsion platform electrification increases, the total energy cost and total emissions declines

Simulation results for total energy consumption and emissions output illustrate that as the level of propulsion platform electrification increases, the total energy cost and total emissions declines, using energy costs for diesel fuel of US$ 1.06/liter and for electricity at US$ 0.16/kWh. As these rates change relative to one another, these findings may change. Increases in diesel fuel cost assumptions with decreases in electricity cost assumptions produce the most favorable results supporting electrification. The least favorable results to support electrification are observed when diesel prices are relatively low and electricity is relatively expensive. Therefore, predictable energy costs or hedging the spread between diesel fuel and electricity costs is an important success factor for electrification.

On deployments where high speed, high energy intensity legs dominate, electrification will be less attractive or even infeasible due primarily to the challenge of balancing energy storage capacity with weight. For example, for the relatively small improvement in energy costs and emissions reduction achieved by the PHEV platform over the diesel platform, in some regions like the GULF and USWC savings are effectively zero. This is due to the large percentage of the time spent on the voyage in energy intense, high speed operation. The GULF operating profile contains two 108 nautical mile (nm) transits to/from the offshore site at high speed while the USWC route has two 48 nautical mile transits at high speed. The other routes have nominal high speed legs (NYB-15 nm, MAR-24 nm, NECL-0 nm). The GULF and USWC deployments would not be recommended for electrification in general.

Emissions output follows the same pattern where deployments where the greatest high speed transits see the greatest emissions reductions through electrification.

A review of seasonal consumption figures reveals no surprises. As expected, winter seasonal simulation results indicate the highest consumption levels, summer season the lowest with full year results falling in between. These results are observed across the five regions and deployments. Using winter seasonal results to inform on vessel propulsion system design will be the prudent, yet considered approach to the specification of a new vessel.

6.1.8 Current Technology Limits

Current energy storage density (ESD) technology does not presently support feasible offshore deployments of fully electrified high speed aluminum catamaran service vessels

Through researching and tracking of hybrid or fully electric vessels of all types in the US, we notice that electrifying vessels is most suitable for those with predetermined routes that operate near shore and have frequent charging availability. For example, ferries are very suitable for electrification because they shuttle between ports and can rapidly charge while passengers are embarking and disembarking. Some of the notable electrified vessels in recent news are ferries, notably the Harbor Charger in New York City, the Wenatchee in Washington State, a retrofit. Meanwhile, hybrid electric ferries have been around since approximately 2010 with the Hornblower ferries supporting San Francisco Bay.

6.1.9 Fully Electric FSV in 10 Years

A fully electric FSV is feasible within a 10-year timeframe for selected offshore deployments with required onshore and offshore charging infrastructure

Future ESD requirements were found using current vessel weights for a conventionally powered FSV with four Tier 3 diesel engines and replacing these with four electric motors capable of meeting mission requirements, batteries and all necessary system components while maintaining the vessel weights of the conventional configuration.

Using 40% min charge required (SOC), fully electric FSV deployment is possible on MAR route assuming an ESD of 454 WH/KG. Considering the design of a fully electric FSV 10-years hence using the same vessel platform as a fully diesel-powered vessel today, design parameters – especially weight – result in a required energy storage capacity for the batteries of ~ 6,300 kWh, and an ESD required of 454 Wh/kg.

Projections using Boltzmann Sigmoid curves for improvement in ESD demonstrate that it is reasonable to expect ESD 10 years from now in the range of 450-550 Wh/kg, while the ESD required to make a fully electric FSV is 454 Wh/kg. This supports the claim that a fully electric FSV can be achieved within 10 years' time, providing the foundation for proving the study's third hypothesis that evolution from diesel propulsion to fully electric propulsion can be achieved cost effectively using one vessel platform.

6.1.10 Phased Electrification

Rather than wait, electrification can be pursued in phases beginning with initial construction of a diesel driven FSV or a parallel hybrid propulsion platform

Cost effectively employing the same vessel, a phased approach is suggested with platform evolution through four modification stages beginning with a newbuilding Tier 3 diesel driven FSV today, then modified with a parallel-hybrid electric propulsion, followed by an advanced parallel-hybrid electric propulsion to a fully electric FSV envisioned in about 10 years. Alternatively, with an infusion of extra capital, a vessel owner could begin with PHEV and then proceed to EPHEV and fully electric within the 10-year timeline.

The current electric motor operational profile for a PHEV platform enables the vessel to save fuel and emissions during certain portions of the voyage. On an annual basis, the cost savings is estimated to be about US$ 50,400 at the assumed diesel pricing of US$ 1.06 per litre. This is in comparison to a similar vessel without batteries or the additional electric equipment associated with the hybrid system, and with all propulsion power from diesel engines and hotel load provided by diesel generators.

The current installed battery capacity assumed for the PHEV is only sufficient for in-port idle and transit and slow speed loitering & transfer at the offshore site, but includes providing energy for hotel loads during these periods as well. To provide assistance during the transit operations greater capacity is required. Double the battery capacity is required for the E-motors to provide their full capability during the slow speed transit (10 knots).

6.1.11 Electrification Value Proposition

There is an attractive value proposition when considering full electrification achieved in stages over a 10-year timeline even without consideration of the social cost of emissions, but it is sensitive to the relative cost of the different forms of energy.

Based on a rough, order-of-magnitude (ROM) cost analysis carried out by Incat Crowther, a Tier 3 diesel propulsion FSV is estimated to cost approximately US$ 14.5 million. Modifications representing increasingly electrified propulsion amount to an estimated US$ 5 million over an implementation period of about 10 years. The key items contributing to the increase in cost are: Electric motors, hybrid control systems, batteries, additional large diameter electrical cables and additional/larger transformers.

Table 39 - Estimated Costs of Electrified Platforms

Tier 3 Diesel FSV Platform	US$ 14.50 million	Estimated Acquisition Price
PHEV FSV Platform	US$ 1.75 million	Incremental capital expense (PHEV modifications)
EPHEV FSV Platform	US$ 2.00 million	Incremental capital expense (EPHEV modifications)
Electric FSV Platform	US$ 1.25 million	Incremental capital expense (Fully electric modifications)

Source: BOT

Reduced energy costs resulting from electrification drive financial analysis results. Two of the three deployments on the US east coast had positive NPV's at a 10% hurdle rate, and all had positive internal rates of return: An IRR of 11.7% for the northeast cluster (NECL); an IRR of 11.1% in the NYB; and an IRR of 5.5% for the MAR. Leveraging modifications with debt will improve equity returns beyond these results as will more realistic financial modeling using monthly compounding.

Reduced capital requirements from design and/or technology improvements or through subsidy can improve the economic attractiveness of the FSV project significantly, increasing returns by 3-4%.

A ten percent variation in energy costs results in an increase/decrease in the IRR of five to seven percentage points across the three regions, making the attractiveness of electrification sensitive to energy cost differentials between diesel fuel and electricity.

Solving for the social cost of carbon emissions that is required to produce a 20% unlevered return on equity on the electrification project described in this study yields values between US$ 60/mt and US$ 155/mt.

The results of the financial analysis confirm our third hypothesis of an economic evolution from diesel to fully electric propulsion, with the caveat that not all offshore FSV deployments are favored for electrification.

6.2 Recommendations

Findings from the study lead to the following recommendations in terms of the continued examination of the topics discussed in this work.

Analysis of the performance of several electrified propulsion platforms on different mission deployments in three different US offshore regions leads to a foundational observation and recommendation. Avoid FSV electrification projects where high speed, high intensity energy legs represent the majority of the operational profile. Not all offshore FSV deployments are favored for electrification.

Further, efforts to develop offshore charging infrastructure should be broadly and vigorously supported. Even with large improvements in ESD of batteries, offshore charging infrastructure is a critical prerequisite for full electrification of FSV deployments.

Research electrification equipment to optimize systems and minimize capital expenses. Investment attractiveness of the electrification FSVs is sensitive to the capital expense of doing so – application of technologies to reduce equipment and overall system cost will improve return on investments.

Additional recommendations to pursue further investigations are highlighted in Section 7, Opportunities for Further Analysis.

[This page left blank for two-sided printing]

7 Opportunities for Further Analysis

7.1 Extension of This Approach to:

7.1.1 Other US and Global Regions

Existing locations developed under this study are the Mid-Atlantic Region, NY/NJ Region, Northeast Region, US Gulf, and West Coast. An additional US site that can be studied is the Alaskan coast with its abundant offshore natural resources. Additionally, offshore Alaska has become more in focus of late as the federal government seeks to develop further oil and gas leasing areas there, with the first of a series of lease sales being held in March 2026. Another region where this research may be applied is the Great Lakes with an abundance of wind and wave energy available and robust maritime industry. Finally, the research methods used here can be applied globally through the collection of buoy data abroad and expansion of the model to these other regions.

7.1.2 Additional Sea State Variables and other Methods of Data Collection

Additional opportunities for extensions of this research include incorporating additional sea state variables into the model and utilizing more robust tools for estimating emissions and energy consumption inputs. With significant wave height being the prime focus for this research as explained in Section 5.1, there remains an opportunity to include the other variables of wave period and wind speed in model simulations in furtherance of this work. Similarly, wave direction was assumed in this study to be the worst-case scenario of 0 degrees with the vessel traveling through waves head on. Further opportunities to use wave heading data are discussed in Section 5.2.1, where three sources of data were assessed and a cost-benefit analysis conducted for this project. While the Delphi method was most appropriate for this initial study, the Empirical and Theoretical approaches, depending on availability of funding, can be used by the project team or other researchers for follow-on work. The Empirical Approach would result in credible, valuable data and expansion of the simulation model to include relative heading of vessel to the wave direction and the Theoretical Approach may be useful for validation and proof of concept in follow-on work as well as of utility to the industry at large.

7.2 Serviceability Tool

As explained in Section 4.2.6, serviceability, as opposed to approachability and accessibility, is of greater utility to operators servicing offshore oil and gas installations and other offshore infrastructure: It identifies the likely percentage of completed missions throughout the construction and O&M phases based on weather and sea state conditions present. The opportunity arises for a Serviceability Support Tool, a web-based decision support tool, which will put advanced decision support capabilities in the hands of operators and charterers via the use of a dashboard. Using the simulation model developed for this paper, a user friendly approach via a General User Interface (GUI) could be developed for a more user-friendly and accessible approach, enabling widespread industry use.

This tool will help offshore project developers in the US to evaluate optimal site selection based on the serviceability assessment at various offshore sites, and will help operators, marine logistics planners and project managers of existing project sites to evaluate logistics deployments (number and type of vessels) for offshore projects across multiple industries including research & survey, aquaculture, buoy maintenance, etc.

Many offshore service companies use static, not dynamic, Operating Profiles to estimate offshore site accessibility. Such an assessment is based on limited use of data that leads to under- or over-estimations of accessibility and results in wasted resources like fuel and provisions during failed missions. This tool will provide another layer of decision-making capability to vessel logistics operations in supporting offshore sites. The tool would provide results based on measurable, predictable, reliable datasets on which to make decisions – to help ensure the safety and comfort of crew and offshore workers.

7.3 Site Planning and Vessel Spread Analysis for Offshore Infrastructure Locations

Appropriate site location is a critical component to a successful offshore energy project. The procurement of a particular offshore site or lease area shall typically include a thorough review of the available and proven marine assets needed to both construct and service the project that are not only available and deliverable, but also proven from the perspectives of safety, efficiency, capability and affordability, to name a few.

For example, to effectively determine if a particular offshore infrastructure site can be successfully developed and maintained during its lifecycle, the site developer will be required to understand that site's full potential and any underlying requirements for serviceability. To determine appropriate serviceability of the offshore site, a vessel spread analysis should be carried out which will include the review of marine logistics parameters such as the characteristics of the site in terms of weather conditions like wind and sea state for annual and seasonal trends and baselines. This analysis will drive the user of the site to determine the most optimum marine spread for their project driven by the characteristics of the site in terms of sea state and other variable weather conditions to effectively determine what size of assets shall be procured to give the user the most probability of success if effectively deploying these assets offshore to carry out their functions given the expected on site conditions.

Efficient and effective management of the vessels within a project's marine spread is a critical component of a successful offshore energy project as operational uptime and project budgets play key roles in the project landscape. Offshore project developers in the US can use the serviceability support tool to evaluate optimal site selection based on the serviceability assessment at various offshore sites, and will help operators, marine logistics planners and project managers of existing project sites to evaluate logistics deployments (number and type of vessels) for offshore projects across multiple industries.

References

ABB. (2024, November 13). All American Marine and ABB to collaborate on new hybrid-electric ocean sampling vessel in California. https://new.abb.com/news/detail/121162/all-american-marine-and-abb-to-collaborate-on-new-hybrid-electric-ocean-sampling-vessel-in-california

Alcatraz City Cruises. (n.d.). Our fleet of vessels. https://www.cityexperiences.com/san-francisco/city-cruises/alcatraz/fleet/

AOS. (n.d.). G-Class. https://a-o-s.com/the-fleet/g-class/

ASOW. (2020). Atlantic Shores offshore wind data. https://erddap.maracoos.org/erddap/tabledap/index.html?page=1&itemsPerPage=1000

Baird Maritime. (2025, July 04). VESSEL REVIEW | Juliette Gordon Low II & Susie King Taylor II – Hybrid electric ferries to serve commuter routes in Savannah, Georgia. https://www.bairdmaritime.com/passenger/ferry/vessel-review-juliette-gordon-low-ii-susie-king-taylor-ii-hybrid-electric-ferries-to-serve-commuter-routes-in-savannah-georgia

Baker, C. (2024). Case study: Hybrid ferries to Alcatraz. National Park Service. https://www.nps.gov/articles/000/alcatraz-hybrid-ferries.htm

Bauman, M. (2025, October 29). Innovative propulsion systems coming for Alaska fishing boats. National Fisherman. https://www.nationalfisherman.com/innovative-propulsion-systems-coming-for-alaska-fishing-boats

Bauman, M. (2026, January 7). Alaska fishing vessel set to trial hybrid propulsion system. National Fisherman. https://www.nationalfisherman.com/alaska-fishing-vessel-set-to-trial-hyrbird-propulsion-system

Bloch, C., Newcomb, J. & Tyson, M. (2019, October 29). Massive Investment Is Accelerating the Era of Clean Electrification. RMI. https://rmi.org/massive-investment-is-accelerating-the-era-of-clean-electrification/

BMT. (2025, May 2). A collaboration built on trust - one vessel at a time. https://www.bmt.org/news/2025/a-collaboration-built-on-trust-one-vessel-at-a-time/

Brintnell, T. (2023, March 10). Mackinac Island Ferry Chippewa set for electric transformation. 9and10 News. https://www.9and10news.com/2023/03/10/mackinac-island-ferry-chippewa-set-for-electric-transformation/

Brooks, J. (2026, February 3). Alaska again seeks U.S. shipyard to build oceangoing ferry to replace Tustumena. Anchorage Daily News. https://www.adn.com/alaska-news/2026/02/03/alaska-again-seeks-american-shipyards-to-build-new-oceangoing-tustumena-replacement-ferry/

Burger Boat. (n.d.). Maid of the Mist. https://www.burgerboat.com/commercial-vessels/commercial/maid_of_the_mist/

Candela. (2026). C-8: Simply a better experience. https://candela.com/leisure-boats/candela-c-8/

Code of Federal Regulations (CFR) Title 33, Part 166. Shipping Safety Fairways. Last modified February 12, 2026. https://www.ecfr.gov/current/title-33/chapter-I/subchapter-P/part-166

Conley, C. (2025, May). Greener discoveries. WorkBoat Magazine. https://issuu.com/workboatmagazine/docs/workboat_may_2025

Corvus Energy. (n.d.). Enhydra. https://corvusenergy.com/projects/enhydra/

Crowley. (2024, January 24). Crowley accepts delivery of eWolf, the first fully electric tugboat in the U.S. https://www.crowley.com/news-and-media/press-releases/crowley-accepts-delivery-of-ewolf-the-first-fully-electric-tugboat-in-the-u-s/

Crowley. (n.d.). eTug. https://www.crowley.com/wp-content/uploads/sites/7/2024/08/24-05635-eWolf-Spec-Sheet-V3.pdf

EBDG (Elliott Bay Design Group). (n.d.). Casco Bay Lines. https://www.ebdg.com/cascobaylines

Empire Wind. (2025, June 30). US-built service operations vessel Eco Liberty launched to support Equinor's Empire Wind project. [Press Release]. https://www.empirewind.com/2025/06/30/us-built-service-operations-vessel-eco-liberty-launched-to-support-equinors-empire-wind-project/

Flagship Cruises & Events, California Climate Investments, & Aurora Marine Design. (2025, December 4). 275 Passenger Flagship ZEST Vessel Procurement, RFP 2509. Part B – Vessel Technical Specifications (Revision 1). https://flagshipsd.com/sites/default/files/userfiles/files/ferry/RFP%202509%20Part%20B-275%20Passenger%20Flagship%20ZEST-Technical%20Specification.pdf

Foxwell, D. (2023, March 23). Third and final CTV for Saint-Nazaire offshore windfarm delivered. Riviera. https://www.rivieramm.com/news-content-hub/news-content-hub/third-and-final-ctv-for-saint-nazaire-offshore-windfarm-delivered-75470

Hammerman, A. (2023, December 19). New ferries and conversions focus on reduced emissions. https://www.workboat.com/new-ferries-and-conversions-focus-on-reduced-emissions

Harmon, J. E. (2023, February 22). New design for lithium-air battery could offer much longer driving range compared with the lithium-ion battery | Argonne National Laboratory. https://www.anl.gov/article/new-design-for-lithiumair-battery-could-offer-much-longer-driving-range-compared-with-the-lithiumion

Haun, E. (2024, November 24). Photon Marine aims to enable the 'workboats of the future.' WorkBoat. https://www.workboat.com/photon-marine-aims-to-enable-the-workboats-of-the-future

Haun, E. (2025a, February 11). Shift to hybrid propulsion gains momentum in the U.S. ferry sector. https://www.workboat.com/shift-to-hybrid-propulsion-gains-momentum-in-the-us-ferry-sector

Haun, E. (2025b, August 18). Keel laid for NOAA research vessel Surveyor. WorkBoat. https://www.workboat.com/keel-laid-for-noaa-research-vessel-surveyor

Haun, E. (2025c, August 26). Fleetzero, Glosten team on hybrid vessel conversion. WorkBoat. https://www.workboat.com/fleetzero-glosten-team-on-hybrid-vessel-conversion

Haun, E. (2025d, August 26). Port Houston orders hybrid electric tour vessel. WorkBoat. https://www.workboat.com/port-houston-orders-hybrid-electric-tour-vessel

Haun, E. (2025e, November). New ferry brings green advantages to the Big Apple. WorkBoat November 2025. https://www.workboat.com/new-ferry-brings-green-advantages-to-the-big-apple

Haun, E. (2025f, December 11). All American lays keel for San Francisco's new battery-electric ferry. WorkBoat. https://www.workboat.com/all-american-lays-keel-for-san-franciscos-new-battery-electric-ferry

Hayden, B. (2024, March 13). Gulf Island delivers new hybrid-electric ferry to Texas. WorkBoat. https://www.workboat.com/shipbuilding/gulf-island-delivers-new-hybrid-electric-ferry-to-texas

Hayden, B. (2025a, March 17). Ferry operators steer toward reducing emissions. WorkBoat. https://www.workboat.com/ferry-operators-steer-toward-reducing-emissions

Hayden, B. (2025b, July 15). Marine Group Boat Works converts diesel yard tug to battery-electric. WorkBoat. https://www.workboat.com/marine-group-boat-works-converts-diesel-yard-tug-to-battery-electric

Hayden, B. (2025c, November). Arc, Curtin Maritime partner on $160 million hybrid-electric tug fleet. WorkBoat November 2025. https://www.workboat.com/arc-curtin-maritime-partner-on-160-million-hybrid-electric-tug-fleet

Hocke, K. (2026, January 20). Matching hybrid-electric propulsion to the mission. WorkBoat. https://www.workboat.com/matching-hybrid-electric-propulsion-to-the-mission

IEA. (2025, July). Global EV Outlook 2025 - Expanding sales in diverse markets.

IMO. (n.d.). Ships' routeing. https://www.imo.org/en/OurWork/Safety/Pages/ShipsRouteing.aspx

Incat Crowther. (n.d.a). IC14127. https://www.incatcrowther.com/ships/ferries/commuter/ic14127/

Incat Crowther. (n.d.b). 32m catamaran wind farm service vessel. https://www.incatcrowther.com/ships/workboats/offshore-wind/ic21008/

Incat Crowther. (2023, June 26). New hybrid crew transfer vessels to begin servicing Germany's offshore wind industry. https://www.incatcrowther.com/news/news-feed/posts/2023/jun/new-hybrid-crew-transfer-vessels-to-begin-servicing-germanys-offshore-wind-industry/

Incat Crowther. (2024, October). Watch this video to see Sadie Ann, the 20-metre hybrid research vessel Incat Crowther designed for University of Wisconsin-Superior [Post]. LinkedIn. https://www.linkedin.com/posts/incat-crowther_underconstruction-shipbuilding-digitalshipbuilding-activity-7247832314712346624-hr3y?utm_source=share&utm_medium=member_desktop

Kitsap Transit. (n.d.). Our ferry fleet. https://www.kitsaptransit.com/agency-information/our-ferry-fleet

LD Armateurs. (2022, August 9). INNO'VENT The first crew transfer vessel designed and manufactured in France [Press Release]. https://www.lda.fr/en/innovent-the-first-crew-transfer-vessel-designed-and-manufactured-in-france/

Maid of the Mist. (2026). Meet the boats. https://www.maidofthemist.com/meet-the-boats/

MaineDOT. (2025). Reducing emissions through renewables. https://www.maine.gov/dot/programs-services/environmental-efforts/climate-initiative/renewables

MARCO. (2026). https://portal.midatlanticocean.org

Marine Jet Power. (2025, January 20). First hybrid waterjet passenger ferries in the U.S. launched for Savannah, Georgia. MarineLink. https://www.marinelink.com/sponsored/pressrelease/first-hybrid-waterjet-passenger-ferries-in-the-us-launched-for-102337

Marine Link. (2023, December 4). Marine News' top vessels of 2023. https://www.marinelink.com/news/marine-news-top-vessels-509883

Marine Link. (2024a, April 23). ABB to provide hybrid-electric propulsion for MaineDOT Ferry. https://www.marinelink.com/news/abb-provide-hybridelectric-propulsion-513188

MarineLink. (2024b, November 19). EBDG, Diversified Marine team on the electrified truckable tug. https://www.marinelink.com/news/ebdg-diversified-marine-team-electrified-519401

Meyer, B. (2024, May). EPA releases updated social cost of carbon estimate. University of Denver, Sturm College of Law.

MHO-Co. (2022, August 2). CTV/FSV MHO-Balder. https://mho-co.dk/wp-content/uploads/2026/01/MHO-Balder-spec.pdf

MHO-Co. (2023). CTV/FSV MHO APOLLO. https://mho-co.dk/wp-content/uploads/2023/11/00-MHO-Apollo-specs.pdf

National Weather Service. (n.d.). Significant wave height. NOAA. https://www.weather.gov/key/marine_sigwave

NOAA. (n.d.). National Data Buoy Center. (n.d.). Station List. https://www.ndbc.noaa.gov/to_station.shtml

NOAA. (2022). WAVEWATCH III model description. https://polar.ncep.noaa.gov/waves/wavewatch/

NOAA Fisheries. (2026, March 09). Reducing vessel strikes to North Atlantic right whales. Last visited January 15, 2025. https://www.fisheries.noaa.gov/national/endangered-species-conservation/reducing-vessel-strikes-north-atlantic-right-whales

NYSERDA (2021). NYSERDA floating LiDAR buoy data https://oswbuoysny.resourcepanorama.dnvgl.com

Oasis Marine. (2024). Powering the future. https://oasismarine.co.uk/powering-the-future/

Oasis Marine. (2025). ScottishPower and Oasis Marine study proves feasibility of offshore charging. https://oasismarine.co.uk/scottishpower-and-oasis-marine-study-proves-feasibility-of-offshore-charging/

Pattanayak, T., & Mavris, D. (2025, June). Battery technology for sustainable aviation: a review of current trends and future prospects. *Applied Energy* 3397.

Petersen, C., Ye, F., Ji, J., Kohut, J., Ezzat, A., Saginaw, D., Montanti, A., & Cammarota, J. (2025a). Accessibility and Serviceability Assessment to Inform Offshore Wind Energy Development and Operations off the U.S. East Coast [Submitted for publication].

Petersen, C., Ye, F., Ji, J., Kohut, J., Ezzat, A., Saginaw, D., Montanti, A., & Cammarota, J. (2025b). Data-Driven Probabilistic Simulation of Vessel Operations to Support the Blue Economy [Submitted for publication]. *Ocean Engineering*.

PNNL. (n.d.). Hybrid electric marine research vessel. https://www.pnnl.gov/hybrid-electric-marine-research-vessel

Professional Mariner Staff. (2018, November 5). 2019 Ship of the year: Enhydra. https://professionalmariner.com/2019-ship-of-the-year-enhydra/

Puttkamer, L. (2024). Electric ship-charging: First station opens in Belgian North Sea. Topos. https://toposmagazine.com/electric-ship-charging-belgian-north-sea/

Redden, J. (2023, August 28). Kirby christens first electric inland towboat. WorkBoat. https://www.workboat.com/shipbuilding/kirby-christens-first-electric-inland-towboat

Reddy, M. V., Mauger, A., Julien, C. M., Paolella, A., & Zaghib, K. (2020). Brief History of Early Lithium-Battery Development. *Materials 13*(8), 1884. doi:10.3390/ma13081884

Richardson, J. (2018, February 25). 38% of American cars were electric in 1900. CleanTechnica, https://cleantechnica.com/2018/02/25/38-percent-american-cars-electric-1900/

SAFE Boats International. (2023, November 28). SAFE Boats and Vita Power Enter into an MOU to Build Zero-Emission Patrol Boat Options [Press Release]. https://safeboats.com/safe-boats-and-vita-power-enter-into-an-mou-to-build-zero-emission-patrol-boat-options/

San Francisco Bay Ferry. (2024, November 2). SF Bay Ferry's Rapid Electric Emission Free (REEF) Ferry Program.

San Francisco Bay Ferry. (2026a). Meet our fleet. https://sanfranciscobayferry.com/meet-our-fleet/

San Francisco Bay Ferry. (2026b). Our history. https://sanfranciscobayferry.com/our-history/

Snyder, J. (2024, December 19). Statue of Liberty ferries will undergo 'electrifying' makeover with Corvus batteries. Riviera Maritime Media. https://www.rivieramm.com/news-content-hub/news-content-hub/statue-of-liberty-ferries-to-be-retrofit-with-corvus-batteries-83393

Spira, J. (2025, May 15). Arc Boat converts a tugboat to electric drive for the Port of LA. ChargedEVs. https://chargedevs.com/newswire/arc-boat-converts-a-tugboat-to-electric-drive-for-the-port-of-la/

State of Alaska Department of Transportation & Public Facilities: Alaska Marine Highways System. (2026, January 23). Documents and Specifications for: AMHS M/V Tustumena Replacement, Project No. AK-2024-025-02-00/SFTAG00719. https://www.documentcloud.org/documents/26587395-sftag00719-specifications/

Statue City Cruises. (2026). Statue special events vessels – Statue Cruises. https://www.cityexperiences.com/new-york/city-cruises/statue/special-events/vessels/

Stephan, A., & Thielmann, A. (2023, September). Alternative battery technologies roadmap 2030+. Fraunhofer Institute for Systems and Innovation Research ISI.

Tasker, G. (2023, March 16). On the horizon: The first electric Mackinac Island ferry. Rural Innovation Exchange. https://ruralinnovationexchange.com/electricferry/

Tiede, B., O'Meara, C., & Jansen, R. (2022). Battery key performance projections based on historical trends and chemistries. NASA Glenn Research Center.

Tidal Transit. (2026, January 21). Insert batteries here. E-GINNY Blog. https://www.tidal-transit.com/e-ginny/e-ginny-blog/insert-batteries-here)

Udel, D. (2023, April 25). University of Miami expands its fleet of research vessels. University of Miami, Rosenstiel School of Marine and Atmospheric Science. https://news.miami.edu/rosenstiel/stories/2023/04/university-of-miami-expands-its-fleet-of-research-vessels.html

University of Vermont, Rubenstein School of Environment and Natural Resources. (n.d.). Research Vessel Marcelle Melosira and Other Boats. https://www.uvm.edu/rsenr/rubensteinlab/research-vessel-marcelle-melosira-and-other-boats

USCG. (n.d.). Rules of the Road. (https://www.dco.uscg.mil/NavRules/)

US Energy Information Administration. (2025). Electric power monthly. https://www.eia.gov/electricity/monthly/

Walter, D., Bond, K., Butler-Sloss, S., Speelman, L., Numata, Y., & Atkinson, W. (2023, December). X-Change: Batteries - The battery domino effect. Rocky Mountain Institute (RMI).

Washington State Department of Transportation. (2026a). M/V Puyallup. https://wsdot.com/ferries/vesselwatch/VesselDetail.aspx?vessel_id=25

Washington State Department of Transportation. (2026b). M/V Tacoma. https://wsdot.com/ferries/vesselwatch/VesselDetail.aspx?vessel_id=32

Washington State Department of Transportation. (2026c). M/V Wenatchee. https://wsdot.com/ferries/vesselwatch/VesselDetail.aspx?vessel_id=37

Washington State Department of Transportation. (n.d.). Ferry system electrification. https://wsdot.wa.gov/construction-planning/major-projects/ferry-system-electrification

WINDEA. (2024, July 3). WINDEA CTV delivers inaugural fleet of new, U.S.-built crew transfer vessels. https://windea.com/windea-ctv-delivers-fleet-of-new-crew-transfer-vessels/

WorkBoat. (2025). 2025 Construction survey. Diversified Communications. https://www.workboat.com/resources/reports/construction-survey-2025

WorkBoat Staff. (2024a, December 13). All American to build San Francisco's new electric ferries. https://www.workboat.com/all-american-marine-to-build-san-francisco-s-new-electric-ferries

WorkBoat Staff. (2024b, December 23). Corvus Energy battery systems to power Statue City Cruises fleet. WorkBoat. https://www.workboat.com/corvus-energy-batteries-to-power-statue-city-cruises-fleet

WorkBoat Staff. (2025a, May 7). Moose Boats to build hybrid patrol vessel for King County Sheriff's office. WorkBoat. https://www.workboat.com/moose-boats-to-build-hybrid-patrol-vessel-for-king-county-sheriff-s-office

WorkBoat Staff. (2025b, December 1). ABB to deliver power to two new hybrid-electric ferries for Washington State Ferries. WorkBoat. https://www.workboat.com/abb-to-deliver-power-two-new-hybrid-electric-ferries-for-washington-state-ferries

WorkBoat 365. (2024, September 13). RV Resilience, US Department of Energy's first hybrid research vessel. https://workboat365.com/rv-resilience-us-department-of-energys-first-hybrid-research-vessel/

WorkBoat 365. (2025, April 7). Nichols Brothers Boat Builders to build two 400-passenger electric ferries for San Francisco Bay Ferry. https://workboat365.com/nichols-brothers-boat-builders-to-build-electric-ferries-for-san-francisco-bay/

Appendix 1 - Project Team

Blue Ocean Transfers

Jack Cammarota

Marine Operations / Supply Chain Services

Jack brings to his position over 15 years of broad international experience in the maritime industry both at sea and ashore. He graduated from SUNY Maritime College in 2007 with a BS in Marine Transportation and an Unlimited 3rd Mate's License, and later received an MS in International Transportation and Trade. Jack began his maritime career sailing aboard Crew, Supply and Anchor Handling vessels for Seacor Marine sailing for five years in the oil and gas industries of West Africa, the Middle East and South America and the US Outer Continental Shelf in the capacities of 2nd Mate, Chief Mate and Dynamic Positioning Operator (DPO). Signing on as a Dynamic Positioning Operator / 2nd Mate for Transocean Inc on a Fifth Generation Dynamically Positioned Drill Ship – Discoverer Deep Seas – he then served three years as Ships Officer and DPO on Chevron and Murphy Oil time charter vessels in the US Gulf of Mexico focusing on Deep and Ultra Deepwater exploratory drilling and completion projects. Returning to SUNY Maritime College, he obtained a Masters Degree in International Transportation and Trade in 2014 to expand his global business outlook and prepare for a career ashore within the maritime industry.

Jack currently holds active USCG Merchant Mariner Credentials as a 2nd Mate with Unlimited Tonnage and Master of 1,600 Gross Registered Ton vessels upon Oceans along with a Master of Towing endorsement and Unlimited Dynamic Positioning Operator Certificate granted by the Nautical Institute. Jack assisted in identifying the opportunities in offshore wind for McQuilling Renewables and Blue Ocean Transfers and specializes in developing various business strategies designed to integrate into the offshore and renewables industries by way of marine and intermodal transportation services, perspectives, and disciplines. He currently sits on the Board of Directors for the International Cargo Gear Bureau (ICGB) & the Marine Chemists Association where he contributes marine operational insight and oversight to the not-for-profit organizations that provide registration, inspection, certification and consultation services for shipboard, offshore and land-based material handling equipment as well as safety and regulatory oversight to marine chemists and the greater marine industry.

Avril Montanti

Marine Logistics

Avril joined the Blue Ocean Transfers team in 2023 with a strong background in project and systems documentation after a decade long career at the federal government. She recently graduated from Virginia Tech with her Master of Natural Resources degree. Relevant coursework included Coastal & Marine Management, where she studied the sustainable use of our oceans by various stakeholders, and Global Issues in Sustainability. Avril started her career at the International Trade Field Office of the U.S. Department of Justice after receiving her BBA in International Management from Pace University in 2009. As a paralegal, she conducted extensive research and later specialized in data management for large criminal cases and for a prestigious national task force.

Combining a rich family history in the maritime sector with her passion for sustainability, Avril was naturally drawn to the offshore wind energy industry. She supports the team's advisory and consulting efforts as well as the company's launch and start-up of Blue Ocean Transfers.

Dave Saginaw

Commercial Advisory

Dave Saginaw has been an agent of change in existing organizations and new project structures. An originator of new concepts, constructs and initiatives, Dave has successfully created value in many forms over more than four decades of commitment in the maritime industry. He brings to his position over 35 years of broad international experience in the maritime industry. Trained as a Naval Architect at the University of Michigan, Dave began his maritime career at National Steel and Shipbuilding in San Diego, California where he played a key role in the introduction of modern ship production techniques.

Returning to Michigan for further academic studies he also taught applied economics, shipping and ship production and received advanced degrees in Naval Architecture (Master of Science in Engineering) and Business Administration (Master of Business Administration). A decade-long career with Chevron Shipping Company included increasing commercial, operational and technical responsibilities, concluding with the leadership of the company's proprietary and chartered fleet deployment.

In 1997 Dave formed McQuilling Services, LLC., a marine transportation consulting and project management enterprise of McQuilling Partners, Inc. and led the firm on a path of continued growth in service offerings and clients through over two decades of service.

Rutgers University

Dr. Ahmed Aziz Ezzat

Assistant Professor of Engineering

Dr. Ahmed Aziz Ezzat is an Assistant Professor of Industrial & Systems Engineering at Rutgers University, where he is a faculty affiliate of the Rutgers AI & Data Science (RAD) collaboratory, and the Rutgers Climate & Energy Institute (RCEI). Prior to joining Rutgers, he obtained his Ph.D. degree at Texas A&M University and his BSc. degree in Alexandria, Egypt, both in Industrial Engineering. Dr. Aziz Ezzat's expertise is in the development of data science solutions for energy, environment, and industrial systems. Dr. Aziz Ezzat was the primary advisor on this research and supported multiple students in the completion of their post-graduate degrees throughout their project contributions.

Dr. Josh Kohut

Professor in Marine and Coastal Sciences

Dr. Josh Kohut is the Dean of Research at the School of Environmental and Biological Sciences at Rutgers University, where he received his PhD in Physical Oceanography. Dr. Kohut is an expert in oceanography and ocean observing technologies with a focus on the future Blue Economy. As a

Professor in the Department of Marine and Coastal Sciences at Rutgers, he advised this team's research into the effects of dynamic ocean conditions on vessel operations.

Cory Petersen

Industrial Engineer, Lockheed Martin Space Systems

Cory Petersen recently graduated with his Master of Science in Industrial and Systems Engineering from Rutgers University, where he also received his Bachelor of Engineering. Cory is the lead researcher on this project and has contributed expertise in multiple disciplines including oceanographic research and systems engineering. With support from his advisors and fellow student collaborators, Cory drove the direction of the research to solve the questions proposed herein and to determine new approaches to studying vessel logistics.

Jiaxiang Ji

Industrial and Systems Engineering

Jiaxiang Ji is a Ph.D. student in Industrial and Systems Engineering at Rutgers University. His contributions in mathematical and statistical modeling were instrumental to his peers throughout the project.

Feng Ye

Assistant Professor, Clemson University

Feng Ye is an Assistant Professor at Clemson University in the Department of Industrial Engineering. He holds a PhD in Industrial Systems and Engineering as well as an MS in Statistics from Rutgers University. His background in offshore wind forecasting as well as environmental data extraction, analysis and visualization made him a key player in this research. As a Graduate Research Assistant at Rutgers, his contributions and guidance were greatly valued by his team.

Incat Crowther

Ed Dudson

Managing Director, Incat Crowther Europe

Ed Dudson is the Managing Director at Incat Crowther Europe and is a highly experienced Naval Architect with a detailed knowledge of design and production. He has experience in project managing very large design and build contracts within difficult timescales and budgets. He is an expert in the fields of ship performance and seakeeping. As of 2018 Ed is responsible for the development of Incat Crowther Europe, a company with a long history in the Fast Ferry Industry. Prior to taking up his new position at Incat Crowther he was responsible for the development of the commercial markets of BMT Nigel Gee Ltd, including ferries, patrol boats and wind farm support vessels.

Grant Pecoraro

Managing Director, Incat Crowther USA

Grant Pecoraro is the Managing Director of Incat Crowther USA and is an experienced and licensed professional engineer in the field of Naval Architecture and Marine Engineering. Grant has overseen the growth and stability of the Incat Crowther US-based office while fostering diversity, capability, and innovation within the broader company. Prior to starting his own design firm which was later amalgamated with Incat Crowther, he was responsible for the product development and detailed design of new vessels at Gulf Craft, a prominent shipyard in southern United States known for its aluminum commercial workboats and passenger vessels.

Matt Jupp

Principal Naval Architect, Incat Crowther

Matt Jupp holds the position of Principal Naval Architect at Incat Crowther after starting with the firm in 2019 as a Senior Naval Architect. Prior to this experience, he spent 8 years at BMT as a Naval Architect and Project Manager for projects including wind farm support vessels, monohull and catamaran fast ferries, fast crew boats, motor and sailing super yachts, specialist military landing craft and military/paramilitary fast patrol boats.

Mitchell Campbell

Naval Architect, Incat Crowther

Mitchell Campbell is a Naval Architect at Incat Crowther and graduate of the University of Southampton with a Master of Engineering in Ship Science.

Appendix 2 - Hybrid Vessel List

Vessel Name	Vessel type	Count	Region/ State	Owner/ Operator	Coastal, Deepwater or Inland	Size	Size	Pax	Mono or Multi	Const. Material	Cruising speed category (kts)	Shipyard	Designer	Hybrid or Fully Electric	Status	Delivery date	Ref
Tustumena	Ferry	1	AK	Alaska DOT	Coastal	330'	L	250 + 28 crew; 58 cars	Mono			TBD		Hybrid	P	2029(N)	Brooks, 2026; State of Alaska DOT, 2026
TBD	Ferry	2	CA	Flagship Cruises & Events; San Diego County Air Pollution Control District	Inland	90' 7" x 27' 11"	M	275	Multi	AL	12 and under	TBD	Aurora Marine Design	Fully Electric	P	TBD(N)	Flagship, 2025
Alcatraz Flyer	Ferry	1	CA	Hornblower	Inland	128'	M	800	Mono	S	12 and under			Hybrid	O	2007(N) 2011(R)	Baker, 2024; WorkBoat Staff, 2024b; Alcatraz City Cruises
Alcatraz Clipper	Ferry	1	CA	Hornblower	Inland	127'	M	800	Mono	S	12 and under			Hybrid	O	2007(N) 2012(R)	Baker, 2024; WorkBoat Staff, 2024b; Alcatraz City Cruises
TBD (1 of 3, option for 4)	Ferry	1	CA	San Francisco Bay Ferry - REEF Program	Inland	100' x 26'	M	150	Multi	AL	15 to 24	All American Marine (AAM)	Teknicraft Design; Aurora Marine Design	Fully Electric	UC	2027(N)	Haun, 2025f
TBD (1 of 3, option for 4)	Ferry	1	CA	San Francisco Bay Ferry - REEF Program	Inland	100' x 26'	M	150	Multi	AL	15 to 24	All American Marine (AAM)	Teknicraft Design; Aurora Marine Design	Fully Electric	P	TBD(N)	Haun, 2025f
TBD (1 of 3, option for 4)	Ferry	1	CA	San Francisco Bay Ferry - REEF Program	Inland	100' x 26'	M	150	Multi	AL	15 to 24	All American Marine (AAM)	Teknicraft Design; Aurora Marine Design	Fully Electric	P	TBD(N)	Haun, 2025f
Argo (1 of 4 Hydrus class vessel conversions)	Ferry	1	CA	San Francisco Bay Ferry - REEF Program	Inland	135.5'x37.7'	M	400	Multi	AL	25 and up	Vigor/Kvichak Marine	Incat Crowther	Fully Electric	P	2018(N) TBD(R)	WorkBoat Staff, 2024a; SF Bay Ferry, 2024, 2026a, 2026b; Incat Crowther, n.d.a

Vessel Name	Vessel type	Count	Region/ State	Owner/ Operator	Coastal, Deepwater or Inland	Size	Size	Pax	Mono or Multi	Const. Material	Cruising speed category (kts)	Shipyard	Designer	Hybrid or Fully Electric	Status	Delivery date	Ref
Carina (1 of 4 Hydrus class vessel conversions)	Ferry	1	CA	San Francisco Bay Ferry - REEF Program	Inland	135.5'x37.7'	M	400	Multi	AL	25 and up	Vigor/Kvichak Marine	Incat Crowther	Fully Electric	P	2019(N) TBD(R)	WorkBoat Staff, 2024a; SF Bay Ferry, 2024, 2026a, 2026b; Incat Crowther, n.d.a
Cetus (1 of 4 Hydrus class vessel conversions)	Ferry	1	CA	San Francisco Bay Ferry - REEF Program	Inland	135.5'x37.7'	M	400	Multi	AL	25 and up	Vigor/Kvichak Marine	Incat Crowther	Fully Electric	P	2017(N) TBD(R)	WorkBoat Staff, 2024a; SF Bay Ferry, 2024, 2026a, 2026b; Incat Crowther, n.d.a
Hydrus (1 of 4 Hydrus class vessel conversions)	Ferry	1	CA	San Francisco Bay Ferry - REEF Program	Inland	135.5'x37.7'	M	400	Multi	AL	25 and up	Vigor/Kvichak Marine	Incat Crowther	Fully Electric	P	2017(N) TBD(R)	WorkBoat Staff, 2024a; SF Bay Ferry, 2024, 2026a, 2026b; Incat Crowther, n.d.a
TBD [1 of 2]	Ferry	1	CA	San Francisco Bay Ferry - WETA	Inland	141'1"x34'9"	M	400	Multi		25 and up	Nichols Brothers Boat Builders (NBBB)	Incat Crowther	Fully Electric	P	TBD(N)	WorkBoat 365, 2025
TBD [2 of 2]	Ferry	1	CA	San Francisco Bay Ferry - WETA	Inland	141'1"x34'9"	M	400	Multi		25 and up	Nichols Brothers Boat Builders (NBBB)	Incat Crowther	Fully Electric	P	TBD(N)	WorkBoat 365, 2025
Juliette Gordon Low II	Ferry	1	GA	Chatham Area Transit	Inland	65x22'	S	149	Multi	AL	12 and under	Derecktor	DeJong and Lebet	Hybrid + waterjet	O	2025(N)	Marine Jet Power, 2025; Baird Maritime, 2025
Susie King Taylor II	Ferry	1	GA	Chatham Area Transit	Inland	65x22'	S	149	Multi	AL	12 and under	Derecktor	DeJong and Lebet	Hybrid + waterjet	O	2025(N)	Marine Jet Power, 2025; Baird Maritime, 2025
Hull 234	Ferry	1	GA	Chatham Area Transit		65x22'	S			AL		Derecktor			UC	TBD(N)	WorkBoat 2025 Constr. Survey
Battery Steele	Ferry	1	ME	Casco Bay Lines	Inland/ Coastal	164x39'	L	599	Mono	S		Senesco	Elliott Bay Design Group (EBDG)	Hybrid	UC	2026(N) (expected)	Haun, 2025a; WorkBoat 2025 Contr. Survey; EBDG, n.d

Vessel Name	**Vessel type**	**Count**	**Region/ State**	**Owner/ Operator**	**Coastal, Deepwater or Inland**	**Size**	**Size**	**Pax**	**Mono or Multi**	**Const. Material**	**Cruising speed category (kts)**	**Shipyard**	**Designer**	**Hybrid or Fully Electric**	**Status**	**Delivery date**	**Ref**
Capt. Almer Dinsmore	Ferry	1	ME	Maine DOT	Inland/ Coastal	154x38'	M	250	Mono	S		Senesco	Gilbert Associates	Hybrid	O	2025(N)	Hayden, 2025a
Margaret Chase Smith	Ferry	1	ME	Maine DOT	Inland/ Coastal	207'	L	200	Mono					Hybrid	P	TBD(N)	Marine Link, 2024a; Maine DOT
Chippewa	Ferry	1	MI	Mackinac Island Ferry Company	Coastal	84'	M	250 - 300	Mono			Mackinac Marine Services (Conversion)		Hybrid	P	1962(N) TBD(R)	Brintnell, 2023; Tasker, 2023
Miss New York and others - Series of 9	Ferry	9	NY	Hornblower's Statue City Cruises	Inland			430 - 870						Hybrid	P	TBD(R)	Snyder, 2024; Statue City Cruises, 2026
Unknown	Ferry	4 (Up to 4)	NY	NY Waterway	Inland									Hybrid	P	TBD(R)	Hammerman, 2023
Harbor Charger	Ferry	1	NY	Trust for Governors Island/ NY Waterway	Inland	190x62'	L	1,200; 30 cars	Mono		12 and under	Conrad	Elliott Bay Design Group (EBDG)	Hybrid	O	2025(N)	Haun, 2025e; Hocke, 2026
Esparanza "Hope" Andrade	Ferry	1	TX	Texas DOT	Inland/ Coastal	293'x66'	L	495; 70 cars	Mono		12 to 15	Gulf Island Fabricators	The Shearer Group (TSGI), Houston	Hybrid	O	2024(N)	Hayden, 2024
Waterman	Ferry	1	WA	Kitsap Transit	Inland	70x26	M	150	Multi	AL	12 and under	All American Marine (AAM)	Glosten	Hybrid	O	2019(N)	Kitsap Transit
Wenatchee	Ferry	1	WA	Washington State Ferries	Inland	460'2"x90	L	1,791; 202 cars	Mono		15 to 24	Todd Pacific Shipyards (Original); Vigor Marine (Conversion)		Hybrid	O	1998(N); 2025(R)	Hocke, 2026; WA DOT 2026c
Tacoma	Ferry	1	WA	Washington State Ferries	Inland	460'2"x90	L	1,791; 202 cars	Mono		15 to 24				P	TBD(R)	WA DOT, n.d.; WA DOT, 2026b

Vessel Name	Vessel type	Count	Region/ State	Owner/ Operator	Coastal, Deepwater or Inland	Size	Size	Pax	Mono or Multi	Const. Material	Cruising speed category (kts)	Shipyard	Designer	Hybrid or Fully Electric	Status	Delivery date	Ref
Puyallup	Ferry	1	WA	Washington State Ferries	Inland	460'2"x90	L	1,791; 202 cars	Mono		15 to 24				P	TBD(R)	WA DOT, n.d.; WA DOT, 2026a
TBD - Series of up to 16 through 2040	Ferry	16	WA	Washington State Ferries	Inland	TBD		U; 160 cars (First 2 vessels)	Mono			Eastern Shipbuilding Group (First 2 vessels)	Elliott Bay Design Group (EBDG) (First 2 vessels)	Hybrid	P	2030(N), 2031(N), TBD(N)	WorkBoat Staff, 2025a
ALFA 1 of 3 - *Mirage*	Fishing	1	AK	Alaska Longline Fishermen's Association (ALFA)	Coastal	50'	S		Mono			Sitka Community Boatyard		Hybrid	O	2026(R)	Bauman, 2025; Bauman, 2026
ALFA 2 of 3 - *Energizer*	Fishing	1	AK	Alaska Longline Fishermen's Association (ALFA)	Coastal									Hybrid	P	2026(R) (expected)	Bauman, 2025; Bauman 2026
ALFA 3 of 3	Fishing-Mariculture	1	AK	Alaska Longline Fishermen's Association (ALFA)	Coastal									Fully Electric	P	2026(R) expected	Bauman, 2025; Bauman 2026
AET Innovator	Lightering support vessel	1	TX	US arm of AET	Coastal	185'	L		Mono		12 and under	Leevac Industries (2011)	Glosten	Hybrid	P	2011(N) TBD(R)	Haun, 2025c; AET, 2025
Unknown	Ocean sampling vessel	1	CA	Orange County Sanitation District	Coastal	63x24	S					All American Marine (AAM)		Hybrid	P	2027(N)	ABB, 2024
Unknown	Patrol Boat	1	U		Inland/ Coastal	23'	S		Mono	AL			SAFE Boats International	Fully Electric	P	TBD(N)	SAFE Boats International, 2023
Unknown	Patrol Boat	1	WA	Washington State	Inland/ Coastal	46'	S		Multi			Moose Boats		Hybrid	P	TBD(N)	WorkBoat Staff, 2025a
Candela hydrofoil C-8 (Flying Research Vessel)	Research Vessel (RV)	1	FL	University of Miami	Coastal	28'3"x8'3"	S	5; 1 operator	Mono	CF	15 to 24		Candela	Fully Electric	O	2023(N)	Udel, 2023; Candela, 2026

Vessel Name	**Vessel type**	**Count**	**Region/ State**	**Owner/ Operator**	**Coastal, Deepwater or Inland**	**Size**	**Size**	**Pax**	**Mono or Multi**	**Const. Material**	**Cruising speed category (kts)**	**Shipyard**	**Designer**	**Hybrid or Fully Electric**	**Status**	**Delivery date**	**Ref**
Oceanographer	Research Vessel (RV)	1	HI	NOAA	Deepwater	244'x51'x22'	L		Mono			Thoma-Sea in Houma, La.	Technology Associates Inc, (In-house)	Hybrid	UC	2026(N) (expected)	Conley, 2025
Discoverer	Research Vessel (RV)	1	RI	NOAA	Deepwater	244'x51'x22'	L		Mono			Thoma-Sea in Houma, La.	Technology Associates Inc, (In-house)	Hybrid	UC	2026(N) (expected)	Conley, 2025
Marcelle Melosira	Research Vessel (RV)	1	VT	University of Vermont	Inland/ Coastal	65'x20'	M	32	Multi			Derecktor	Chartwell Marine	Hybrid	O	2023(N)	Marine Link, 2023; University of Vermont, n.d.
Resilience	Research Vessel (RV)	1	WA	DOE-PNNL	Inland/Coastal	50'x16'	S		Multi	AL	20 kts (diesel); 7 kts (electric)	Snow & Co (Seattle)	Incat Crowther	Hybrid	O	2024(N)	PNNL, n.d.; WorkBoat 365, 2024
Sadie Ann	Research Vessel (RV)	1	WI	University of Wisconsin	Inland/ Coastal	65'x24'	S	49 + 8 crew	Multi	AL	12 to 15	Midship Marine, Harvey, La.	Incat Crowther	Hybrid	O	2024(N)	Incat Crowther, 2024; Hocke, 2026
Surveyor	Research Vessel (RV)	1	AK	NOAA	Deepwater	270'x50'	L		Mono			Thoma-Sea in Houma, La.		Hybrid	UC	2027/2028 (N)	Conley, 2025; Haun, 2025b
Navigator	Research Vessel (RV)	1		NOAA	Deepwater	270'x50'	L		Mono			Thoma-Sea in Houma, La.		Hybrid	UC	2027/2028 (N)	Conley, 2025; Haun, 2025b
ECO Liberty	Service Operation Vessel (SOV)	1	NY	Equinor; Edison Chouest Offshore (ECO)	Coastal/ Deepwater	262'	L	Houses up to 60 technicians	Mono	S		Edison Chouest Offshore		Hybrid	O	2025(N)	Empire Wind, 2025
Enhydra	Tour boat	1	CA	Red and White Fleet (San Francisco)	Inland/ Coastal	128'	M	600	Mono	AL	12 to 15	All American Marine	Teknicraft Design	Hybrid	O	2018(N)	Professional Mariner Staff, 2018; Corvus, n.d.
James V. Glynn (Maid of the Mist)	Tour Boat	1	NY	Maid of the Mist Corp.	Inland	90'6"x33'4"	M	600	Multi	AL	12 and under	Burget Boat Company (hull & superstructure); Maid of the Mist (final assembly)	Data Propulsion Services	Fully Electric	O	2020(N)	Maid of the Mist, 2026; Burger Boat, n.d.

Vessel Name	Vessel type	Count	Region/ State	Owner/ Operator	Coastal, Deepwater or Inland	Size	Size	Pax	Mono or Multi	Const. Material	Cruising speed category (kts)	Shipyard	Designer	Hybrid or Fully Electric	Status	Delivery date	Ref
Nikola Tesla (Maid of the Mist)	Tour Boat	1	NY	Maid of the Mist Corp.	Inland	90'6"x33'4"	M	600	Multi	AL	12 and under	Burget Boat Company (hull & superstructure); Maid of the Mist (final assembly)	Data Propulsion Services	Fully Electric	O	2020(N)	Maid of the Mist, 2026; Burger Boat, n.d.
Replacing the *Sam Houston*	Tour boat	1	TX	Port Houston	Inland	73'x28'	M	150	Multi	AL	12 and under	Breaux Brothers Enterprises	Incat Crowther	Hybrid	UC	2026(N) (expected)	Hocke, 2026; Haun, 2025d
Green Diamond	Towing vessel	1	TX	Kirby Inland Marine	Inland	73.6'x30'	M		Mono			San Jac Marine	San Jac Marine	Hybrid	O	2023(N)	Marine Link, 2023; Redden, 2023
eWolf	Tugboat	1	CA	Crowley	Inland/ Coastal	82'x40'	M		Mono			Master Boat Builders in Coden, Ala.	Crowley	Fully Electric	O	2024(N)	Crowley, n.d.; Crowley, 2024
Unknown	Tugboat	1	CA	Port of L.A.	Inland/ Coastal	26'	S					Arc Boat Company; Diversified Marine		Fully Electric	P	TBD(R)	Spira, 2025
8 ship assist tugboats	Tugboat	8	WC	Arc Boats (owner); Curtin Maritime Corp. (operator)		80'9"x42'3" (first 4 vessels)	M					Snow & Co	Jay Edgar	Hybrid	P	2026 and on (N) (expected)	Hayden, 2025c
Marco V	Tugboat - Truckable /yard tug	1	CA	Marine Group Boat Works	Inland	25x14x5	S					Progressive Industrial Inc. (original build)			O	2025(R)	Hayden, 2025b
Unknown	Tugboat - truckable	1+			Inland	26x3.6'	S			AL		Diversified Marine	Elliott Bay Design Group (EBDG)		P	TBD(R)	Marine Link, 2024b; WorkBoat, 2025 Constr. Survey
Unknown	Workboat	1+	U		Inland/ Coastal	24'	S		Mono	AL	25 and up	Silverback Marine			O	2025(N)	Haun, 2024

Notes:

Region/ State:
AK = Alaska, CA = California, GA = Georgia, GULF = US Gulf, HI = Hawaii, ME = Maine, MI = Michigan, NY = New York, RI = Rhode Island, TX = Texas, VT = Vermont, WA = Washington State, WC = West Coast, WI = Wisconsin

Owner/Operator:
REEF = Rapid Electric Emission Free Ferry Program; WETA = Water Emergency Transportation Authority

Pax
U = Unknown

Size:
S = 65' and under; M = 66' – 164'; L = 165' and up

Mono or Multi:
Mono = monohull; Multi = multi-hull

Const. Material:
AL = Aluminum, S = Steel, CF = Carbon Fiber

Status:
O = Operating; UC = Under Construction; P = Planned

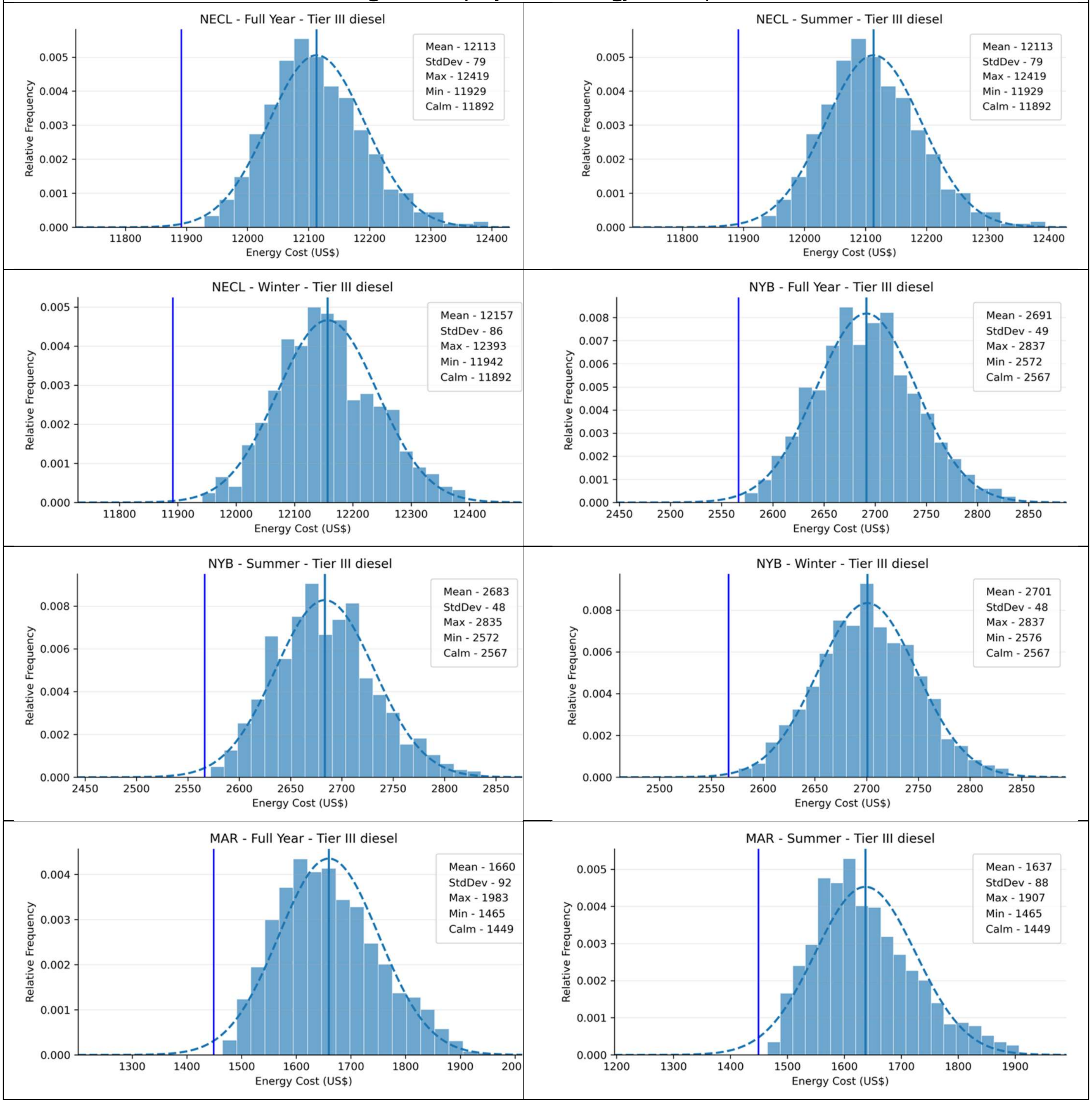
Delivery Date:
N = Newbuild; R = Retrofit/Conversion

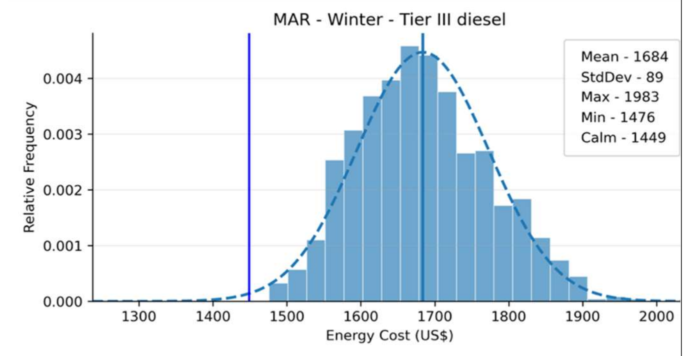
Source: BOT

[This page left blank for two-sided printing]

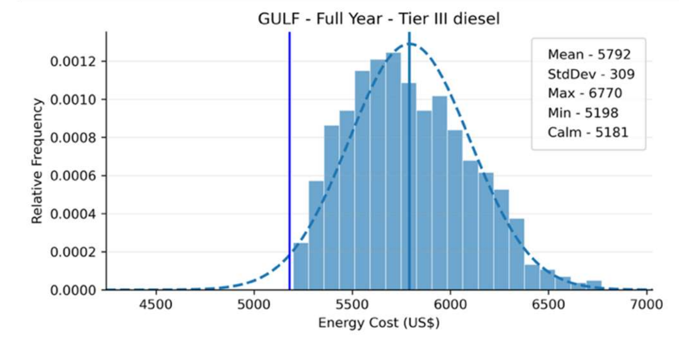
Appendix 3 - Data Excerpts – All Regions

Regional Deployment Energy Costs (US$

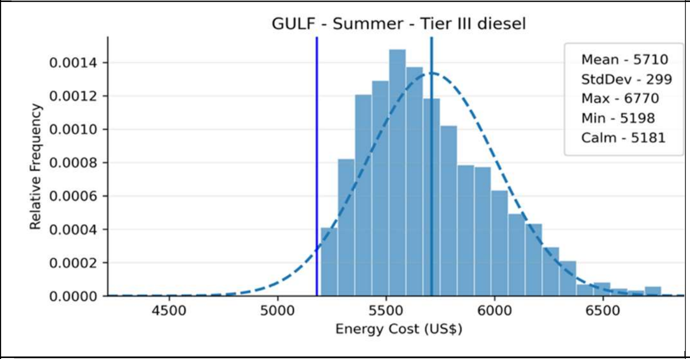




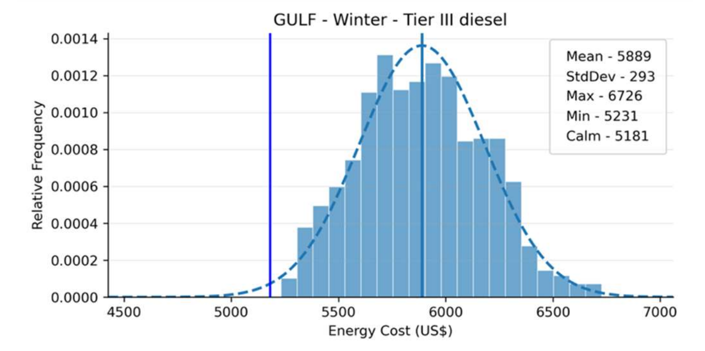
MAR - Winter - Tier III diesel



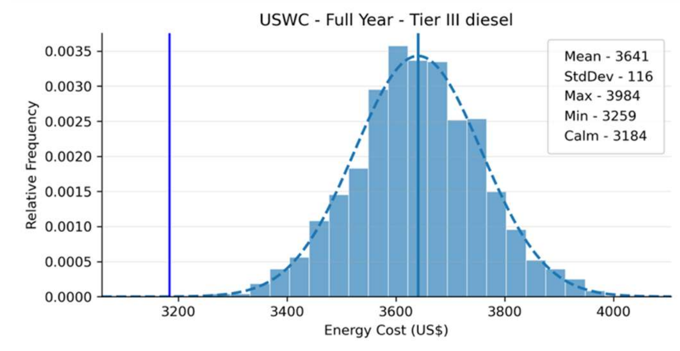
GULF - Full Year - Tier III diesel



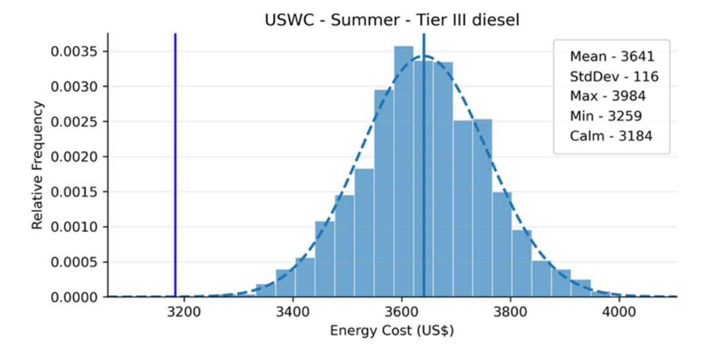
GULF - Summer - Tier III diesel



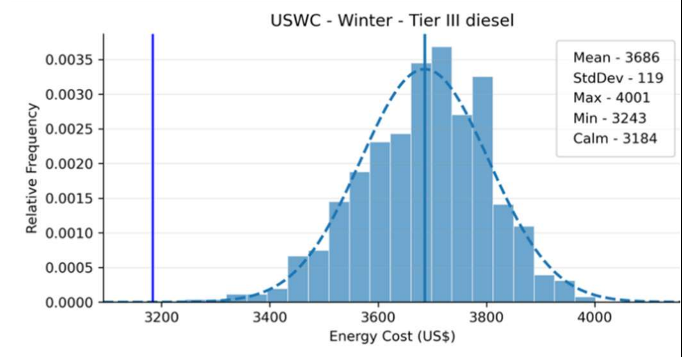
GULF - Winter - Tier III diesel



USWC - Full Year - Tier III diesel

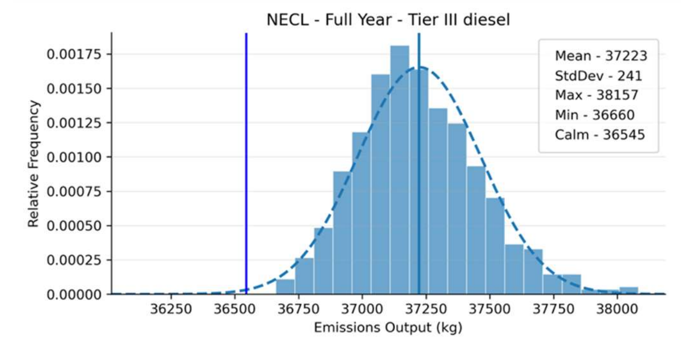


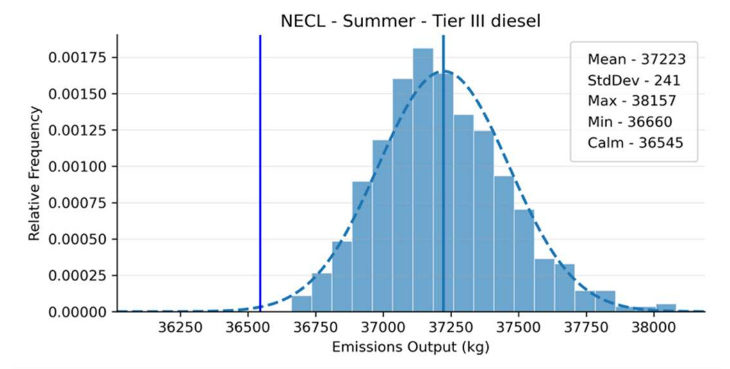
USWC - Summer - Tier III diesel

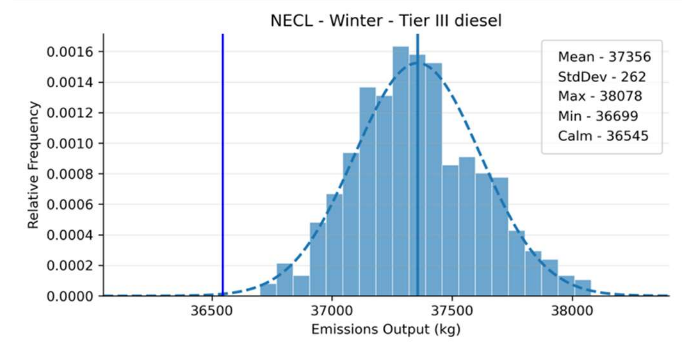


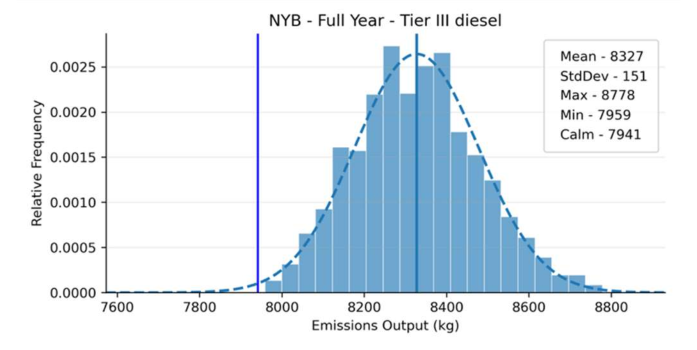
USWC - Winter - Tier III diesel

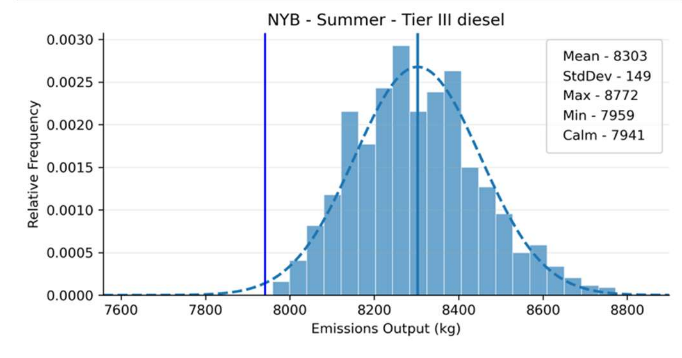
Regional Deployment Emissions (kgCO2)

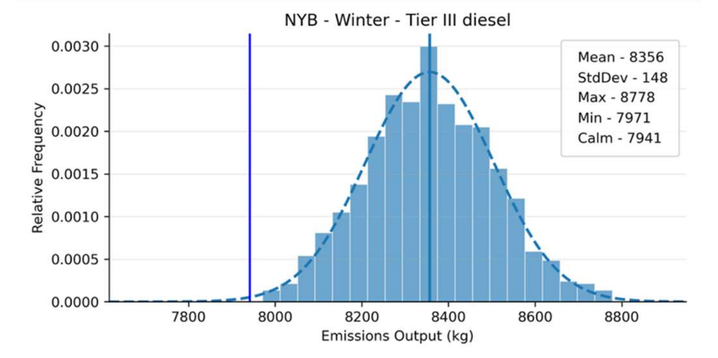


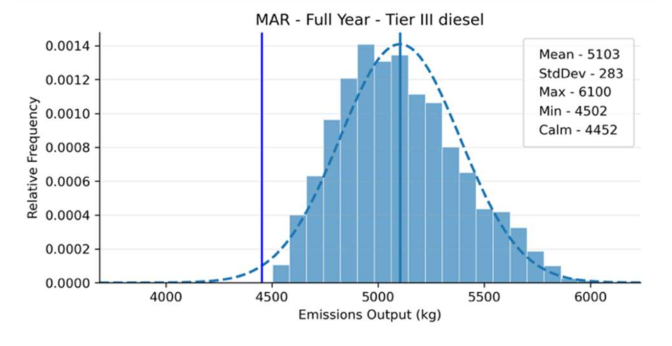


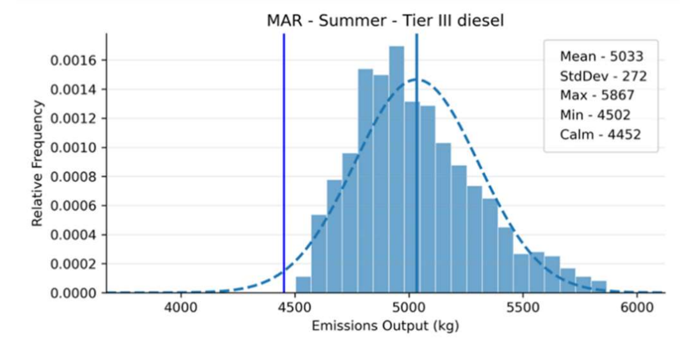


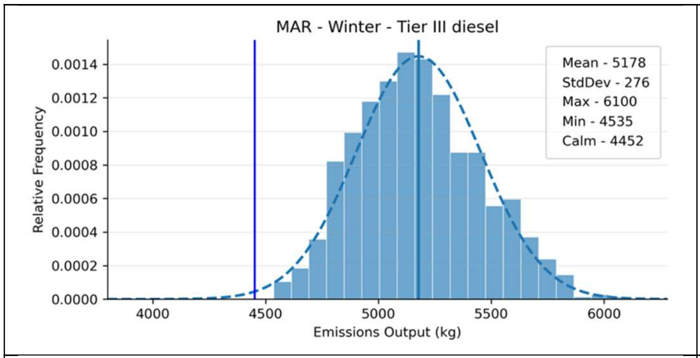


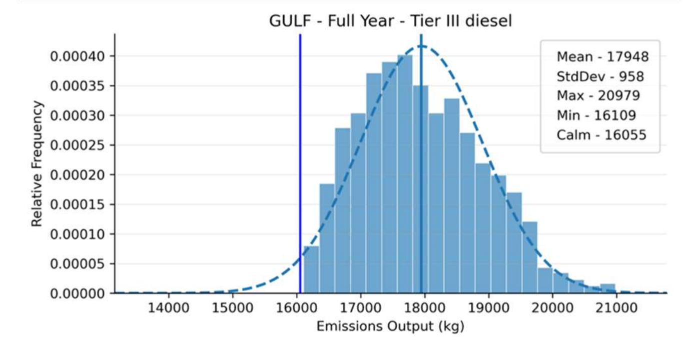


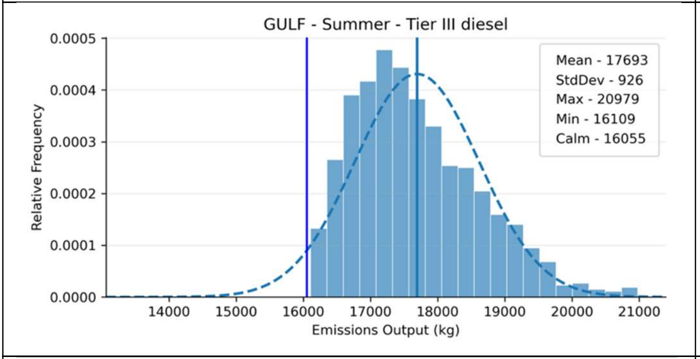


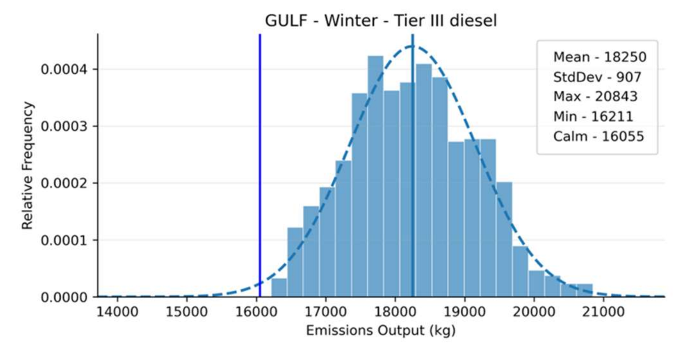


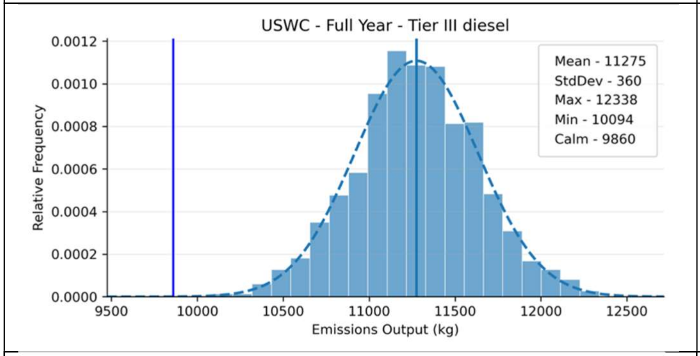


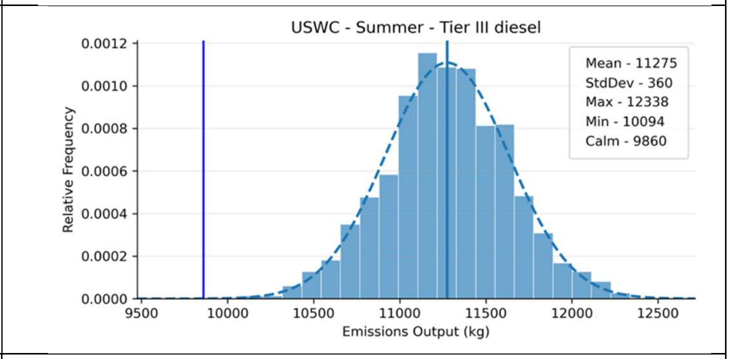

MAR - Winter - Tier III diesel
Relative Frequency
0.0000
0.0002
0.0004
0.0006
0.0008
0.0010
0.0012
0.0014
4000
4500
5000
5500
6000
Emissions Output (kg)
Mean - 5178
StdDev - 276
Max - 6100
Min - 4535
Calm - 4452

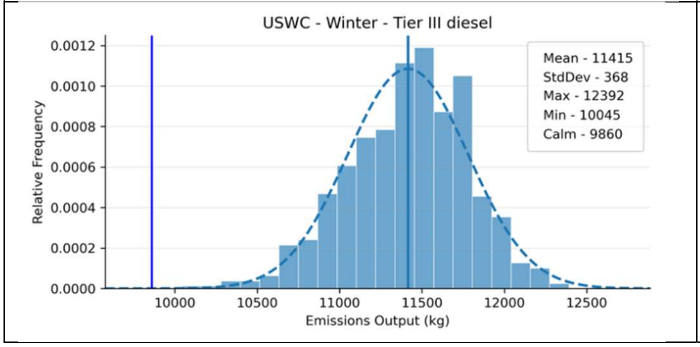

GULF - Full Year - Tier III diesel
Relative Frequency
0.00000
0.00005
0.00010
0.00015
0.00020
0.00025
0.00030
0.00035
0.00040
14000
15000
16000
17000
18000
19000
20000
21000
Emissions Output (kg)
Mean - 17948
StdDev - 958
Max - 20979
Min - 16109
Calm - 16055


GULF - Summer - Tier III diesel
Relative Frequency
0.0000
0.0001
0.0002
0.0003
0.0004
0.0005
14000
15000
16000
17000
18000
19000
20000
21000
Emissions Output (kg)
Mean - 17693
StdDev - 926
Max - 20979
Min - 16109
Calm - 16055


GULF - Winter - Tier III diesel
Relative Frequency
0.0000
0.0001
0.0002
0.0003
0.0004
14000
15000
16000
17000
18000
19000
20000
21000
Emissions Output (kg)
Mean - 18250
StdDev - 907
Max - 20843
Min - 16211
Calm - 16055

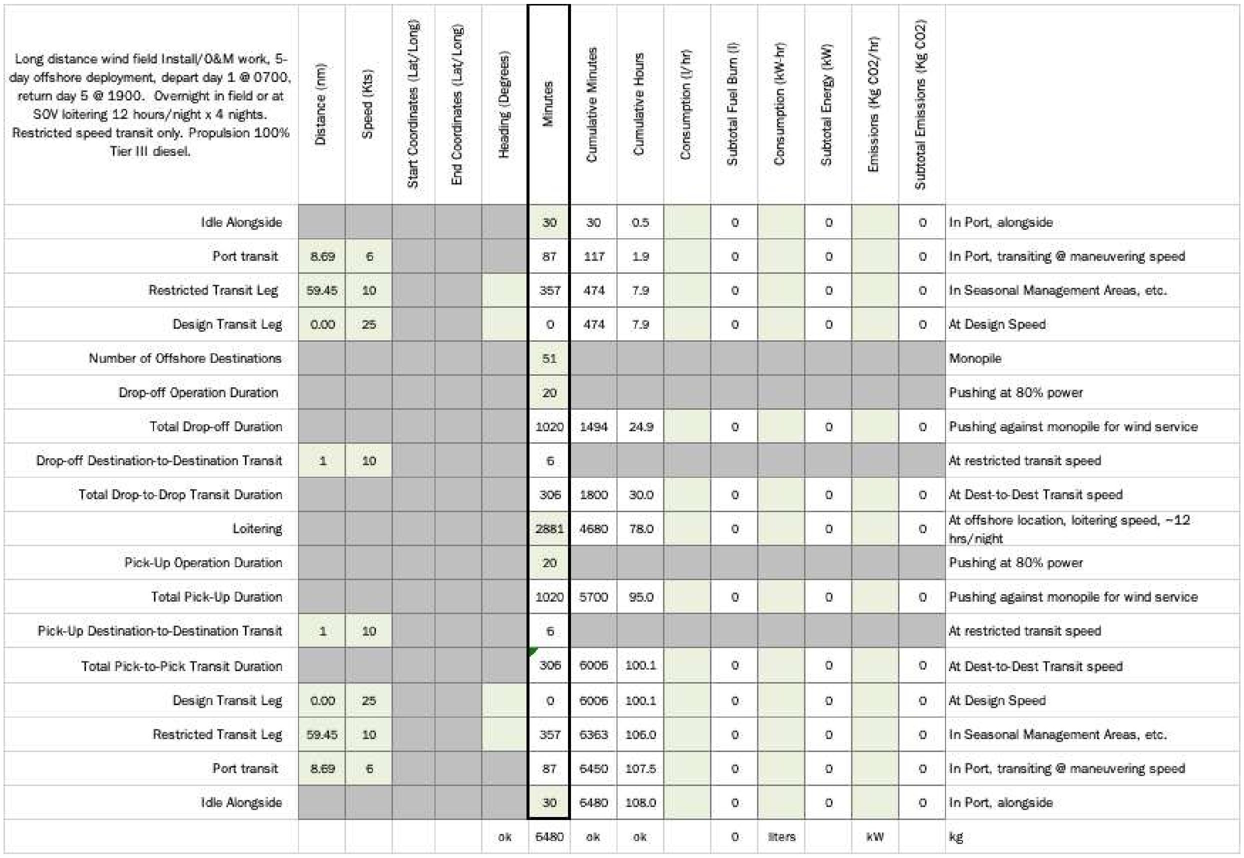

USWC - Full Year - Tier III diesel
Relative Frequency
0.0000
0.0002
0.0004
0.0006
0.0008
0.0010
0.0012
9500
10000
10500
11000
11500
12000
12500
Emissions Output (kg)
Mean - 11275
StdDev - 360
Max - 12338
Min - 10094
Calm - 9860


USWC - Summer - Tier III diesel
Relative Frequency
0.0000
0.0002
0.0004
0.0006
0.0008
0.0010
0.0012
9500
10000
10500
11000
11500
12000
12500
Emissions Output (kg)
Mean - 11275
StdDev - 360
Max - 12338
Min - 10094
Calm - 9860


USWC - Winter - Tier III diesel
Relative Frequency
0.0000
0.0002
0.0004
0.0006
0.0008
0.0010
0.0012
10000
10500
11000
11500
12000
12500
Emissions Output (kg)
Mean - 11415
StdDev - 368
Max - 12392
Min - 10045
Calm - 9860

Appendix 4 - Operating Profiles

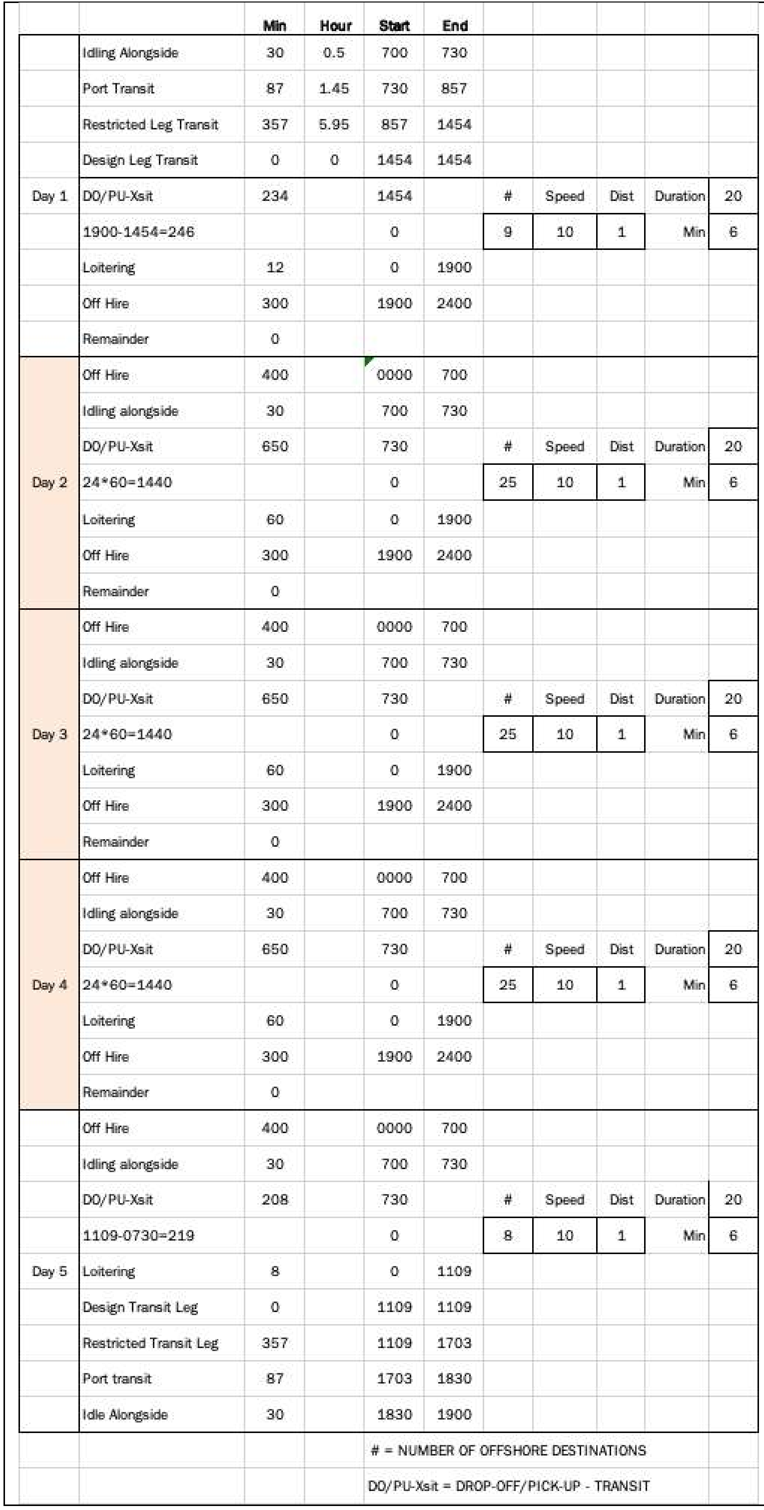
NECL Operating Profile (Transit Round Trip Activities)



Long distance wind field Install/O&M work, 5-day offshore deployment, depart day 1 @ 0700, return day 5 @ 1900. Overnight in field or at SOV loitering 12 hours/night x 4 nights. Restricted speed transit only. Propulsion 100% Tier III diesel.	Distance (nm)	Speed (Kts)	Start Coordinates (Lat/Long)	End Coordinates (Lat/Long)	Heading (Degrees)	Minutes	Cumulative Minutes	Cumulative Hours	Consumption (l/hr)	Subtotal Fuel Burn (l)	Consumption (kW-hr)	Subtotal Energy (kW)	Emissions (Kg CO2/hr)	Subtotal Emissions (Kg CO2)	
Idle Alongside						30	30	0.5		0		0		0	In Port, alongside
Port transit	8.69	6				87	117	1.9		0		0		0	In Port, transiting @ maneuvering speed
Restricted Transit Leg	59.45	10				357	474	7.9		0		0		0	In Seasonal Management Areas, etc.
Design Transit Leg	0.00	25				0	474	7.9		0		0		0	At Design Speed
Number of Offshore Destinations						51									Monopile
Drop-off Operation Duration						20									Pushing at 80% power
Total Drop-off Duration						1020	1494	24.9		0		0		0	Pushing against monopile for wind service
Drop-off Destination-to-Destination Transit	1	10				6									At restricted transit speed
Total Drop-to-Drop Transit Duration						306	1800	30.0		0		0		0	At Dest-to-Dest Transit speed
Loitering						2881	4680	78.0		0		0		0	At offshore location, loitering speed, ~12 hrs/night
Pick-Up Operation Duration						20									Pushing at 80% power
Total Pick-Up Duration						1020	5700	95.0		0		0		0	Pushing against monopile for wind service
Pick-Up Destination-to-Destination Transit	1	10				6									At restricted transit speed
Total Pick-to-Pick Transit Duration						306	6006	100.1		0		0		0	At Dest-to-Dest Transit speed
Design Transit Leg	0.00	25				0	6006	100.1		0		0		0	At Design Speed
Restricted Transit Leg	59.45	10				357	6363	106.0		0		0		0	In Seasonal Management Areas, etc.
Port transit	8.69	6				87	6450	107.5		0		0		0	In Port, transiting @ maneuvering speed
Idle Alongside						30	6480	108.0		0		0		0	In Port, alongside
					ok	6480	ok	ok		0	liters		kW		kg

Source: BOT

NECL Operating Profile (Offshore Site Activities)



		Min	Hour	Start	End					
	Idling Alongside	30	0.5	700	730					
	Port Transit	87	1.45	730	857					
	Restricted Leg Transit	357	5.95	857	1454					
	Design Leg Transit	0	0	1454	1454					
Day 1	DO/PU-Xsit	234		1454		#	Speed	Dist	Duration	20
	1900-1454=246			0		9	10	1	Min	6
	Loitering	12		0	1900					
	Off Hire	300		1900	2400					
	Remainder	0								
	Off Hire	400		0000	700					
	Idling alongside	30		700	730					
	DO/PU-Xsit	650		730		#	Speed	Dist	Duration	20
Day 2	24*60=1440			0		25	10	1	Min	6
	Loitering	60		0	1900					
	Off Hire	300		1900	2400					
	Remainder	0								
	Off Hire	400		0000	700					
	Idling alongside	30		700	730					
	DO/PU-Xsit	650		730		#	Speed	Dist	Duration	20
Day 3	24*60=1440			0		25	10	1	Min	6
	Loitering	60		0	1900					
	Off Hire	300		1900	2400					
	Remainder	0								
	Off Hire	400		0000	700					
	Idling alongside	30		700	730					
	DO/PU-Xsit	650		730		#	Speed	Dist	Duration	20
Day 4	24*60=1440			0		25	10	1	Min	6
	Loitering	60		0	1900					
	Off Hire	300		1900	2400					
	Remainder	0								
	Off Hire	400		0000	700					
	Idling alongside	30		700	730					
	DO/PU-Xsit	208		730		#	Speed	Dist	Duration	20
	1109-0730=219			0		8	10	1	Min	6
Day 5	Loitering	8		0	1109					
	Design Transit Leg	0		1109	1109					
	Restricted Transit Leg	357		1109	1703					
	Port transit	87		1703	1830					
	Idle Alongside	30		1830	1900					
				# = NUMBER OF OFFSHORE DESTINATIONS						
				DO/PU-Xsit = DROP-OFF/PICK-UP - TRANSIT						

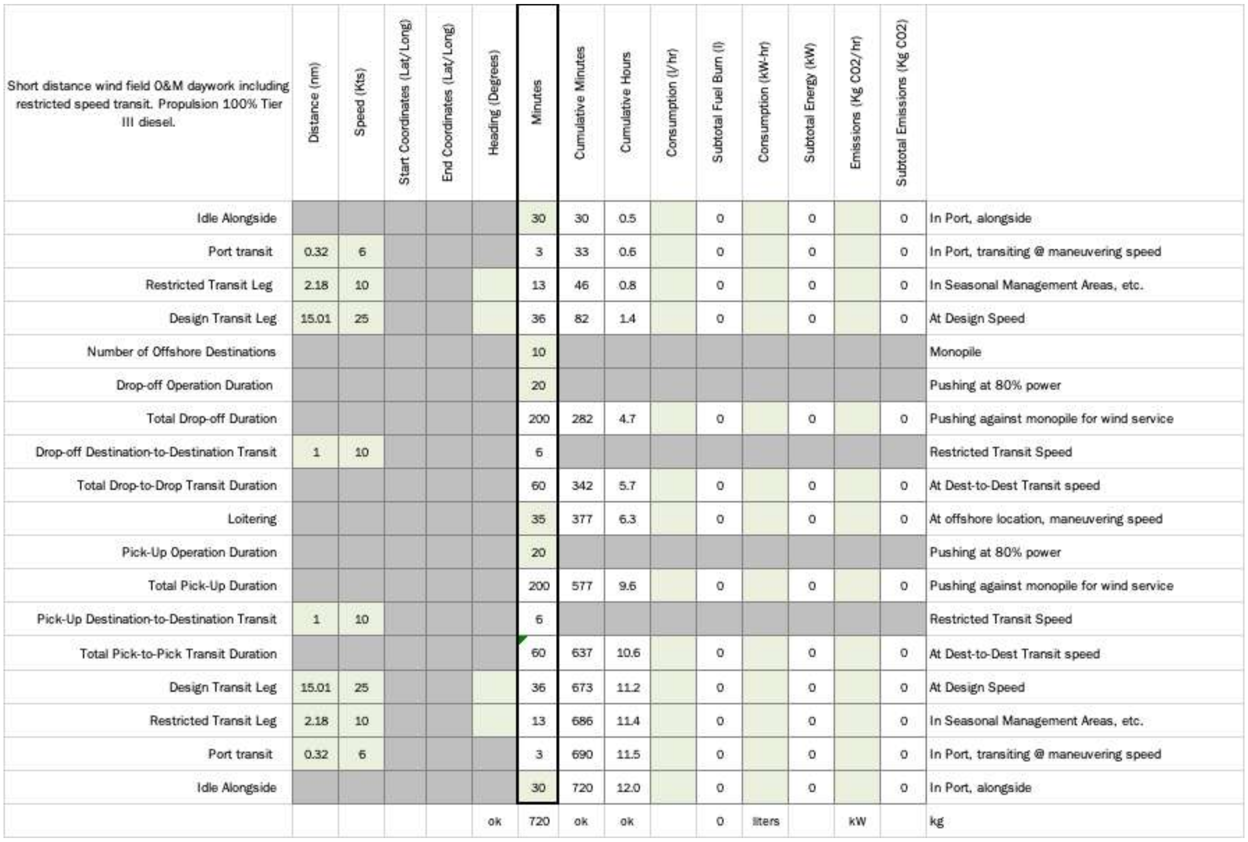
This table provides a timeline for the sequence of activities comprising the operating profile for an FSV deployed in the Northeast Cluster (NECL). This deployment is unique from the other four considered in the study due to its extended stay offshore. Instead of departing in the morning and returning in the evening of the same day, the vessel travels to the site on the first day, then remains offshore at the work location during days 2, 3 and 4 before transiting back to shore on day 5.

During each of the days offshore, the vessel spends it time shuttling technicians, gear and equipment between the work areas and the accommodations platform or Service Operation Vessel (SOV). Due to its extended stay offshore, it is assumed the vessel charges at the platform or SOV as needed during the day/night in the case of a PHEV, EPHEV or electric vessel.

Note that the entire deployment is conducted at 10-knots or less due to restricted areas with speed limitations transited.

Source: BOT

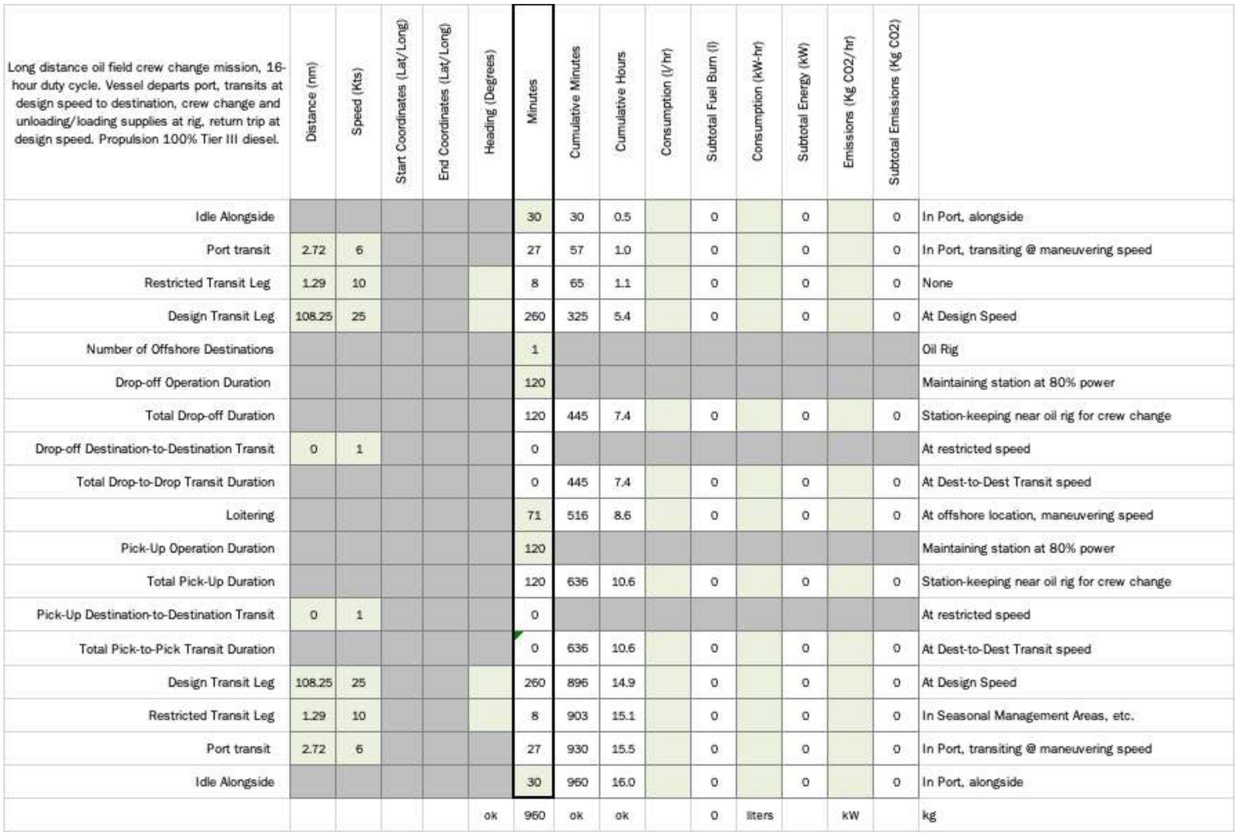
NYB Operating Profile



Short distance wind field O&M daywork including restricted speed transit. Propulsion 100% Tier III diesel.	Distance (nm)	Speed (Kts)	Start Coordinates (Lat/Long)	End Coordinates (Lat/Long)	Heading (Degrees)	Minutes	Cumulative Minutes	Cumulative Hours	Consumption (l/hr)	Subtotal Fuel Burn (l)	Consumption (kW-hr)	Subtotal Energy (kW)	Emissions (Kg CO2/hr)	Subtotal Emissions (Kg CO2)	
Idle Alongside						30	30	0.5		0		0		0	In Port, alongside
Port transit	0.32	6				3	33	0.6		0		0		0	In Port, transiting @ maneuvering speed
Restricted Transit Leg	2.18	10				13	46	0.8		0		0		0	In Seasonal Management Areas, etc.
Design Transit Leg	15.01	25				36	82	1.4		0		0		0	At Design Speed
Number of Offshore Destinations						10									Monopile
Drop-off Operation Duration						20									Pushing at 80% power
Total Drop-off Duration						200	282	4.7		0		0		0	Pushing against monopile for wind service
Drop-off Destination-to-Destination Transit	1	10				6									Restricted Transit Speed
Total Drop-to-Drop Transit Duration						60	342	5.7		0		0		0	At Dest-to-Dest Transit speed
Loitering						35	377	6.3		0		0		0	At offshore location, maneuvering speed
Pick-Up Operation Duration						20									Pushing at 80% power
Total Pick-Up Duration						200	577	9.6		0		0		0	Pushing against monopile for wind service
Pick-Up Destination-to-Destination Transit	1	10				6									Restricted Transit Speed
Total Pick-to-Pick Transit Duration						60	637	10.6		0		0		0	At Dest-to-Dest Transit speed
Design Transit Leg	15.01	25				36	673	11.2		0		0		0	At Design Speed
Restricted Transit Leg	2.18	10				13	686	11.4		0		0		0	In Seasonal Management Areas, etc.
Port transit	0.32	6				3	690	11.5		0		0		0	In Port, transiting @ maneuvering speed
Idle Alongside						30	720	12.0		0		0		0	In Port, alongside
					ok	720	ok	ok		0	liters		kW		kg

Source: BOT

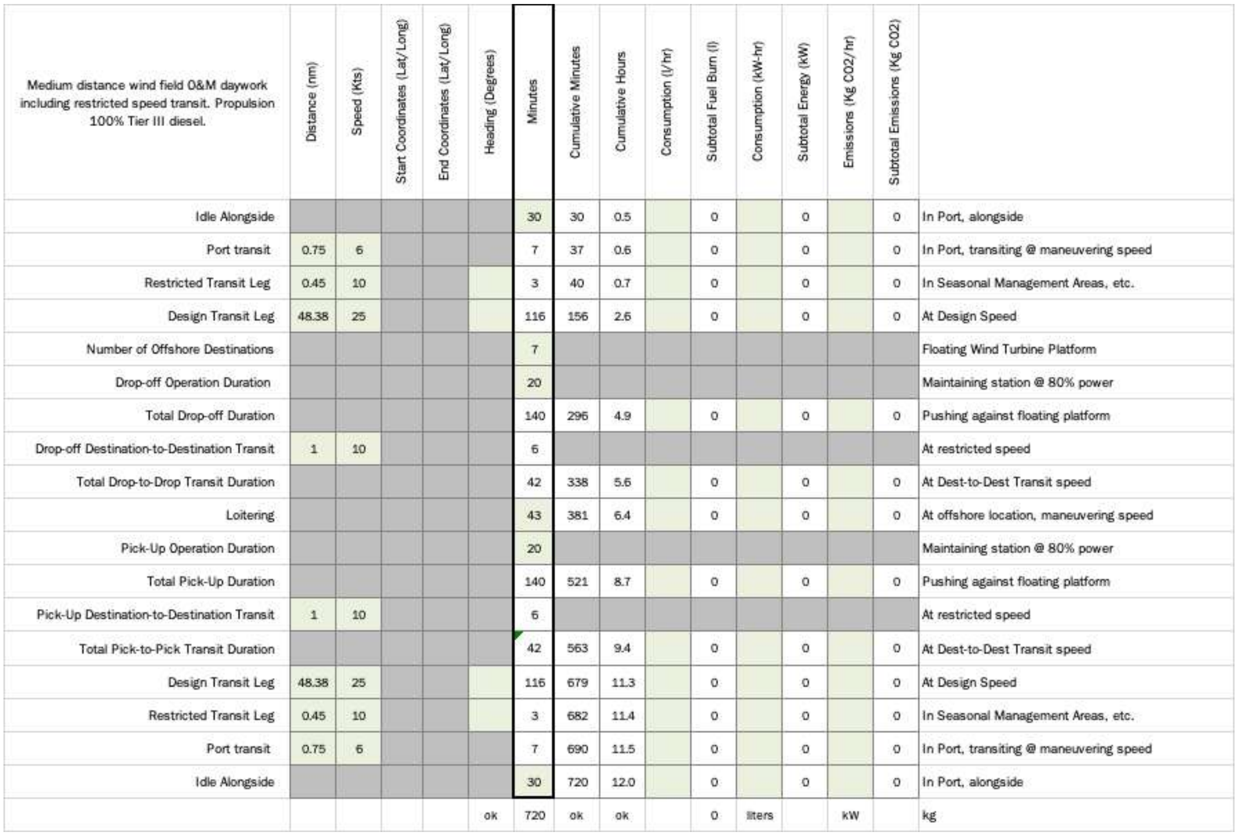
GULF Operating Profile



Long distance oil field crew change mission, 16-hour duty cycle. Vessel departs port, transits at design speed to destination, crew change and unloading/loading supplies at rig, return trip at design speed. Propulsion 100% Tier III diesel.	Distance (nm)	Speed (Kts)	Start Coordinates (Lat/Long)	End Coordinates (Lat/Long)	Heading (Degrees)	Minutes	Cumulative Minutes	Cumulative Hours	Consumption (l/hr)	Subtotal Fuel Burn (l)	Consumption (kW-hr)	Subtotal Energy (kW)	Emissions (Kg CO2/hr)	Subtotal Emissions (Kg CO2)	
Idle Alongside						30	30	0.5		0		0		0	In Port, alongside
Port transit	2.72	6				27	57	1.0		0		0		0	In Port, transiting @ maneuvering speed
Restricted Transit Leg	1.29	10				8	65	1.1		0		0		0	None
Design Transit Leg	108.25	25				260	325	5.4		0		0		0	At Design Speed
Number of Offshore Destinations						1									Oil Rig
Drop-off Operation Duration						120									Maintaining station at 80% power
Total Drop-off Duration						120	445	7.4		0		0		0	Station-keeping near oil rig for crew change
Drop-off Destination-to-Destination Transit	0	1				0									At restricted speed
Total Drop-to-Drop Transit Duration						0	445	7.4		0		0		0	At Dest-to-Dest Transit speed
Loitering						71	516	8.6		0		0		0	At offshore location, maneuvering speed
Pick-Up Operation Duration						120									Maintaining station at 80% power
Total Pick-Up Duration						120	636	10.6		0		0		0	Station-keeping near oil rig for crew change
Pick-Up Destination-to-Destination Transit	0	1				0									At restricted speed
Total Pick-to-Pick Transit Duration						0	636	10.6		0		0		0	At Dest-to-Dest Transit speed
Design Transit Leg	108.25	25				260	896	14.9		0		0		0	At Design Speed
Restricted Transit Leg	1.29	10				8	903	15.1		0		0		0	In Seasonal Management Areas, etc.
Port transit	2.72	6				27	930	15.5		0		0		0	In Port, transiting @ maneuvering speed
Idle Alongside						30	960	16.0		0		0		0	In Port, alongside
					ok	960	ok	ok		0	liters		kW		kg

Source: BOT

USWC Operating Profile

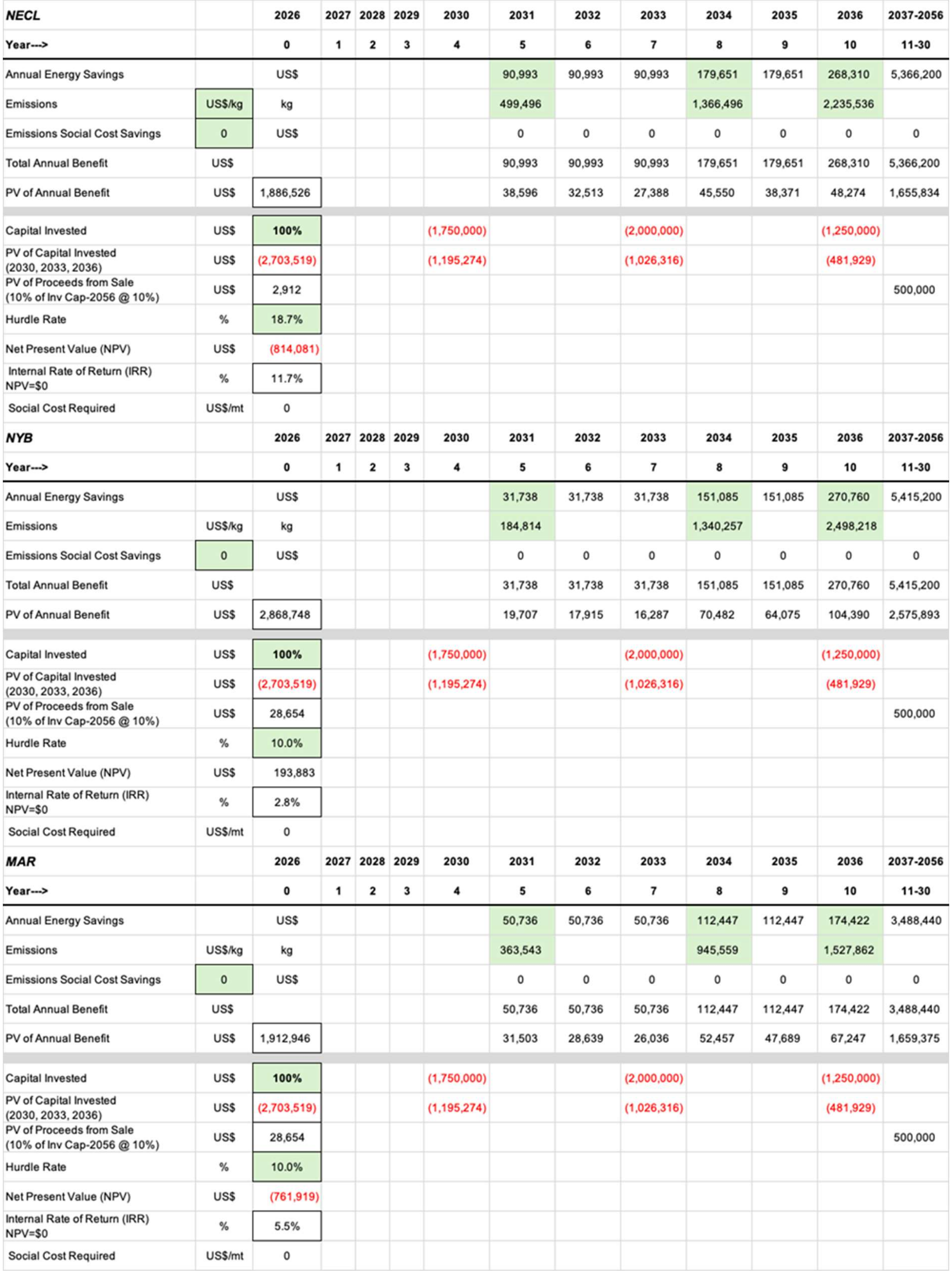


Medium distance wind field O&M daywork including restricted speed transit. Propulsion 100% Tier III diesel.	Distance (nm)	Speed (Kts)	Start Coordinates (Lat/Long)	End Coordinates (Lat/Long)	Heading (Degrees)	Minutes	Cumulative Minutes	Cumulative Hours	Consumption (l/hr)	Subtotal Fuel Burn (l)	Consumption (kW-hr)	Subtotal Energy (kW)	Emissions (Kg CO2/hr)	Subtotal Emissions (Kg CO2)	
Idle Alongside						30	30	0.5		0		0		0	In Port, alongside
Port transit	0.75	6				7	37	0.6		0		0		0	In Port, transiting @ maneuvering speed
Restricted Transit Leg	0.45	10				3	40	0.7		0		0		0	In Seasonal Management Areas, etc.
Design Transit Leg	48.38	25				116	156	2.6		0		0		0	At Design Speed
Number of Offshore Destinations						7									Floating Wind Turbine Platform
Drop-off Operation Duration						20									Maintaining station @ 80% power
Total Drop-off Duration						140	296	4.9		0		0		0	Pushing against floating platform
Drop-off Destination-to-Destination Transit	1	10				6									At restricted speed
Total Drop-to-Drop Transit Duration						42	338	5.6		0		0		0	At Dest-to-Dest Transit speed
Loitering						43	381	6.4		0		0		0	At offshore location, maneuvering speed
Pick-Up Operation Duration						20									Maintaining station @ 80% power
Total Pick-Up Duration						140	521	8.7		0		0		0	Pushing against floating platform
Pick-Up Destination-to-Destination Transit	1	10				6									At restricted speed
Total Pick-to-Pick Transit Duration						42	563	9.4		0		0		0	At Dest-to-Dest Transit speed
Design Transit Leg	48.38	25				116	679	11.3		0		0		0	At Design Speed
Restricted Transit Leg	0.45	10				3	682	11.4		0		0		0	In Seasonal Management Areas, etc.
Port transit	0.75	6				7	690	11.5		0		0		0	In Port, transiting @ maneuvering speed
Idle Alongside						30	720	12.0		0		0		0	In Port, alongside
					ok	720	ok	ok		0	liters		kW		kg

Source: BOT

[This page left blank for two-sided printing]

Appendix 5 – Financial Model



NECL		**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037-2056**
Year--->		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11-30**
Annual Energy Savings		US$					90,993	90,993	90,993	179,651	179,651	268,310	5,366,200
Emissions	US$/kg	kg					499,496			1,366,496		2,235,536	
Emissions Social Cost Savings	0	US$					0	0	0	0	0	0	0
Total Annual Benefit	US$						90,993	90,993	90,993	179,651	179,651	268,310	5,366,200
PV of Annual Benefit	US$	1,886,526					38,596	32,513	27,388	45,550	38,371	48,274	1,655,834
Capital Invested	US$	**100%**				(1,750,000)			(2,000,000)			(1,250,000)	
PV of Capital Invested (2030, 2033, 2036)	US$	(2,703,519)				(1,195,274)			(1,026,316)			(481,929)	
PV of Proceeds from Sale (10% of Inv Cap-2056 @ 10%)	US$	2,912											500,000
Hurdle Rate	%	18.7%											
Net Present Value (NPV)	US$	(814,081)											
Internal Rate of Return (IRR) NPV=$0	%	11.7%											
Social Cost Required	US$/mt	0											
NYB		**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037-2056**
Year--->		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11-30**
Annual Energy Savings		US$					31,738	31,738	31,738	151,085	151,085	270,760	5,415,200
Emissions	US$/kg	kg					184,814			1,340,257		2,498,218	
Emissions Social Cost Savings	0	US$					0	0	0	0	0	0	0
Total Annual Benefit	US$						31,738	31,738	31,738	151,085	151,085	270,760	5,415,200
PV of Annual Benefit	US$	2,868,748					19,707	17,915	16,287	70,482	64,075	104,390	2,575,893
Capital Invested	US$	**100%**				(1,750,000)			(2,000,000)			(1,250,000)	
PV of Capital Invested (2030, 2033, 2036)	US$	(2,703,519)				(1,195,274)			(1,026,316)			(481,929)	
PV of Proceeds from Sale (10% of Inv Cap-2056 @ 10%)	US$	28,654											500,000
Hurdle Rate	%	10.0%											
Net Present Value (NPV)	US$	193,883											
Internal Rate of Return (IRR) NPV=$0	%	2.8%											
Social Cost Required	US$/mt	0											
MAR		**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037-2056**
Year--->		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11-30**
Annual Energy Savings		US$					50,736	50,736	50,736	112,447	112,447	174,422	3,488,440
Emissions	US$/kg	kg					363,543			945,559		1,527,862	
Emissions Social Cost Savings	0	US$					0	0	0	0	0	0	0
Total Annual Benefit	US$						50,736	50,736	50,736	112,447	112,447	174,422	3,488,440
PV of Annual Benefit	US$	1,912,946					31,503	28,639	26,036	52,457	47,689	67,247	1,659,375
Capital Invested	US$	**100%**				(1,750,000)			(2,000,000)			(1,250,000)	
PV of Capital Invested (2030, 2033, 2036)	US$	(2,703,519)				(1,195,274)			(1,026,316)			(481,929)	
PV of Proceeds from Sale (10% of Inv Cap-2056 @ 10%)	US$	28,654											500,000
Hurdle Rate	%	10.0%											
Net Present Value (NPV)	US$	(761,919)											
Internal Rate of Return (IRR) NPV=$0	%	5.5%											
Social Cost Required	US$/mt	0											