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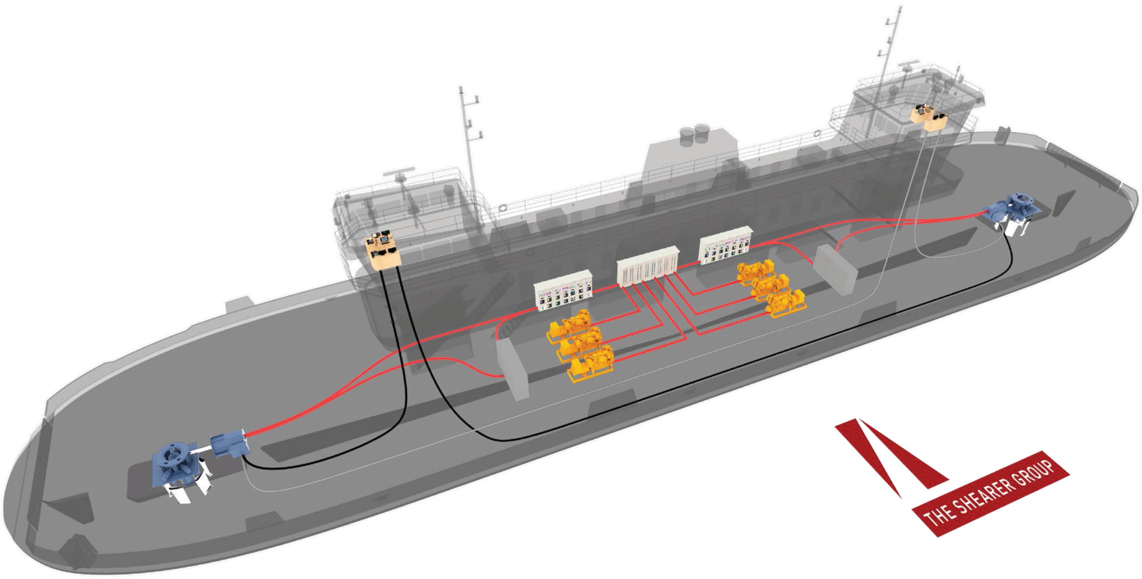
ENERGY STORAGE DESIGN



Joshua Slade Sebastian, P.E.
The Shearer Group, Inc.
06 February 2020

Introduction

"It is a capital mistake to theorize before one has data."

The above quote came from Sir Arthur Canon Doyle through his famous detective Sherlock Holmes in *A Scandal in Bohemia* and is as applicable to modern marine hybrid propulsion design as it is to solving mysteries in classic novels.

Usually, the first question naval architects are asked by owners contemplating a propulsion solution that incorporates energy storage is "How much will we save per year?" which is usually followed by "How much will the system cost?". For owners and operators, this is a fundamental question that is vital to determining the viability for any alternative power system arrangement.

However, this is not a question that a naval architect can answer quickly without information. In the past, when the industry has seen new propulsion technology emerge such as Z Drives, Kort nozzles, or improvements in prime mover efficiency, it was easy to estimate the potential gains with minimal upfront effort. If a Z drive offers an improved thrust of approximately 15%, we as engineers can easily estimate a reduction in fuel consumption will be 15%.

With hybrid propulsion systems, the answer is not as simple. The best analogy I have seen was done by a British car show that pitted a hybrid car against a performance sedan around a track. They had the hybrid drive around a track as fast as it could and had the performance sedan follow it. The result was the performance car with more than four times the power of the hybrid got 10% better mileage. That is analogous to a hybrid vessel being designed without data. Without proper data and operational goals, an electrified propulsion system can end up with worse results than a conventional mechanical drive system.

Typical Benefits of Energy Storage Systems

For typical marine applications, the use of Lithium-Ion batteries (Li-ion) will add spinning reserve, peak shaving, and efficient engine loading to increase the overall efficiency of the vessels. With those system improvements, operators can experience an overall reduction in engine hours, fuel consumption, and maintenance costs while improving the responsiveness and reliability of the vessel's propulsion system. These benefits can be realized with a variety of propulsion systems, including both Z-drives, cycloidal propellers, and conventional shafted propellers.

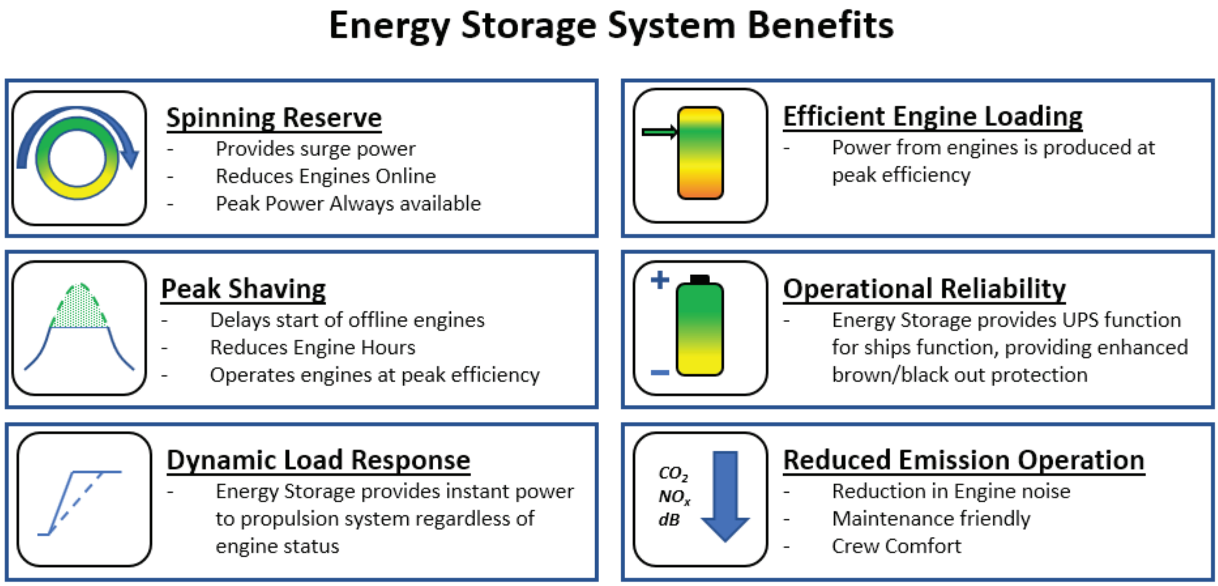


Figure 1: Energy Storage Benefits

There may be many goals that an operator wishes to pursue when considering any alternative fuel source. Below are some of the most common goals for an energy storage system:

- Zero-Emission Operations
- Reduced Emissions Operations
- Increased Operational Redundancy
- Increased Vessel Performance
- Reduction in Operation Expenses

Zero-emission operations can only be achieved currently with full battery operations. This usually requires a significant investment in the vessel and in shore side infrastructure. In general, operations interested in zero-emission operations are water taxis and tourist vessels desiring to improve their customers' experience. However, there may be operational, infrastructure, and capital limitations that make full zero-emission operations unfeasible or impractical.

Reduced emission operations will seek to reduce emissions by optimizing the energy storage to take advantage of natural efficiencies from engines. Where engines run most efficiently is also where they have the best emissions per brake specific power generation. This provides benefits to operations like harbor tugs, water taxis, ferries, and sightseeing vessels. Vessels can operate in a zero-emission state (and zero noise state) in sensitive areas around docks, harbors and sightseeing destinations. When more range or power is needed the primary power generation can be brought online as needed. The energy storage can also reduce unsightly black smoke that can result in quick power increase demands on the engine by providing a temporary boost to available power while the main engines slowly come up to the new power demand, reducing smoke stacking.

Increased operational redundancy and reliability can be increased with a properly designed system including energy storage. Reliability is improved through items such as black out/brown out protection, cleaner power for electronics, and back up propulsion power in the event of a main propulsion engine failure or temporary loss of power generation.

Vessel performance and responsiveness can be increased through the use of energy storage. Whether using a mechanical hybrid system or a diesel-electric with energy storage system, the responsiveness of the propulsion system can improve significantly. Mechanical engines require some ramp-up times to deliver full power. Likewise, a diesel-electric system operating in an auto start/stop function for the generators will require time to bring a generator online and deliver power to the propulsion system. Energy storage can be integrated to remove this delay in power delivery since its power is always available to provide an electric motor with electricity. For some operations this can also result in keeping the loads on engines at the most efficient especially if a power demand is only for a short period, i.e. approaching a dock.

Typically, the most commonly asked goal is for a reduction in operational expenses on the vessel. Energy storage can improve operational expenses for both fuel consumption and machinery maintenance costs. Energy storage offers fuel consumption benefits by optimizing engine fuel efficiency through optimized engine loading. Even after one accounts for the efficiency losses by converting the energy, storing it, and then delivering the energy, there is still a net benefit.

Maintenance costs can be reduced with the use of energy storage by reducing overall engine hours depending on the set up of the system. Diesel-electric systems will typically benefit more from the inclusion of energy storage as part of the system design than a mechanical hybrid system. In addition to reducing overall engine hours, by using the spinning reserve function of the batteries the short burst peak loads (>80% BHP) can be reduced since the batteries can provide that short-term power requirement to the vessel.

Owners need to be aware of their goals for an energy storage system when discussing any potential designs with their naval architect. While energy storage systems can see improvements in all the above goals, by prioritizing the goals, systems can be optimized for that particular vessel. However, it needs to be made clear that reduction in operational expenses is not always an obtainable benefit, depending on the operational profile of the vessel.

A clear sense of expectations for an energy storage system is vital. However, without good performance data, the final design may not be able to fully realize all the potential gains from an energy storage system, or could perform worse than the conventional propulsion system it was meant to improve upon.

There's data, then there's DATA…

What makes good data or actually what makes data good? Operational profile data can be presented in a few ways. For vessels operating on a randomized route and schedule (i.e. harbor tugs), operational profile data may only show us a high-level summary. This will help in initial analysis to determine if further analysis is warranted. However, this is not the data that is needed to properly estimate a potential energy storage system and give a proper response to the question of operational and capital cost impacts.

The first example below is from a harbor tug. Figure (2) shows a summarized data from two weeks of operation for a harbor assist tug.

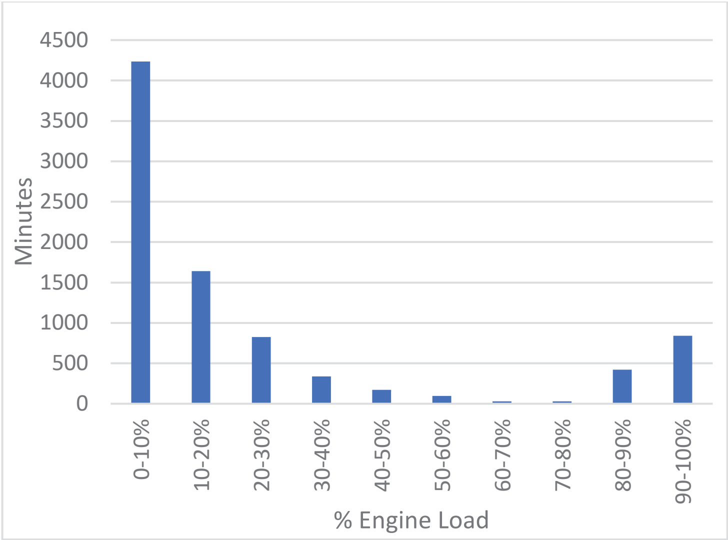


Figure 2: Two Weeks of Operation for Harbor Assist Tug

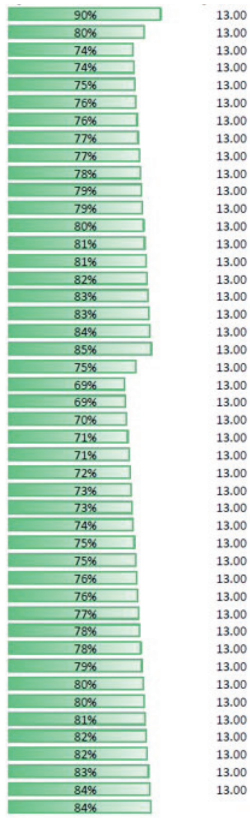
The summarized data indicates that this vessel is a strong candidate for a diesel electric, either with or without energy storage simply since the majority of its operational time is spent below 50% of total power output. Additionally, with a significant amount of time spent at or near idle conditions the vessel would like benefit greatly from the inclusion of battery technology.

The chief goal for this particular operation was to reduce emissions in the harbor they were operating in. The harbor has tight emission requirements so any new design had to minimize emission both while operating and while sitting idle. Secondary to that was reducing operational expenses such as fuel and maintenance. But cost as always is a factor. How much would a system cost? How much could emissions be improved over a baseline vessel? Could there be an improvement in operational expenses to offset the capital costs?

The first question that needs to be answered is how the batteries fit into those goals. Does the owner want to try to use the batteries as a spinning reserve or as a power boost function for those high load times? If so, the summary of operational hours does not provide enough information to determine if that is a feasible request. The time spent above 90% load averages around 60 minutes per day but does that occur as one 60-minute block per day, four 15-minute blocks per day, or one 120-minute block every other day? The size of the battery required for those three different scenarios is vastly different, and may not even be a feasible solution.

Ferries are typically easier to quantify with the theoretical operational profiles since they tend to operate on set schedules and well-defined routes. However, even with that information, there can be large variations in the results.

For example, below is a comparison that was done using a ferry's idealized transit schedule versus an actual transit schedule. This particular vessel was being designed for diesel-electric with energy storage. This study was done while working to optimize the design of the diesel-electric system and the energy storage capacity. Figure (3) shows the ideal listed transit with loading/unloading time while Figure (4) shows an actual record day of transits and loading/unloading times. The green bars represent battery charge levels ad the end of a transit.



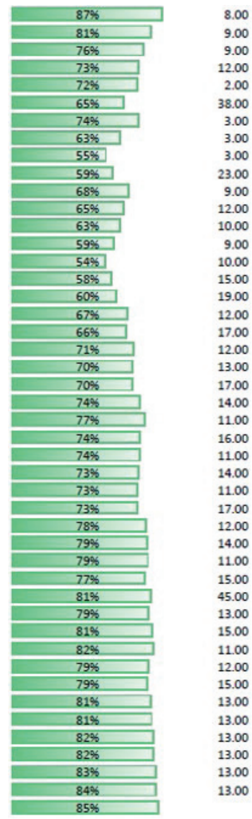


Figure **Figure 4**

While this represents the same number of trips per day, with the same throughput, the difference in the idealized versus actual data results in approximately 20% difference in fuel savings. For this particular design this degree of uncertainty on the schedule makes a noticeable difference in the return on investment.

Why the variation? This vessel's energy storage system is designed to be charged by the vessels diesel generators while conducting loading/unloading operations. When underway that stored energy is returned to the propulsion system to cover the power deficit that occurs with only two generators online at a time. The loading/unloading times varied on a daily basis due to excess demand at peak times, too little demand off hours, and even due to providing emergency response vehicles with associated quick departures.

The main goal for this operator was to increase operational reliability. Maintaining energy storage on board as a reserve in the event that the onboard power generation failed meant that the ferry would be able to safely run on batteries for 30 minutes at full power in order to safely return to the dock. The difference in the battery size to meet this requirement was significantly different using the theoretical operational schedule versus an actual operational schedule. Using an idealized schedule versus the actual when optimizing battery size to reduce fuel consumption while also meeting this reserve power requirement resulted in increasing the size of the battery by approximately 25%. This was a solution driven by better data availability.

Data Acquisition

Since the tug operation was lacking in sufficient detail in its data, the team needed to collect better data to help make informed decisions on the design of the propulsion system. Such operational profile data can be obtained by a few different methods. If a new vessel is being designed to replace an existing vessel, obtaining existing operational data can be a very beneficial process worth the time and effort. Many modern engines have some onboard data logging capability. Some of them only offer summaries of engine loads as a count of total operational times, similar to Figure 2. Others can provide you a break down of engine load every time the engine load changes by a percent. While this represents a lot of data, it is the most useful for making final design considerations.

Other techniques exist such as data logging using fuel flow meters or shaft torque meters. Torque meters are typically the least intrusive to install, requiring only an exposed area of the shaft and local power supply to power the data logging equipment. 1 TSGI uses the TorqueTrack 10ks to obtained highly detailed operational profiles.

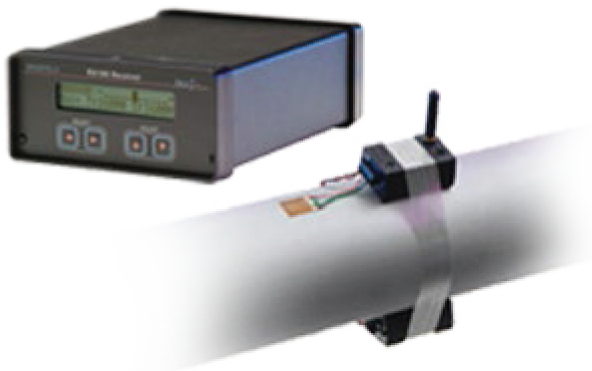


Figure 5

Such data is very important, especially when making design decisions for vessels that do not operate on a repetitive route or schedule. However, even vessels that do operate with standardized frequency can benefit from such data acquisition to further assist in fine-tuning an energy storage system and aid in the power management system design.

Detailed Case Study

Below is an example of how a detailed operational profile and analysis can help guide the design spiral early in the process so that informed decisions can be made. The following analysis is an example of a detailed comparison for a new ferry operation that was looking to determine the feasibility of diesel mechanical, mechanical hybrid (with and without energy storage) and diesel electric (with and without energy storage). The vessel required approximately 1000BHP of installed propulsion power.

Figure (6) is an overall summary of estimate engine loads.

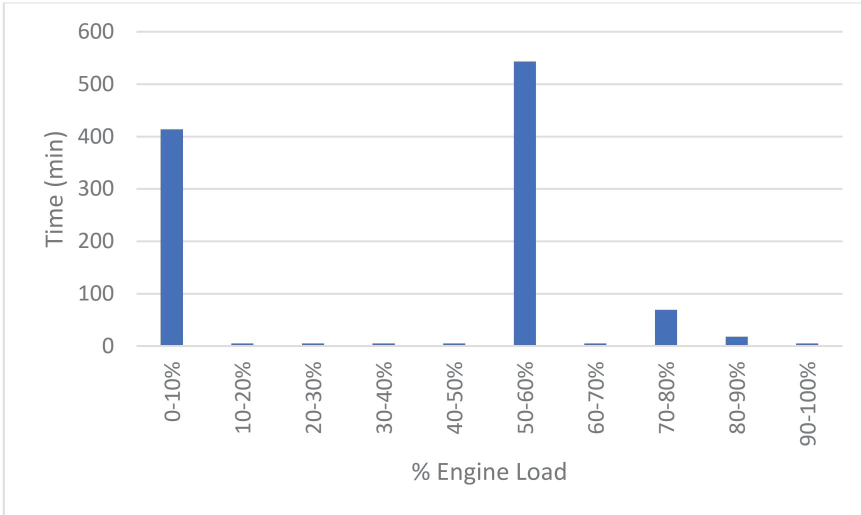


Figure 6

The profile demonstrates the typical profile key elements we look for in determining the viability of hybrid, diesel-electric and energy storage for use in the design. The vessel spends a significant portion of its time at or near idle, a majority of its operational load below 60% of installed power, and a minimal amount of time above 80% of engine load.

Using time schedules and data logged operating profiles, a detailed operational profile was developed. Figure 7 is a summary of that information, averaged around key time elements. The profile was originally provided in a second by second interval but summarized below for clarity.

Time	Operation	Power Demand
8:00:00 AM	Loading @ A	2.4%
8:06:00 AM	Loading Complete	2.4%
8:07:00 AM	Departing A	81.4%
8:12:00 AM	Transit	55.7%
8:17:00 AM	Transit	59.8%
8:22:00 AM	Transit	52.6%
8:23:00 AM	Approaching B	55.7%
8:24:00 AM	Docking @ B	76.1%
8:30:00 AM	Unloading @ B	2.4%
8:36:00 AM	Loading @ B	2.4%
8:37:00 AM	**Departing B**	79.6%
8:42:00 AM	Transit	58.0%
8:47:00 AM	Transit	56.2%
8:52:00 AM	Transit	59.8%
8:53:00 AM	Approaching A	77.9%
8:54:00 AM	Docking @ A	74.3%
9:00:00 AM	Unloading @ A	2.4%
9:06:00 AM	Loading Complete	2.4%
9:07:00 AM	Departing A	81.4%

Figure 7

From discussions with the operator, a weighting of design and operational factors was determined. In this example, values were equally weighted between capital costs, operational costs, and reliability. Rankings were based on a sliding scale where the value of one (1) represented the best performing system for a particular category.

Capital costs were compared based on preliminary designs for various propulsion options:

	Capital Cost	
	Capital Cost	Ranking
Diesel Mechanical	$ 494,000	1.00
Diesel Mechanical Hybrid (ESS)	$ 1,072,000	2.17
Diesel Mechancial Hybrid w Shore Charging (ESS)	$ 1,488,000	3.01
Diesel Electric	$ 1,053,800	2.13
Diesel Electric w ESS	$ 1,138,800	2.31
Diesel Electric w ESS w Shore Charging	$ 1,568,800	3.18
	Weight:	33%

As expected, for the size of the propulsion plant required, the diesel mechanical was the lowest in terms of capital costs. The most expensive was the Diesel Electric with energy storage and shore charging due to the cost of shore-side infrastructure.

The next item for comparison was operational costs. This was broken down into estimated maintenance costs and fuel/electricity costs. Since final engine selection had not been determined at the time of the analysis, maintenance costs were only analyzed as a function of total engine operational hours on an annual basis. The hours include the operation of a ship service generator as required by the various design options.

	Operational Costs					
	Maintenance Costs	Ranking	Fuel Costs	Electricity Costs	Total Fuel Costs	Ranking
Diesel Mechanical	19053	3.83	$ 686,354	$ -	$ 686,354	1.36
Diesel Mechanical Hybrid (ESS)	19053	3.83	$ 526,404	$ -	$ 526,404	1.04
Diesel Mechancial Hybrid w Shore Charging (ESS)	12702	2.56	$ 452,275	$ 52,514	$ 504,789	1.00
Diesel Electric	10713	2.16	$ 610,086	$ -	$ 610,086	1.21
Diesel Electric w ESS	5651	1.14	$ 528,973	$ -	$ 528,973	1.05
Diesel Electric w ESS w Shore Charging	4970	1.00	$ 465,200	$ 52,514	$ 517,713	1.03
		17%				17%

For this particular design, the energy storage option when added to the mechanical hybrid system did not significantly reduce the operational hours of the engines, however, it did significantly reduce engine fuel consumption. Adding in the option for shore charging made the diesel mechanical hybrid option for this vessel the most energy-efficient of all the options. However, this fuel savings would need more than 15 years to pay for the investment in shore-side infrastructure, assuming the electricity rates stay at present value.

The diesel-electric (with and without energy storage) provided the biggest benefit to maintenance costs when compared to the traditional diesel mechanical system. This resulted from the engines being able to cycle offline while not needed instead of idling or under less than full load.

The last part of the analysis was reliability. This part of the analysis was done using standard reliability engineering practices and established failure rates for various parts of the propulsion power generation plant. All values are based against an idealized system and is not indicative that a system will fail a certain percentage of the time or be out of service for a certain percentage of time.

	Reliability	
	Reliability	Ranking
Diesel Mechanical	54%	4.34
Diesel Mechanical Hybrid (ESS)	52%	4.50
Diesel Mechancial Hybrid w Shore Charging (ESS)	52%	4.50
Diesel Electric	76%	2.30
Diesel Electric w ESS	89%	1.00
Diesel Electric w ESS w Shore Charging	89%	1.00
		33%

The most unreliable part of any propulsion power system is the mechanical engine due to the number of moving parts. This is where diesel-electric options provide a significant increase in the operations. For the analysis, the requirement for operations is that both shafts have available full power. With the mechanical and mechanical hybrid options, the majority of the power for this particular design came from the mechanically linked engine. If the engine failed on one shaft, the vessel would be required to be removed from operation. For the diesel-electric options, three generators were provided. Each generator was to provide 60% of the required horsepower, thus allowing one engine to be out of commission with no impact on the operations of the vessel.

The other item of note is that when adding energy storage to the mechanical hybrid system, the overall reliability decreased. However, when adding energy storage to the diesel-electric system, the overall reliability improved. This is a function of the system design with this particular hybrid design which placed the batteries in series, functionally speaking, to the power delivery system, instead of in parallel to the functioning of the propulsion system is was designed for the diesel-electric system.

When all the rankings were summarized using the weighting determined by the operator, the following was the result.

	Overall Ranking	
	Expanded Score	Ranking
Diesel Mechanical	2.64	4
Diesel Mechanical Hybrid (ESS)	3.03	5
Diesel Mechancial Hybrid w Shore Charging (ESS)	3.08	6
Diesel Electric	2.03	3
Diesel Electric w ESS	1.46	1
Diesel Electric w ESS w Shore Charging	1.72	2

Diesel-electric with energy storage was considered the most well-rounded choice. Also, of note, this information could now by used by the engineers and operators to better develop the options for the vessel, such as refinement of the mechanical hybrid solutions with other engine and energy storage combinations and configurations to improve certain short comings from the initial design.

This analysis should not be interpreted as a final conclusion for this vessel or any other vessel, but only as an example of how good data early in the design process can help answer key questions for the operation and designer.

Conclusion

As with any system or technology, an electrified propulsion system with energy storage may not be a viable solution for all vessel owners. Careful analysis with good data is the key to making determinations for the vessel operators.

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