# Electric power systems for fishing vessels: Feasibility, fuel savings and costs

**January 20, 2021**

Chandler Kemp
Kempy Energetics

Samer Atshan
Pardee RAND
Graduate School

Funding for this project was provided by Alaska Longline Fishermen's Association, Alaska Conservation Foundation, and unrestricted gifts from Pardee RAND Graduate School supporters.

Contact information

Chandler Kemp
Kempy Energetics
3005 Clinton Drive A5
Juneau, AK 99801

ckemp@kempyenergetics.com
907.209.5897
www.kempyenergetics.com

Samer Atshan
Pardee RAND Graduate School
1700 Main Street
Santa Monica, CA 90405

satshan@prgs.edu
310.393.0411 x8257
www.prgs.edu

# Table of Contents

# Executive Summary

The commercial fishing fleet in Southeast Alaska stands to benefit from emerging technologies that make hybrid, battery-electric and alternative fuel vessels more practical and affordable than ever before. A transition from diesel fuel to batteries is underway in ferries serving short transit routes, and hybrid propulsion systems have already been demonstrated in sport and commercial fishing vessels [1]–[3]. The commercial fishing fleet in Southeast Alaska poses unique challenges to alternative power systems due to the unpredictable nature of fishing and the extended trips that some fisheries require. Nonetheless, a battery-electric hybrid gillnet vessel is under development in Sitka, AK and more fishermen are considering similar investments [4].

This report focuses on battery-electric and hybrid propulsion systems in troll, gillnet and longline vessels. It aims answer two critical questions for these systems:

1. How much will equipment costs be for battery or hybrid systems in realistic scenarios?
2. How much fuel can be saved by implementing one of these systems?

We address these questions by highlighting the critical equipment essential to alternative systems, documenting the range costs incurred by recent projects or provided by manufacturers in budgeting quotes, and estimating the battery and fuel requirements in various example scenarios.

Fishing vessels that operate at low speeds for extended periods are the best candidates for alternative power systems. Vessels participating in gillnet, longline and troll fisheries are highlighted here because they often fit this load profile. These types of vessels are good candidates because their diesel engines operate inefficiently when lightly loaded, resulting in disproportionately large fuel savings per unit of alternative energy storage on board the vessel.

The amount of fuel that can be saved with an alternative propulsion system will depend on the vessel's load profile, the efficiency of the hull and deck gear, and the amount of energy storage available. Given the average engine efficiency and fishing loads observed in previous work, we estimate fuel savings of 0.07-0.17 gallons per kWh of energy storage capacity per trip. The range is due the efficiency of diesel engines: on average, an optimally loaded engine in the fishing fleet consumed approximately 0.07 gal/kWh of useful work while in transit [5]. However, while trolling or setting fishing gear propulsion engines are lightly loaded and often consume more than two times as much fuel per unit of useful work.

In order to evaluate the feasibility, cost and fuel savings of all electric or hybrid fishing vessels, we consider a series of example scenarios that highlight the strength of each type of system. We find that the cost and volume requirements of battery storage for an all-electric system are impractical for existing vessels unless they exclusively participate in fisheries very close to their homeport. However, vessels that can switch between diesel power and battery-electric power are feasible in many cases. In an example scenario where the vessel fishes within two hours of its homeport and has enough battery storage for one full day of fishing, we estimate a reduction in fuel consumption of 37%.

The equipment cost of converting a vessel from diesel to electric or hybrid propulsion will be driven by the batteries, electric motor, controller, and installation hardware. Currently available batteries that could be used in a vessel retrofit project range in cost from \$300-800/kWh [4], [6]. The US Department of Energy has short term and long term target battery costs of \$100 and \$80/kWh [7]. In order to supply energy for a full day of fishing, most longline, troll and gillnet vessels will require 50-100 kWh of battery

capacity. Motor costs will likely range from $4,300 to $20,000 for a hybrid vessel, and higher for an all-electric vessel. Controller and installation hardware contributed more than $15,000 to expenses in the FV Sunbeam project underway in Sitka, AK [4].

In most cases, the payback time of a hybrid or all electric system will be longer than the expected life of the system. However, the benefits of near-silent operation, reduced engine maintenance and avoided greenhouse gas emissions may also motivate fishers to invest electric or hybrid systems. Incremental support from grants or subsidies would reduce payback times, spur investment in hybrid systems and lead to economies of scale as the systems become more common.

## Acknowledgements

This work was developed with invaluable support from many contributors throughout Southeast Alaska and beyond. The work was funded by the Alaska Conservation Foundation and the Alaska Longline Fishermen's Association. Linda Behnken, Kent Barkhau, and Dan Falvey contributed perspective from the fishing fleet and unwavering support. Fabian Grutter spent many hours sharing his experience in retrofitting FV Sunbeam as a hybrid gillnet vessel, and Bob Varness of Tongass Rain Electric Cruise LLC shared his experience and expertise earned by developing the first all-electric passenger vessel in Alaska. Cora Dow provided valuable discussion throughout the project representing the Sitka Conservation Society. Erik de Jong of Bagheera Sailing shared his expertise in efficient vessel design. The Colorado Hydrogen Network provided valuable discussion of the potential for hydrogen powered vessels in the future. In addition to these key contributors, we also want to thank the many others who answered my questions, developed budgeting quotes for their products and provided helpful discussion.

# 1 Introduction

Diesel-electric, hybrid, battery-electric and alternative fuel vessels are now proven technologies in cruise ships, sport fishing vessels, and ferries. The commercial fishing fleet in Southeast Alaska stands to benefit from these recent advances in alternative power systems, but existing vessels rely almost exclusively on direct drive diesel propulsion systems and diesel driven auxiliary loads. This report evaluates the technical feasibility of adopting alternative power systems, quantifies their impact on fuel consumption, and summarizes the range of equipment costs that should be expected to retrofit a vessel with one of the systems.

In many alternative power systems, the cost of energy storage will be much greater than the cost of the power plant. For example, in a battery-electric system the number of kilowatt-hours (kWh) stored has a large impact on the system cost, but the size of the electric motor used to turn the propeller is less important. In a traditional diesel system the opposite is true: a diesel engine costs much more than a fuel tank. This distinction may drive future changes in hull design and vessel operation, and determines which existing vessels are best suited to proposed alternative propulsion systems.

Efficiency measures have a critical impact on the economic feasibility of alternative power systems. Energy efficiency measures that apply to existing vessels are briefly addressed in this report, but further detail can be found in documentation of the Vessel Energy Analysis Tool developed for the Alaska fishing fleet [5]. The existing fishing fleet developed over the past century to maximize reliability and functionality while minimizing cost and diesel engines have been the favored power system for achieving those objectives. In the past 15 years, the cost of battery energy storage has declined by over 10% per year while efforts to reduce emissions worldwide gained strength [8]. The reduced cost and improved performance of alternatives to diesel fuel coupled with increased interest in emission reduction is driving investment in alternative power systems.

This report focuses on technology for energy storage and delivery to the propeller shaft. We consider their performance as a retrofit to existing vessels with little change in operations as well as in “high efficiency” scenarios with significantly reduced energy demands. In each case, we will provide a brief description of how the high efficiency scenario might be achieved but refer the reader to other publications for further detail. Our goal is to describe how alternative power systems will perform under a range of realistic and relevant conditions while relying on other references to establish that range.

We focus on **battery-electric, hybrid diesel-electric** and traditional **direct drive diesel** systems in this report. There are many other power systems that are not considered here, including fuel cell-electric, biofuel, sails, and renewable energy technologies that could be deployed away at sea. While these systems may be promising, they are beyond the scope of this report.

# 2 Fishing vessel energy systems

Fishing operations in Southeast Alaska are diverse. Vessels range from 30 to 80 feet in length, fishing trips range from one day to several weeks, and propulsion engines range from 100 to over 1000 horsepower in rated capacity. It is impossible to choose a “representative” vessel to consider as an example, and propulsion systems that may be cost effective for one vessel will be utterly infeasible for another. As a result, this work does not prescribe a system for vessels to adopt. Rather, we provide a range of technologies and costs that may be applicable to many vessels that participate in a fishery.

Figure 1 provides a visualization of nine propulsion systems divided into three classes. Existing systems fall in the first class: **direct drive internal combustion**. These systems are characterized by an engine mechanically connected to the propeller shaft. While existing systems in this class rely on petroleum diesel, they could be retrofitted to burn an alternative fuel such as biodiesel or ammonia. Depending on how the alternative fuel is produced displacing diesel fuel with it could reduce greenhouse gas emissions. Biodiesel and ammonia fuels are beyond the scope of this report, but they are noted as systems of interest in Figure 1.

**Electric drive** systems rely on an electric motor to provide all of the power to the propeller. The electricity may come from a variety of sources, including a diesel powered generator (often called a "diesel-electric" system), a battery storage system or a fuel cell system. Diesel electric systems are common in cruise ships and military vessels that have large electrical loads in addition to propulsion loads and benefit from the flexibility that comes with eliminating a mechanical connection between engines and propeller [9]. An all-electric gillnet vessel has also been demonstrated in Norway that uses batteries that can charge on shore or from an onboard diesel generator (as illustrated in Figure 1.E) [3]. Battery storage systems have proven effective in applications that support frequent charging like ferries that cross rivers or narrow fjords [1], [10]. Fuel cell electric vessels may be more cost effective for longer trips and several pilot projects are currently under development [11]–[13].

**Hybrid drive** systems allow two different sources to supply power to the propeller—typically an electric motor and a diesel engine coupled directly to the shaft. Hybrid systems can derive electricity from a diesel-powered generator, battery, or fuel cell. If the vessel uses batteries, they may be charged by an onboard diesel engine (similar in concept to a hybrid car like the Toyota Prius), shore power (similar in concept to a plug-in hybrid car like the Chevy Volt) or from any other electricity source. The following sections will show how much fuel (if any) these systems are likely to save in comparison to a traditional direct drive diesel system and estimate the cost of retrofitting existing vessels.

We focus on fisheries that require vessels to operate their propulsion engines at less than 10% of the engines' rated capacity for extended periods. Troll, longline and gillnet vessels often fit this profile. We focus on these vessels because diesel engines generally operate inefficiently when under 10% of rated load, and little energy storage is needed to meet the low-load demand in comparison to typical transit or towing loads. The combination of inefficient engine operation and minimal energy storage requirements make these vessels the best candidates for the alternative propulsion systems considered here.

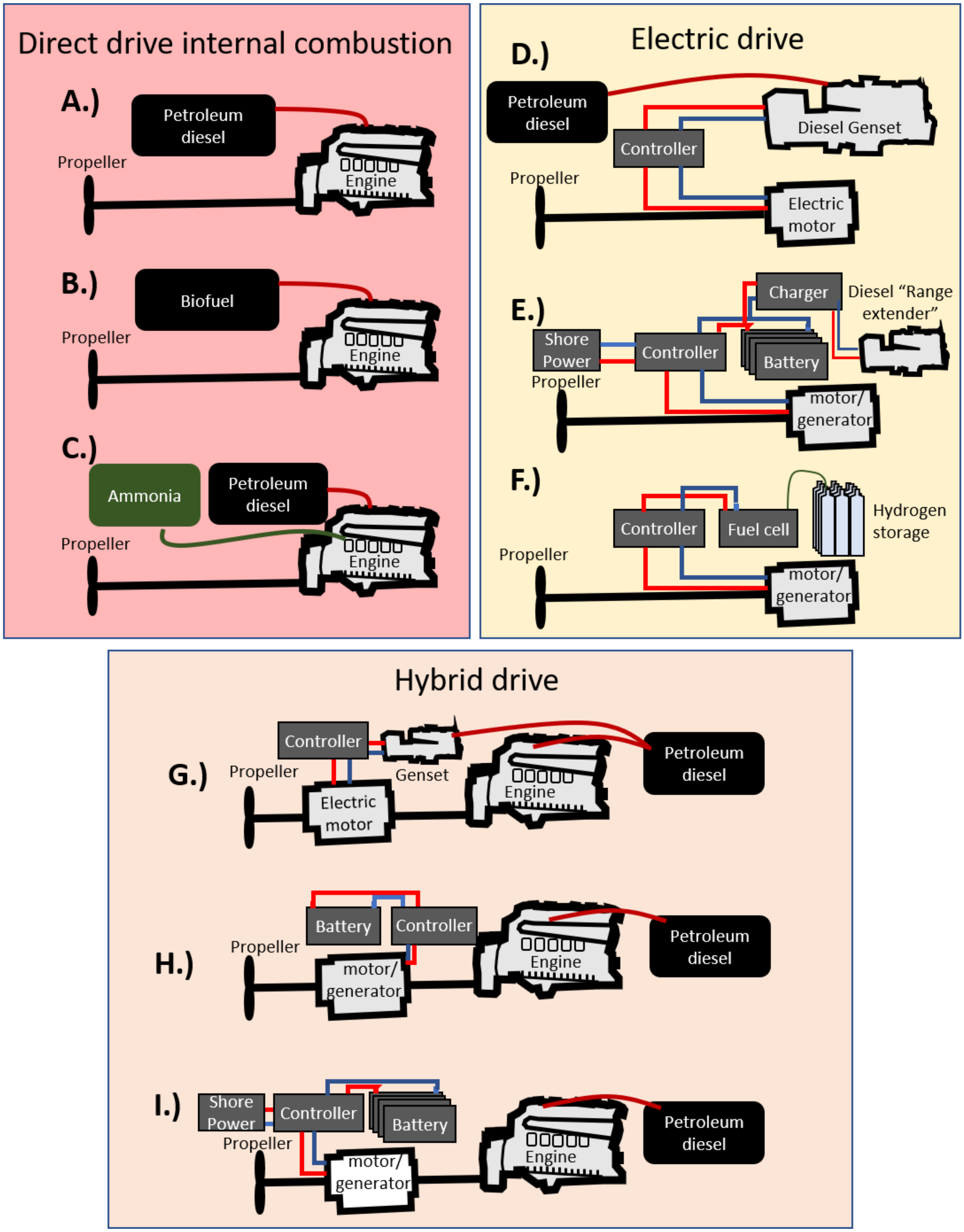


*Figure 1 Existing and proposed propulsion systems in marine vessels. A.) Direct drive petroleum diesel engine B.) Direct drive biofuel engine C.) Direct drive diesel engine with partial ammonia combustion D.) Petroleum diesel electric drive E.) Battery electric drive with a diesel generator to extend range. Sometimes called a "hybrid electric serial." F.) Fuel cell electric drive G.) Hybrid drive with auxiliary genset H.) Hybrid drive with battery storage I.) Hybrid drive with additional battery storage and charging from shore power.*

# 3 Existing fleet energy consumption

Fishing vessels consume energy for propulsion, refrigeration, hydraulics, and electronics. With few exceptions, the energy for all these systems is derived from diesel fuel on existing vessels. Figure 2 shows an example propulsion engine equipped with a belt driven alternator and hydraulic pump. The engine burns diesel fuel to provide propulsion, hydraulic and DC electric power. In a set up like the one shown in Figure 2, an inverter may be used to provide AC power to hotel loads. In addition, many vessels use an auxiliary diesel genset to supply large AC loads. Many variations on this design exist. For example, hydraulic pumps may be driven by a power take-off shaft rather than a belt drive, refrigeration compressors may be driven by hydraulic pumps rather than by electricity, and additional loads may be added to the propulsion engine. In any case, all of the energy used by these vessels is derived from diesel fuel.

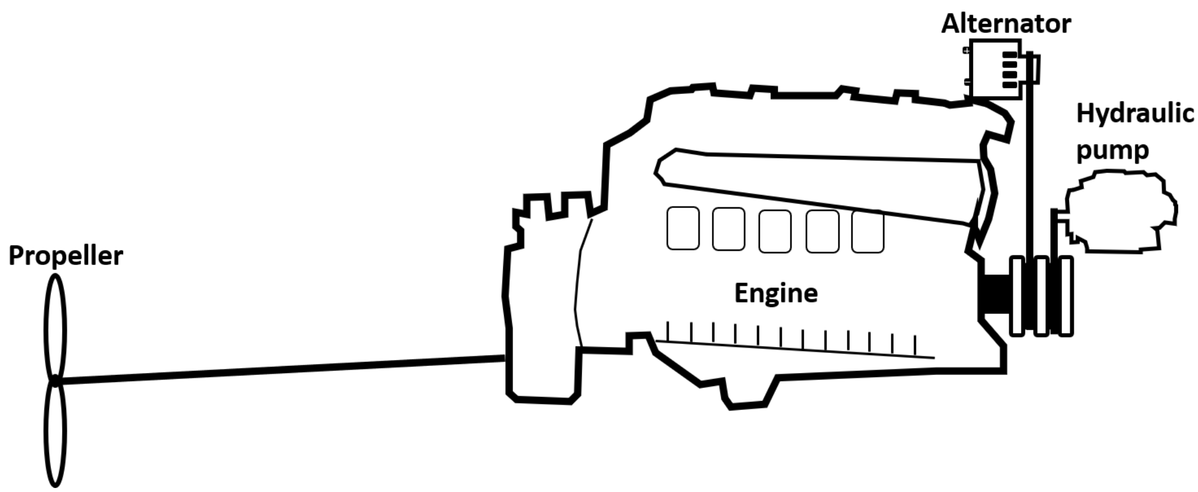


*Figure 2 Example propulsion engine with belt driven alternator and hydraulic pump.*

The following sections will summarize the range of power required to satisfy each of these loads on existing vessels as well as the efficiency improvements that may be possible without changing the engine or installing an alternative propulsion system. The data were collected during sea trials and energy audits on 30 Alaskan fishing vessels conducted during the Fishing Vessel Energy Efficiency Project (FVEEP). Additional information describing the methods used to measure vessel energy loads and the analysis approach are described in [5]. The following sections are intended to provide the tools to create a preliminary estimate of energy storage requirements for many types of Alaska fishing vessels based on the loads relevant to their fisheries, as well as the energy efficiency measures that might be adopted to reduce storage requirements.

Short of considering each vessel load separately, the Rule of Thumb below gives a quick method for estimating the amount of electric power required to deliver as much mechanical power as a diesel

Rule of Thumb: In order to estimate useful power delivered by your engine in kW, subtract 0.5 from the fuel consumption rate in gal/hr and multiply by 14.

engine based on fuel consumption. Details and limitations for this Rule of Thumb are provided in Appendix A.

## 3.1 Propulsion energy and power requirements

Propulsion is the dominant load on fishing vessels. For gillnet, longline and troll vessels without refrigeration systems, propulsion accounts for over 65% of total energy consumption. In order to design an optimal alternative propulsion system, the vessel drag and propeller efficiency need to be accurately estimated. However, drag varies dramatically between different hull designs, and can even vary between vessels with the same hull design depending on the hull condition and vessel trim. Propeller efficiency also spans a broad range depending on the rate of rotation, polish and interference from the hull. This section will introduce the typical trends in vessel drag for 35-50 foot vessels in the Southeast Alaska fishing fleet, the amount of power required to meet propulsion loads on existing vessels, and the potential to reduce propulsion loads through changes in cruising speed or hull design.

### 3.1.1 Estimating propulsion power requirements

One practical method for estimating propulsion energy requirements for small fishing vessels was provided by the Fishing Vessel Energy Efficiency Project (FVEEP) [5]. The FVEEP measured propulsion power on 29 fishing vessels in Alaska by fastening a strain gauge to the propeller shaft during sea trials. Results from sea trials on 9 vessels 40-50 feet in length are shown in Figure 3. The data show a broad range in delivered power to achieve the same speed with similar length vessels. For example, the plot shows a range of 35-49 hp at 7 knots. The variability is primarily due to differences in hull shapes, hull roughness (due to fouling), underwater appendages and propeller efficiencies. Without a practical method for fishers to quantify these variables, power will need to be measured to achieve better precision than that indicated by Figure 3.

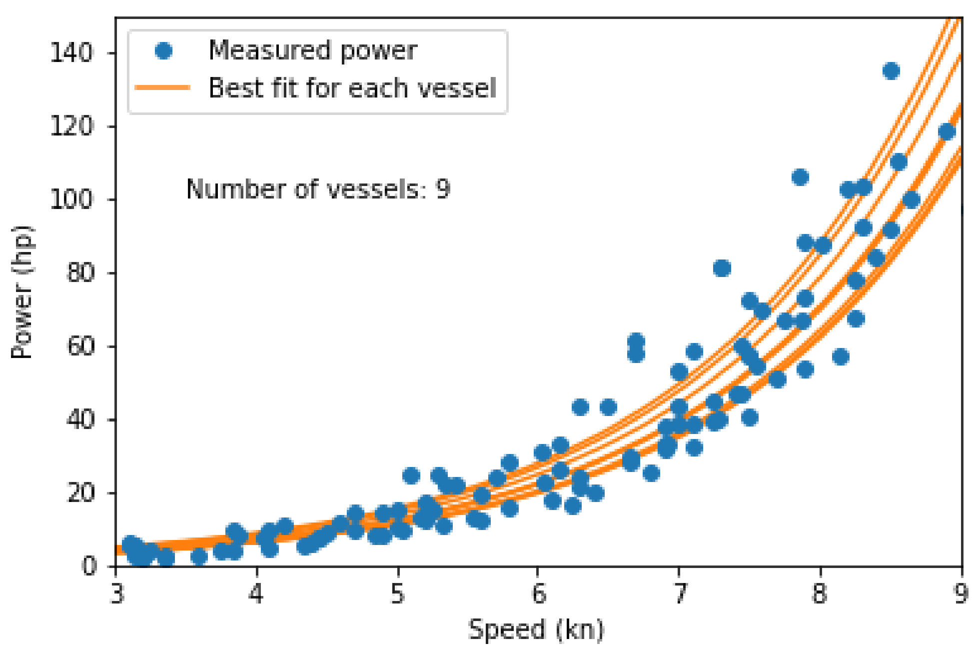


*Figure 3 Delivered power versus speed measured on nine working fishing vessels in Alaska.*

Given these limitations, Equation 1 shows the best correlation found between propulsion power and speed for the data collected in the FVEEP based on speed (*s* in knots), length and beam (*L* and *B* in feet) only. At cruising speeds, the root mean squared error for this correlation was found to approximately 30% of predicted power. The correlation can be used to make preliminary estimates of power requirements, but it must be used with caution: deviations from model predictions of 30% should be expected at cruising speeds; the sample size used to develop the correlation is small; and the accuracy is expected to be further limited at lower speeds. The correlation will be used for some preliminary design considerations in this work, but a more accurate estimate should be used before making investments for any specific vessel.

$$P_D = \begin{cases} 3.6 \times 10^{-3} L\sqrt{B} e^{0.57s} & if\ s \geq 3\ knots \\ 2.0 \times 10^{-2} \left(\frac{s}{3}\right)^3 & if\ s < 3\ knots \end{cases} \qquad (1)$$

With additional vessel details specifying the hull prismatic coefficient, roughness and propeller design, peer reviewed drag and propeller models may provide more accurate power estimates than the method described by Equation 1. For example The “WUMTIA” model of hull resistance was developed for vessels 33 to 230 feet in length based on trials of over 600 hull forms [14]. The model estimates calm water resistance based on vessel length, beam, displacement, wetted surface area and speed. Empirical tests of propeller series provide propeller efficiencies in a range of operating conditions [15].

If an existing vessel is considering a retrofit to their propulsion system, propulsion power can be measured directly, as described in Appendix A.

### 3.1.2 Opportunities to reduce propulsion power

Minimizing propulsion loads can dramatically reduce the energy storage requirements for alternative propulsion systems. The methods listed below range from relatively simple procedures that many fishers already follow to capital intensive or deep operating practice changes that may be infeasible for many fishers.

1. Keep the hull and propeller clean. Measurements during the FVEEP showed a 10-30% reduction in delivered power before and after vessels hauled out, cleaned the hull and polished the propeller.
2. Keep transit speeds low. A 45 foot vessel can expect to reduce delivered power requirements by 40% by slowing from 8 to 7 kt.
3. Travel with tides. Fishing operations might require transiting at specific times, but a tidal current of one knot could reduce or increase delivered power requirements by over 15% depending on if the tide is with or against the direction of transit.
4. Consider alternative hull forms. Measurements made during the FVEEP showed 10-20% reductions in propulsion power required at transit speeds achieved by fishing vessels that lengthened their hull (without increasing their beam) or added a bulbous bow.

In subsequent sections, status quo example calculations will be provided using the average values for propulsion power observed during the FVEEP. The efficiency measures above suggest that reducing energy demand by 30% or more may be feasible for many vessels.

## 3.2 Hydraulic energy and power requirements

Troll, gillnet and longline vessels use hydraulic systems to power gurdies; net drums and rollers; and longline drums and sheaves or autoline systems, respectively. Hydraulic loads are most significant when the pumps operate for long hours and the other vessel loads are small. The hydraulic load may account for 30% of total energy demand on ice-troll vessels with positive displacement pumps that circulate fluid continuously during long fishing days.

Table 1 shows power requirements estimated during the FVEEP. The data are based on measurements from 2-3 vessels in each category[1]. This work will use the values to develop preliminary estimates of energy requirements, but the loads are known to vary significantly between vessels and should be verified for any specific vessel design.

*Table 1 Hydraulic deck loads*

| Hydraulic load | Average delivered power (kW) | Duty cycle |
|---|---|---|
| Troll gurdies | 3.7 | 1 |
| Gillnet drum | 3.5 | 0.15 |
| Gillnet drum AND power roller | 5.2 | 0.15 |
| Autoline haul system | 7.4 | 0.48 |
| Longline sheave OR drum | 2.3 | 0.48 |
| Longline sheave AND drum | 2.8 | 0.48 |

In addition to the average delivered power, the fraction of time that the load is applied determines the energy requirements for the system. This time fraction is shown in the duty cycle column of Table 1. Troll gurdies are shown with a duty cycle of 1 because the two troll vessels with hydraulic measurements in the FVEEP used positive displacement pumps that incurred a large, constant load on the engine that averaged 3.7 kW during fishing hours. The other loads show the fraction of time while fishing that the load is expected to be applied based on long term recordings during the FVEEP.

### 3.2.1 Opportunities to reduce hydraulic power requirements

Hydraulic loads were found to be highly variable between vessels during the FVEEP, suggesting that existing design and operating choices can have a large impact on efficiency. Several opportunities are listed below:

1. Minimize fluid flow when the hydraulic system is not doing any work. This can be accomplished by using a load sensing pump, declutching the hydraulic system when not in use or otherwise removing power to the hydraulic pump. Systems that continuously circulate fluid when the hydraulic system is not actively performing work are inefficient.
2. Practice good maintenance and installation procedures. Fluid leaking past worn seals in hydraulic pumps and motors results in wasted energy. Using dirty or poorly filtered hydraulic oil causes seals to wear more quickly. Minimizing fittings reduces energy loss in the hydraulic lines during transmission.
3. Consider alternative methods to supply the required loads. Although hydraulic pumps and motors may be rated to >90% efficiency, the hydraulic systems observed in the field performed

[1] The autoline haul system hydraulic load was estimated based on manufacturer specifications rather than measurements.

at significantly lower overall efficiencies. If feasible, electronic systems may offer significant efficiency gains.

## 3.3 Electrical loads

Existing longline, troll and gillnet vessels use up to two systems to supply electrical power. All vessels have an alternator that is powered by the main engine and used to charge batteries, supply 12 volt loads including navigation equipment and lighting, and an inverter to provide 110 volt AC power for plug-in electronics. In addition, some vessels have an auxiliary diesel powered generator to supply three phase AC power to large electrical loads. The generator may also provide 110 volt AC power rather than an inverter in some cases. In the fisheries of interest here, generators are most often present on vessels that have refrigeration systems. Therefore, AC generators will be addressed in the following Refrigeration Section, while this section addresses alternator and DC systems only.

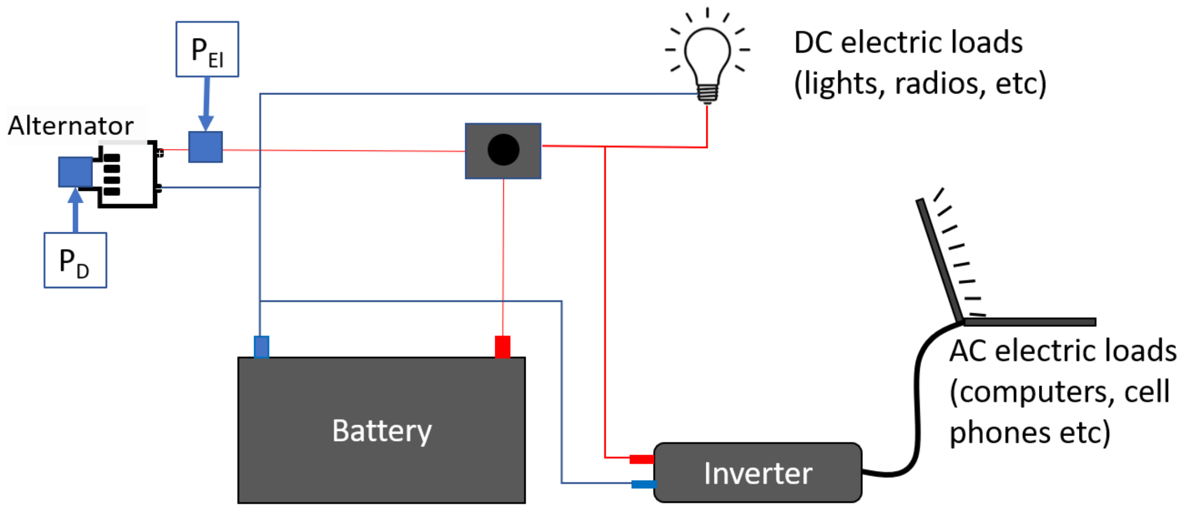


*Figure 4 Electrical schematic. Blue squares indicate locations where various types of power could be measured.*

In the context of the basic DC system illustrated in Figure 4, **delivered power** ($P_D$) refers to the power supplied to the alternator, while **electric power** ($P_{El}$) is equal to the product of DC current and voltage produced by the alternator. Electric power is related to delivered power by the alternator efficiency ($\eta_{alt}$): $P_{El}= \eta_{alt} P_D$. $\eta_{alt}$ varies from zero at no load up to 70% for an efficient alternator optimally loaded..

### 3.3.1 Opportunities to reduce DC electric power consumption

DC loads typically account for less than 5% of total energy consumption on a vessel, so the significance of energy savings through DC system efficiency are limited. However, the DC energy efficiency measures listed below are worthwhile and low cost.

1. "Right-size" the alternator: alternator efficiency depends on both load and rate of rotation. Choosing an alternator that has peak efficiency under typical operating conditions can improve efficiency by 20%.
2. Switch to LED lighting: LED lighting is up to 10 times more efficient than incandescent lights and about twice as efficient as compact fluorescents.

## 3.4 Refrigeration Loads

Refrigeration systems can use nearly as much energy as propulsion on troll and gillnet vessels. While many troll and gillnet vessels purchase ice from tenders or onshore to preserve their fish until delivery, some have on board refrigeration systems. Gillnet fishers use refrigerated sea water (RSW) systems to keep their hold near 32°F. Troll fishers use blast freeze systems to maintain their hold near -40°F. Both systems have three major components that consume energy: compressor, circulation pump or fan, and a condenser pump.

Three distinct methods are used to deliver power to refrigeration systems: direct drive, electric or hydraulic. The effective power required by the compressor and pumps is independent of the type of power system used, but the delivered power from an engine or battery will differ based on the efficiency of each system. Hydraulic systems observed in the FVEEP provided the least efficient transfer of energy from the diesel engine to the compressor. However, hydraulic systems can be powered by the propulsion engine, negating the need to run a second engine for the refrigeration system. Electric systems offer a more efficient transfer of energy but typically require an additional auxiliary generator to run continuously. Direct drive systems offer the most efficient coupling to the refrigeration equipment.

Troll blast freeze compressors observed in the FVEEP drew 6 kW of mechanical power on average with a duty cycle of 0.75 and 0.96 while in transit and fishing, respectively. The circulation fan and condenser pump measured in the FVEEP had an average power demand of 0.7 kW. The primary energy demand on the system was maintaining the hold temperature while fishing.

Gillnet RSW systems were not observed in the FVEEP, but modeling performed for the Rural Energy for America Program has shown that compressors installed in the Bristol Bay fishing fleet typically demand 5-10 kW and have a duty cycle of around 30% (once the hold is at temperature). Unlike in troll fisheries, the circulation pump and condenser pump typically run continuously in the Bristol Bay gillnet fishery to ensure that cold water circulates past the fish continuously. The circulation pumps typically demand approximately 1.6 kW, while the condenser pumps demand 0.6 kW.

### 3.4.1 Opportunities to reduce refrigeration power consumption

The opportunities to reduce refrigeration power consumption depend on the type of fishing operation considered. In blast freeze systems insulation and seals are critical to ensure that heat does not infiltrate the hold. Maximizing the heat removed from refrigerant in the condenser by keeping the condenser flow valve open will lower discharge pressure and improve efficiency, as long as enough lift is maintained across the thermal expansion valve. If the improved capacity of the compressor leads to short cycling after increasing condenser water flow, a variable frequency drive can be installed in electric systems to slow down the compressor once the hold is at temperature.

In RSW systems minimizing the amount of water that must be cooled can result in the greatest savings. Some vessels reduce the amount of water that must be cooled by subdividing their hold and determining how many sections are filled with water based on the amount of fish they catch. Having at least one inch of spray foam insulation or equivalent is also important for RSW systems, but additional insulation has limited benefit. If the hold has an inch of insulation and the hold is refilled daily, the majority of the work performed by the compressor will likely be dedicated to cooling the water pumped into the hold rather than removing heat that infiltrates through the walls.

## 3.5 Example vessel profiles

The previous sections summarized the types of loads present on longline, troll and gillnet vessels. A vessel owner will be able to use these data to develop a rough estimate of how much energy is used on their vessel and, therefore, how much energy storage would be needed for an alternative energy system. The Vessel Energy Analysis Tool (VEAT) is designed to assist fishers in this process. Fishers may provide information about their vessel and fishing practices to the VEAT, and the VEAT will use the same data presented above to develop an estimate of energy consumption for each load on the vessel. Before investing in a new system fishers should measure the performance of their vessel to achieve more accurate results. The data presented here and the VEAT will give a general indication of the amount of energy storage and power required to supply all vessel loads, but are not precise enough for design.

The following sections present more information about each type of propulsion system introduced in Figure 1. In each case, an example scenario is considered to illustrate the functionality, cost and fuel consumption of the technology. The examples *are not* indicative of how the technologies will perform generally; they are simply examples that may be adapted to evaluate the performance of a proposed technology for a specific vessel. The assumptions regarding energy consumption for each vessel profile represent the average values recorded in the FVEEP. In some cases, a "high efficiency" scenario may also be considered that assumes the severe energy efficiency measures described have been taken before implementing the alternative propulsion system. The assumptions for each of these categories are listed in the tables below.

Troll, longline and gillnet fisheries consist of a transit period and a fishing period. In some cases, vessels may also consume power during an "anchor" period when the vessel is neither fishing nor in transit, but still has lights on or runs a refrigeration system. The average electric energy listed for each fishery allows 500 Watts of electrical demand to account for lights and other electrical loads that are not included in propulsion or hydraulic loads.

In the status quo scenario, the average value for each parameter used to estimate energy requirements is copied directly from the Vessel Energy Analysis Tool Model Documentation [5]. The "Energy Efficient" scenarios assume that the vessel transits at lower speeds, improves propeller efficiency through cleaning or replacement, and replaces hydraulic gear with electric or equivalently high efficiency equipment. The status quo case represents the energy requirements of installing a system on a typical vessel operating today with no further changes, while the energy efficient systems represent an extreme scenario in which a captain chooses to make deep changes to their behavior in order to minimize the energy requirements for their operation.

### 3.5.1 Troll

Troll vessels typically operate by transiting to fishing grounds, moving slowly through the water while trolling, and then transiting back to shore to unload fish. The table below shows average values reported in vessel audits for the Fishing Vessel Energy Efficiency Project [5].

*Table 2 Parameters characterizing and "average" troll vessel and a hypothetical high efficiency vessel.*

| Parameter | Status quo value | Energy efficient value |
|---|---|---|
| Length (ft) | 44 | 44 |
| Beam (ft) | 13.5 | 13.5 |
| Transit speed (kt) | 6.7 | 5 |

| | | |
|---|---|---|
| Fishing speed (kt) | 2.8 | 2.8 |
| Transit propulsion power (kW) | 26 | 9 |
| Fishing propoulsion power (kW) | 3 | 3 |
| Hydraulic power (kW) | 3.7 | 1 |
| Hydraulic duty cycle | 1 | 0.5 |
| Electric power (kW) | 0.5 | 0.5 |
| Fraction of time tanked | 0.2 | 0.2 |

### 3.5.2 Gillnet

Gillnet vessels also have transit periods at relatively high speed and fishing periods at low speed. The average values reported by [5] result in the assumptions for gillnet operations shown below.

*Table 3 Parameters characterizing and "average" gillnet vessel and a hypothetical high efficiency vessel.*

| Parameter | Status quo value | Energy efficient value |
|---|---|---|
| Length (ft) | 37 | 37 |
| Beam (ft) | 11 | 11 |
| Transit speed (kt) | 8.3 | 5 |
| Fishing speed (kt) | 2.9 | 2.9 |
| Transit propulsion power (kW) | 52 | 8 |
| Fishing propoulsion power (kW) | 2 | 2 |
| Hydraulic power—drum only (kW) | 3.5 | 2.0 |
| Hydraulic duty cycle | 0.15 | 0.15 |
| Electric power (kW) | 0.5 | 0.5 |
| Fraction of time tanked | 0.5 | 0.5 |

### 3.5.3 Longline

Longline vessel parameters shown below are taken from [5]. Hours fishing per day are estimated based on the author's conversations with longline fishermen.

*Table 4 Parameters characterizing an "average" longline vessel and a hypothetical high efficiency vessel.*

| Parameter | Status quo value | Energy efficient value |
|---|---|---|
| Length (ft) | 49 | 49 |
| Beam (ft) | 15 | 15 |
| Transit speed (kt) | 7.1 | 5 |
| Fishing speed (kt) | 2 | 2 |
| Transit propulsion power (kW) | 36 | 36 |
| Fishing propoulsion power (kW) | 1 | 1 |
| Hydraulic power (kW) | 2.3 | 1 |
| Hydraulic duty cycle while fishing | 0.48 | 0.5 |
| Electric power (kW) | 0.5 | 0.5 |
| Fraction of time tanked | 0 | 0 |

## 3.6 Summary of conventional vessel loads

In summary, the energy loads on existing vessels include (in order of average energy consumption per season in troll, gillnet and longline fisheries) propulsion, refrigeration, hydraulic and electric loads. Propulsion loads are typically 26-52 kW in transit and less than 3 kW while fishing. Hydraulic loads are typically 3-3.5 kW, but the duty cycle while fishing ranges from 0.15-1 depending on the fishery. Blast freeze systems typically demand approximately 6 kW when present on fishing vessels. Electric loads are small compared to other loads in most cases, estimated to be an average of 500 watts for most vessels. Fuel efficiency measures may reduce the power requirements for all loads.

# 4 Electric drive systems

Electric drive systems rely on electricity for propulsion. The electricity may be supplied by a variety of sources. In this work, we explicitly address electric drive systems powered by diesel gensets and batteries (Cases D and E in Figure 1). Fuel cell technology (Case F in Figure 1) would require developing hydrogen storage on vessels as well as developing hydrogen generation infrastructure. While the technology shows some promise, evaluating these complexities is beyond the scope of this report. In comparison with traditional systems, electric drive systems can reduce emissions by displacing fossil fuel combustion with an alternative energy source.

## 4.1 Electric drive major components

An electric drive system consists of an electricity source (such as batteries or a diesel generator), an electric motor to drive the propeller, a controller for the electric motor and a battery management system, including the charger. Each of these system components can be sourced separately to minimize cost and maximize flexibility, or they can be purchased as a package from system integrators like Transfluid, Elco or Torqeedo to minimize design work and maximize reliability.

The following sections describe the requirements that fishing vessels have for batteries, generators, motors, controllers and chargers and provide a range of costs that should be expected in a retrofit project. The data are intended to serve vessel owners aiming to develop a conceptual budget for a retrofit project and references are provided for more detailed information about each system component.

### 4.1.1 Electric motors

Electric motors must be sized to satisfy the maximum anticipated power and torque required, while also operating efficiently during fishing operations with low load. Therefore, the motor should be selected based on the propulsion load expected for the vessel.

Propulsion load depends on the vessel's hull, propeller efficiency, sea state, gear deployed over board, speed through the water and other factors. In sea trials during the Fishing Vessel Energy Efficiency Project (FVEEP), troll, gillnet and longline vessels with displacement hulls less than 50 feet in length required 25-35 kW to maintain a speed of 7 kt in calm conditions with neutral current. Additional details of the propulsion loads measured in Alaskan fishing vessels for the FVEEP are provided in Section 3.1. Additional capacity must be provided to support transit in challenging conditions or while towing. Based on these measurements, most existing vessels in the Alaska fishing fleet under 50' will require an electric motor with a continuous rating of 40-100 kW to provide transit at 7 kt without any modifications to the hull or propeller.

At fishing speeds, the required propulsion power is much lower. During sea trials in the FVEEP, vessels that participated in troll, longline or gillnet fisheries typically required less than 3 kW to maintain a speed of 2.5 kt in neutral current with no gear overboard. Stabilizers and troll gear can increase the required propulsion power by 50-100%. Allowing for tides and sea states, a propulsion motor intended to be used only at fishing speeds may require 10-20 kW of capacity.

The shaft RPM required to achieve transit speed depends on the propeller design in addition to hull configuration. In the vessels considered here, propeller shaft speed ranged from 349 to 817 RPM at 7 kt. Traction motors often operate most efficiently at speeds over 4,000 RPM. Therefore, a reduction gear will be needed to achieve efficient motor operation at the required propeller speeds.

The efficiency of electric motors depends on their load (kW) and speed (RPM), as well as the type and quality of motor. As an example, Figure 5 shows an efficiency map for an interior permanent magnet motor, adapted from [16]. The data show a broad range of conditions with efficiency greater than 95%, between 3,000 and 10,000 RPM and five and 50 kW. However, for loads less than 5 kW (as expected in fishing conditions) or speeds less than 2000 RPM, the efficiency of the motor decreases. This characteristic emphasizes the value of choosing an appropriately sized motor and reduction gear in order to maximize efficiency.

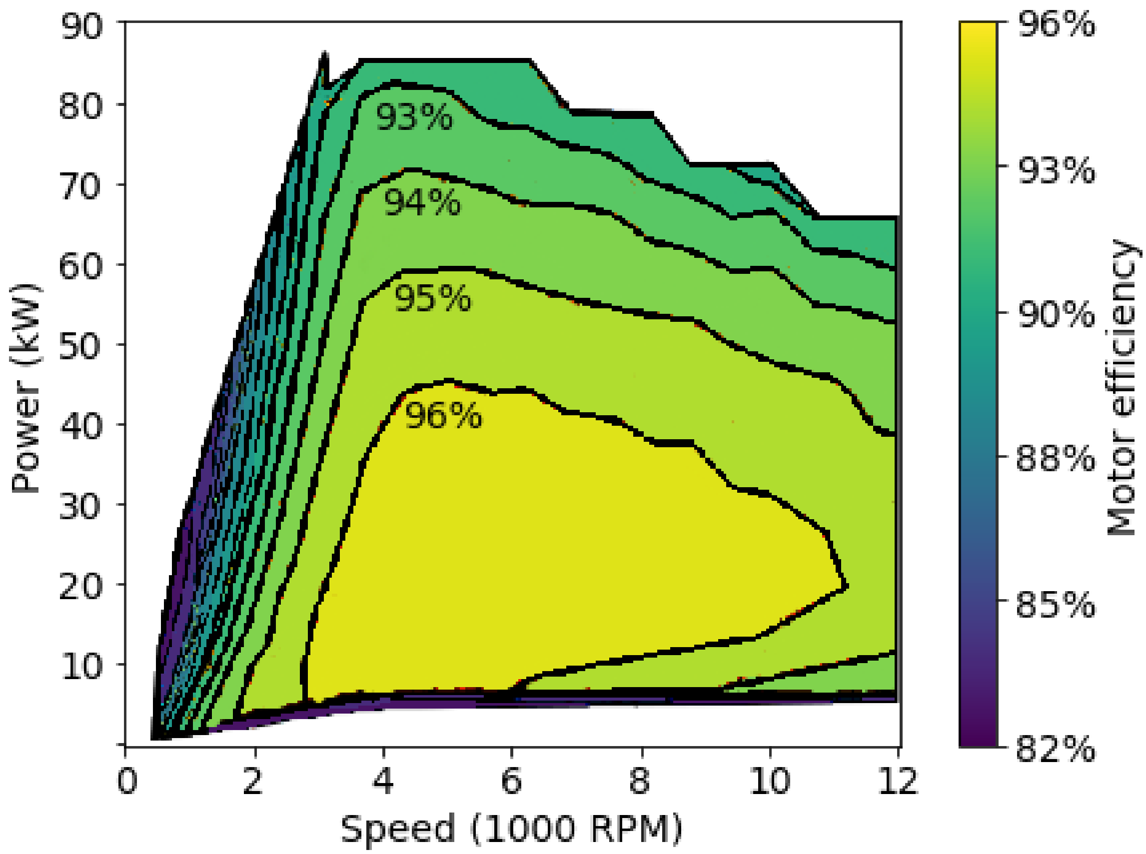


*Figure 5 Efficiency map of a 50 kW Interior Permanent Magnet Motor adapted from* [16].

Given the broad range in propulsion power required by vessels in sea trials, the propulsion requirements for any vessel should be considered individually to aid in the decision process for a propulsion motor. However, considering the cost, dimensions and weight of motors that may be suitable for this application provides enough information for budgeting and feasibility evaluations.

*Table 5 Electric motor specifications and retail prices*

| Manufacturer | Model | Rated Continuous Power (kW) | Length (in) | Width (in) | Height (in) | Weight (lbs) | Price | Reference |
|---|---|---|---|---|---|---|---|---|
| Elco | EP-100 | 43 | 35 | 19 | 19 | 740 | 22570 | [17] |
| Torqeedo | Deep Blue i900 | 100 | 46 | 31 | 25 | 990 | 45000 | [6], [18] |
| Transfluid | 300-100 | 100 | 28 | 14 | 14 | 425 | - | [19] |

### 4.1.2 Electricity source

The following sections address systems that source electricity from diesel gensets or batteries.

#### *4.1.2.1 Diesel genset*

Some large vessels including cruise ships and drill rigs have opted to use a diesel genset powered electric motor rather than a diesel engine coupled directly to the shaft [9]. The system loses some efficiency due to the energy transitions between the diesel engine and electric motor, but the design provides the flexibility to position the engine(s) anywhere in the vessel rather than in line with the shaft. Electric systems also allow diverse auxiliary loads and propulsion loads to be carried by the same engine. In some cases, the flexibility afforded by electronic propulsion systems allows for more optimal loading of the engines, offsetting generator and motor losses inherent to a diesel electric system.

Diesel-electric systems may prove an integral part of battery powered vessels that require a diesel generator for extended range. Diesel-electric systems without battery energy storage are explored here as a useful concept that may be integrated with a battery electric system, although they are unlikely to benefit fishing operations on their own.

A fully diesel electric system will require a genset with a similar capacity to the electric motors described in the previous section. Table 6 provides some examples of marine diesel gensets in the correct power ranges and their expected cost.

*Table 6 Marine generator example costs*

| Manufacturer | Model | Rated continuous power (kW) | Height | Width | Length | Weight | Cost | Reference |
|---|---|---|---|---|---|---|---|---|
| Kubota | 30kW V3300-E3BG | 30 | 28 | 28 | 73 | 776 | 21999 | [20] |
| Bollard | MG50 | 50 | 40 | 31 | 62 | 620 | 32000 | [21] |
| John Deere | 100kW 4045AFM85 | 100 | 38 | 32 | 66 | 2584 | 43299 | [20] |

#### *4.1.2.2 Battery storage*

Batteries are available with a broad range of chemistries, properties, costs, and customer support. We summarize the cost and important battery characteristics in the context of fishing vessels here. Additional information about the advantages of specific battery chemistries is available in reference

[22]. Critical attributes of batteries include their cost, volumetric energy density (kWh/m$^3$), mass energy density (kWh/kg), cycle life and safety ratings.

The Department of Energy has published near term cost targets of $100/kWh for battery manufacturers [7]. However, private fishing vessel owners are unlikely to access new batteries at those prices in the next five years. In the used market, electric vehicle batteries are available for less than $200 per kWh but purchasing them requires accepting additional risk: it may be difficult to determine the health of a used battery and sellers typically do not offer warranties. The Sitka based vessel FV Sunbeam purchased batteries through an electric vehicle support company for $300/kWh but found the lack of support accompanying the system to be challenging [4]. Batteries manufactured by Torqeedo are more expensive, but the price includes technical support and integrated user-friendly battery management systems. Table 7 provides an illustration of the range of costs that fishermen should expect to see when selecting batteries, based on budgeting quotes provided by manufactures as well as projections and market evaluations.

*Table 7 Examples of battery costs provided in budgeting quotes or published research and cost targets.*

| Description | Energy storage cost ($/kWh) | Volume energy density (kWh/m$^3$) | Mass energy density (kWh/kg) | Cycle life | Source |
|---|---|---|---|---|---|
| Torqeedo BMW i3 40 kWh HV battery | $823 | 144 | 0.14 | 3200 | [23] |
| Electric Car Parts sourced 75 kWh battery pack 2020 | $293 | - | - | - | [4] |
| Lithium ion battery market price 2015 | $399-615 | - | - | - | [24] |
| Used 13.2 kWh SDI ESS 60 Volt battery | $130 | - | - | - | [25] |
| DOE Battery Cost Target (long term) | $80 | - | - | - | [26] |

## 4.2 Case D: Diesel electric

A diesel electric system is represented in Figure 6. The propeller is mechanically connected to an electric motor. A diesel engine coupled with an electric generator provides electricity to the motor.

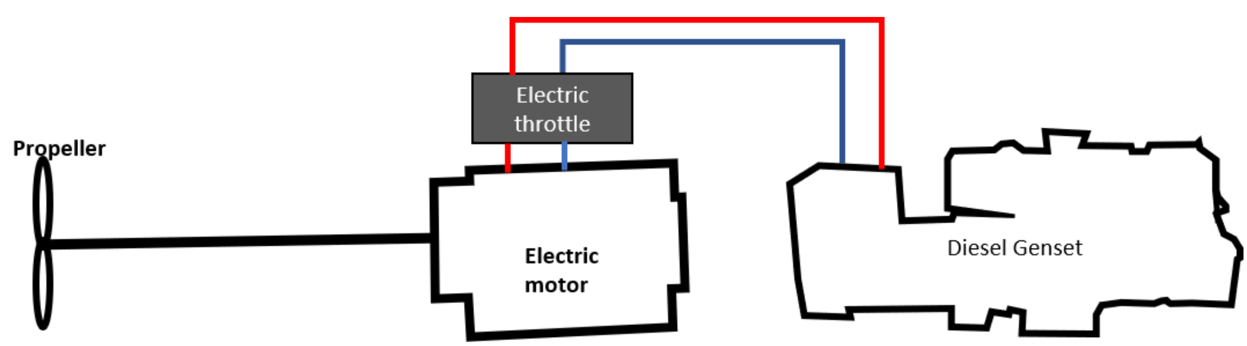


*Figure 6 A basic diesel electric system*

Fuel consumption for a the diesel electric system shown in Figure 6 can be calculated according to Equation 2, where $E_{prop}$ is the propulsion energy required, $\eta_{motor}$ is the efficiency of the electric motor, $\eta_{generator}$ is the efficiency of the electric generator, $\eta_{engine}$ is the efficiency of the diesel engine and $E_{fuel}$ is the energy that must be available in the fuel. In comparison to a traditional diesel system, Equation 2 shows that the fuel consumption will be increased due to the inefficiency of the electric generator and motor in an electric drive system.

$$E_{fuel} = \frac{E_{prop}}{\eta_{motor}\eta_{generator}\eta_{engine}} \tag{2}$$

There are rare scenarios in which operating conditions may favor an electric drive system. For example, a troll vessel that deploys drag while fishing in order to slow the vessel beyond its idle speed may not need to deploy the drag with an electric drive system, resulting in a reduction in propulsion energy that may reduce fuel consumption while fishing. However, the losses in the generator and motor would result in a net increase in fuel consumption for most vessels.

## 4.3 Case E: Battery Electric

The results of this section show that in addition to expense, the volume required to store sufficient energy may limit the feasibility of a 100% battery powered vessel to a small number of vessels that exclusively make very short trips.

Figure 7 illustrates a basic battery electric system. The vessel stores energy on board using batteries. The propeller is powered by an electric motor and the batteries are charged at shore. A diesel genset can be added to the system in order to extend range and recharge the batteries at sea if needed. Incorporating a diesel genset into the system provides a cost-effective safety margin for trips to sea with unpredictable range requirements. The example below illustrates how a diesel generator can supplement batteries for a vessel with insufficient electricity storage to complete a trip.

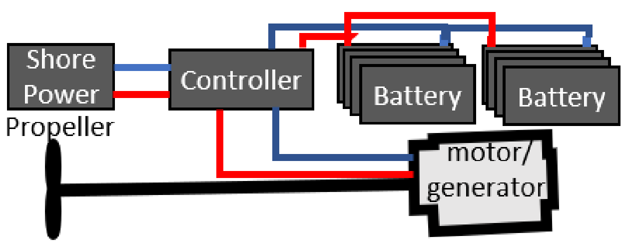


*Figure 7 A basic battery electric propulsion system*

The system reduces diesel fuel consumption simply by replacing diesel fuel with electricity. The technologies required are readily available, but the cost, volume and weight of the battery storage will be considerable for most fishing vessels. Fuel savings and system costs are considered below for an example fishing scenario.

### 4.3.1 Battery electric example scenario

Consider a troll vessel with the characteristics and operating patterns described in Table 8. In this example, the vessel makes a trip with a duration of five days. The vessel is in transit for 12 hours each way from its harbor to the fishing grounds, and fishes 18 hours per day for three days between transit periods. There is an additional 30 minutes of transit each day from anchor to the fishing grounds. The vessel does not have a refrigeration system and uses negligible power when it is at anchor.

*Table 8 Fishing operation assumptions for an example scenario with a battery electric troll vessel*

| Vessel Characteristics | Units | Value | Note |
|---|---|---|---|
| vessel length | ft | 44 | Average for troll vessels [5] |
| vessel beam | ft | 13.5 | Average for troll vessels [5] |
| hydraulic power demand while fishing | kW | 1 | Average for troll vessels is 3.8 kW. An extremely efficient system (possible electric gurdies) is assumed here [5]. |
| Drag due to fishing gear | lbs | 125 | results in a speed reduction of 0.5 kt if the gear is deployed at 3 kt (i.e., the gear causes the vessel to slow from 3 to 2.5 kt) |
| Operating Patterns | | | |
| fraction of time with stabilizers deployed | - | 0.3 | Average for Troll vessels [5] |
| fraction of time with hold tanked | - | 0.2 | Average for Troll vessels [5] |
| Fishing hours | hrs | 54 | Assumed 18 hours per day for three days |
| Transit hours | hrs | 27 | Assumed 12 hours transit one way from harbor to fishing grounds, plus 30 minutes to and from anchor for three fishing days |
| Transit Speed | kt | 6 | Troll vessel average is 6.7--assumed 6.0 for reduced energy demand |
| Fishing Speed | kt | 2.8 | Troll vessel average [5] |

On a conventional vessel, the full propulsion load would be met by the diesel engine mechanically connected to the propeller shaft. Hydraulic loads would be provided by a hydraulic pump also driven by the main engine. In the vessels audited during the FVEEP, the hydraulic pumps used by troll vessels required an average of 3.8 kW during fishing operations. However, the pumps typically operated continuously during those times, and over 2 kW of power was consumed even when there was no load on the gurdies. In this scenario, we assume that the conventional hydraulic system has been replaced by an electric system that consumes zero power when the deck gear is not turning, resulting in an average load of 1 kW. *This type of system has not been demonstrated in the fleet, so the load estimate is uncertain.* Hydraulic power contributes significantly to overall battery capacity requirements in this scenario, and the efficient system is assumed to provide an estimate of feasibility on a vessel with efficient deck equipment systems that are likely—though unproven—on an electric fishing vessel.

The battery electric vessel simulated here also includes a diesel genset that provides power after the battery storage is exhausted. The efficiencies of components in the conventional and battery electric system are summarized in Table 9.

*Table 9 Generator, battery and engine efficiency assumptions*

| System efficiencies | Units | Value | Note |
|---|---|---|---|
| motor efficiency | - | 0.93 | |

| | | | |
|---|---|---|---|
| controller efficiency | - | 0.98 | |
| battery discharge efficiency | - | 0.95 | |
| Generator efficiency | - | 0.93 | |
| Genset engine overhead fuel | gal/hr | 0.4 | Overhead fuel consumption at zero load |
| Genset marginal brake specific fuel consumption | gal/kWh | 0.07 | Additional fuel consumed per additional kWh of mechanical energy delivered |
| Conventional engine overhead fuel | gal/hr | 0.5 | Overhead fuel consumption at zero load |
| Conventional engine marginal brake specific fuel consumption | Gal/kWh | 0.07 | Additional fuel consumption (gal/hr) per increase in load (kW) |

Figure 8 shows fuel consumption required for the trip using a conventional or a battery-electric system with diesel generator range extender. The simulation assumes that the batteries are not recharged while at sea[2].

In this example, a diesel electric system without battery storage consumes more fuel than the conventional system due to the losses in the electric motor, generator and controller (as explained in Section 4.2). However, once the battery storage capacity surpasses 50 kWh, the battery electric system with diesel genset conserves fuel.

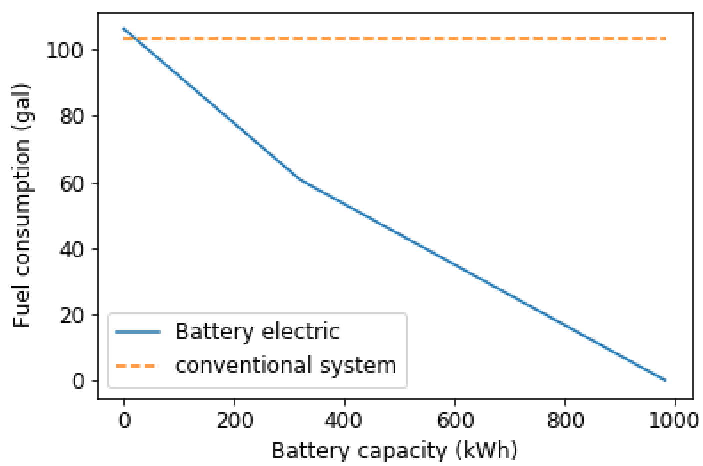


*Figure 8 Battery-electric example fuel consumption*

Figure 9 shows the range of equipment costs expected for converting a conventional vessel to a battery electric vessel with a diesel genset for range extension. The cost of the electric motor, genset, controls and associated equipment are estimated to be $58-$95 thousand. The remaining costs are due to batteries, estimated at $300-$800 per kWh based on quotations from manufacturers and local

[2] In some scenarios, cycling the diesel genset on and off to provide propulsion and battery charging periodically may reduce fuel consumption (similar in principle to a hybrid vessel without shore power). Those savings are excluded to produce a conservative estimate of fuel savings.

experience. In addition, the costs that would apply if the DOE's long term goal of $80/kWh is achieved are indicated by the dashed line [26].

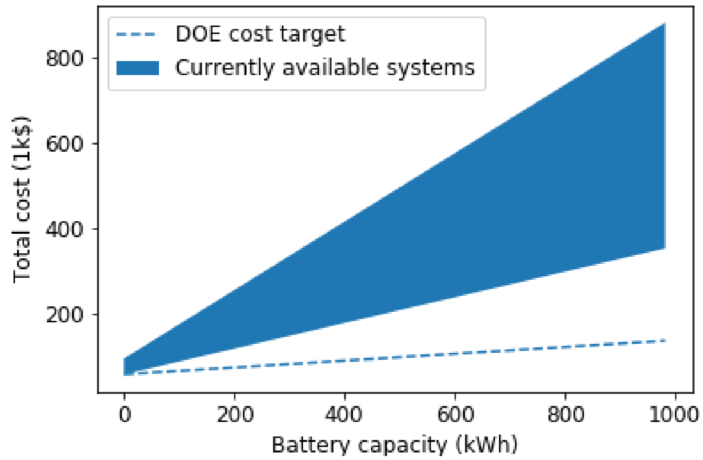


*Figure 9 Range of equipment costs expected for converting a battery electric vessel*

Battery size and shape are a critical consideration in designing a high capacity battery system. Volumetric energy storage density can be specified for the individual cells, or for an assembled pack that contains many cells, as well as the necessary spacing between cells and protective casing. The pack size and shape varies between manufacturers, and a few examples are provided in Table 7.

As an example of how much space the batteries will require, consider Torqeedo's BMW i3 40 kWh battery pack. One unit is 65" long, 38" wide, 7" tall and weighs 612 lbs. In order to power the entire trip described above, a vessel would require 25 of these batteries, for a total weight of 15300 lbs. Allowing for 1" of ventilation between packs, the total volume would be 285 $ft^3$. That is roughly equal in volume to two cords of firewood or a stack of plywood 8 feet high. That much volume simply will not fit in most engine rooms.

The optimal battery storage system will need to be chosen based on the unique attributes of each vessel, fishing operations, and financial resources. The greatest fuel savings will be achieved when the battery is used to power the vessel during fishing operations. In this example, supplying all fishing hours from a single battery charge would require 290 kWh. Such a battery would be approximately 3,000 pounds, 80 $ft^3$ and $80-230 thousand. Few fishing scenarios would warrant pursuing a battery capacity beyond this size.

# 5 Hybrid drive systems

Hybrid drive systems allow more than one source to supply power to the propeller shaft. Hybrid drives can eliminate engine hours at low loads thereby reducing maintenance costs, noise and fuel consumption, while also providing a redundant propulsion system. However, they require additional space in the engine room, capital investment and increased complexity of the propulsion system. We discuss three classes of hybrid drive here, as illustrated in Figure 1.G-I. The following section provides an overview of the equipment used in all types of hybrid drives, the range of costs that should be expected, and some of the advantages and disadvantages of each choice. Later sections describe each type of hybrid system in more detail and provide an estimate of fuel savings for an example scenario.

## 5.1 Hybrid drive major components

In addition to the electric motor, controller and electricity source required by all electric systems, hybrid systems also require a method for shifting between motor power and engine power. The shifting system adds expense to these systems, but that cost can be offset by the smaller motor requirements and the opportunity to avoid removing the diesel engine in a retrofit project.

### 5.1.1 Electric motors

Hybrid vessels benefit from only requiring the electric motor to provide power at low speeds, such as while trolling, pulling longline gear or setting a gillnet. The fishing propulsion requirements provided in Section 3.5 indicate a load of less than 3 kW. Stabilizers can increase this load by double the power requirement, and additional capacity should be provided for sea margins. Therefore, a hybrid vessel that only intends to use the electric system while fishing should require a motor with a rated capacity of approximately 10 kW.

In addition to providing power, if the system includes batteries the motor should also serve as a generator that can use power from the diesel engine to charge the batteries. Generator capability will allow fishers to recharge their batteries when their propulsion engine is efficiently loaded during transit in order to extend the amount of time that they can operate with engines off during a fishing trip.

Motor-generators in the power range and size required for hybrid fishing vessels are commercially available. Examples of three motor-generators that have been used in hybrid vessels for low speed propulsion are listed below:

1. **EM220-20 by Transfluid** The EM220-20 is an electric motor that Transfluid uses in its packaged hybrid propulsion systems. The EM220-20 is rated to 20 kW of output power as a motor and can generate up to 17 kW electricity [27].
2. **EP20 by Elco** The EP 20 is rated to 15 kW of output power as a motor. The EP 20 provides electric propulsion while sport fishing in Huckins' Hybrid Sportsman 28 yacht [2]. The EP20 has a retail price of $8995 and includes motor controls.
3. **HyPer9 by NetGain Motors Inc** The HyPer9 motor was designed for use in electric cars and trucks, and has also been used in the hybrid gillnet vessel FV Sunbeam developed by Fabian Grutter [4]. The HyPer9 is rated to 75 kW of output power and has been used to regenerate 12 kW for battery charging on FV Sunbeam [28]. The HyPer9 including necessary controls has a retail price of $4300 (depending on the grade of the control system chosen).

The motors listed above are provided as examples of the price range and sources that may be expected for electric motors in hybrid applications. Many other motors that may perform similarly are commercially available from a variety of manufacturers.

### 5.1.2 Coupling systems

We consider three methods for coupling an electric motor to a propeller in a hybrid system:

1.) **Secondary shaft:** In a secondary shaft system, the electric propulsion system is fully independent of the diesel driven system. A secondary shaft can be routed into the engine room and coupled to the motor. Alternatively, the motor and propeller can both be mounted outside the hull as an outboard or a sail drive. A secondary shaft system allows manufacturers to produce a standard package that can be installed independently of the existing system, but may introduce additional drag outside the hull or additional cost. For example, Torqeedo manufactures the Cruise 10.0 FP sail drive with an MSRP of $8,999 [29]. The unit includes a potted 10 kW motor and propeller. In order to reduce drag when the drive is not in use, a folding propeller can also be purchased with an MSRP of $1,499 [30].
2.) **Gear box:** Transfluid manufactures hybrid drive gear systems that allow for multiple power take-in and take-off points [27]. The hybrid drive is only sold as part of a larger system, but its contribution to the total system cost is $21,426. In order to retrofit a vessel with one of these systems, the shaft would need to be cut and then coupled to the gear box and the gear box would also need to be mechanically coupled to both the main engine and the electric motor. Once installed, the gear box provides a robust and simple method for switching between electric drive, diesel drive and recharge modes.
3.) **Belt drive:** In a belt drive system, a cog is attached to the propeller shaft. The primary benefit of this system is that the shaft does not need to be cut or moved: the cog can simply be slid onto the shaft and clamped in place. The belt then drives a second cog to turn the motor. In order to maximize motor efficiency, a gear ratio should be used so that the motor can turn at a higher rate of rotation than the propeller. Figure 10 shows the cog system installed on FV Sunbeam. The custom-built cogs cost a total of $1000 and the mount was custom made in Sitka for a cost of $10,000 [4].

*Figure 10 Cog system installed on FV Sunbeam in Sitka, Alaska*

### 5.1.3 Control systems

The Elco and HyPer 9 motors described above include control systems, but additional expense will be incurred to connect the motor controls to an operable throttle.

### 5.1.4 Electricity source

The electricity source for a hybrid propulsion system can be a traditional diesel generator or a battery. A troll, gillnet or longline vessel will typically require a 20-30 kW genset to satisfy all loads reliably, depending on whether the vessel has a refrigeration system.

Battery-hybrid systems will require the greatest investment in the batteries themselves. The primary requirement of the battery bank will be to have enough energy storage capacity (kWh) to power the vessel for the desired amount of time. The batteries should also be able to supply enough power (kW) for propulsion and auxiliary loads (10-20 kW if a refrigeration system is not present), but most battery systems with sufficient storage will be rated to supply much more power than required.

## 5.2 Case G: Auxiliary genset hybrid drive

An auxiliary genset hybrid drive consists of the primary diesel engine coupled directly to the propulsion shaft, and a lower power auxiliary genset that can provide power to the shaft via an electric motor. Figure 11 illustrates an example system. All of the energy used by this system is derived from diesel fuel, but it nonetheless provides redundancy, reduced engine hours, and fuel savings for some load profiles.

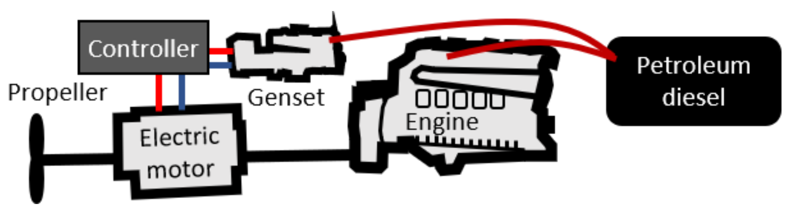


*Figure 11 Auxiliary genset hybrid*

In order to save fuel, the system must provide an efficiency gain greater than losses incurred by the genset system. The genset system incurs several losses in converting the mechanical rotation of its crankshaft into electric power, modulating the frequency of the voltage through the controller, and converting electrical power back into mechanical rotation in the electric motor. The direct drive system avoids these losses by mechanically coupling the propeller shaft to the engine. Therefore, the hybrid genset system can only reduce fuel consumption if the primary engine would otherwise operate very inefficiently, as shown in Equation 3.

$$\eta_{aux}\eta_{gen}\eta_{controller}\eta_{motor} > \eta_{primary} \qquad (3)$$

The best scenario for retrofitting a fishing vessel with an auxiliary genset hybrid drive is a vessel that already has an auxiliary generator, often runs the genset and primary engine at the same time, and operates the primary engine at less than 10% of its rated load for the majority of its operating hours. Many freeze-troll vessels fit this description.

The fuel efficiency trade-off between the additional energy conversions required by an auxiliary generator and using a lightly loaded diesel engine can only be determined by quantitatively comparing an existing system with a proposed system. Since the efficiency curves of a primary diesel engine and auxiliary genset both vary between installations and engine models, the results of a quantitative analysis will depend on the vessel. Nonetheless, the following section provides an example analysis for a freeze troll vessel using average engine efficiency curves measured during the FVEEP and assuming a one week fishing trip.

### 5.2.1 Auxiliary genset hybrid drive fuel efficiency example

Freeze-troll vessels in Southeast Alaska maintain hold temperatures close to -40°F in order to rapidly freeze fish as they are brought on board. In order to maintain that hold temperature, the vessels have on board freezer systems that are powered using a hydraulic pump supplied by the main engine or an auxiliary engine, an auxiliary engine coupled directly to the compressor, or an auxiliary genset that provides electricity to the compressor. For this example, we consider a vessel with an auxiliary electric genset. In that case, the system will not incur capital costs for the auxiliary generator.

Suppose that the vessel makes week-long fishing trips. In the existing system, the auxiliary generator runs continuously for the full duration of the trip in order to bring the hold to temperature and maintain it. The main engine runs for 15 hours of transit from harbor to the fishing grounds on the first day of the trip. For the next five days, the engine runs lightly loaded for 18 hours per day while fishing, and lightly loaded for 1 hour per day to transit to an anchorage. The vessel makes another 15 hour transit on the seventh day to return to port. Table 10 summarizes the total time fishing, in transit, and at anchor for this example.

*Table 10 Auxiliary genset hybrid drive example assumptions*

| Operating mode | Time in each mode (hours) |
|---|---|
| Transit time | 35 |
| Fishing time | 90 |
| Anchor time with freezer running | 43 |
| Total time | 168 |

Multiplying the fuel consumption rate associated with transit, fishing and anchor by the times listed in Table 10 provides an estimate of fuel consumption.

Fuel savings result from reducing the main engine operating hours by the amount of time spent fishing (the auxiliary engine hours do not change since it is already required to provide power to the freezer system). When the engine is lightly loaded while fishing, most of the fuel consumption is required to simply keep the engine running. In the FVEEP, the average “engine-overhead” fuel consumption rate required to idle propulsion engines with no useful load was observed to be 0.5 gal/hr. In this example with 90 hours of fishing time, the hybrid system would reduce the main engine overhead fuel consumption by 45 gallons. Those fuel savings are reduced due to the drag of the clutch system and the imperfect efficiency of converting the mechanical power from the auxiliary engine into electricity then back to mechanical power. Under reasonable assumptions of the clutch drag (1 kW) and motor efficiency (93%), we estimate those two factors to increase fuel consumption by approximately 10 gallons, resulting in an overall fuel savings of 35 gallons. Additional details of the calculation are provided in Appendix D.

## 5.3 Case H: Battery Hybrid Drive without shore power

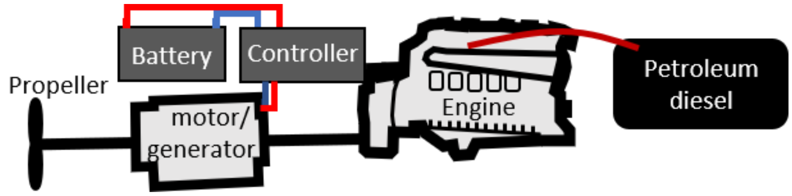


*Figure 12 Case H: Battery hybrid drive without shore power*

A battery hybrid drive without shore power allows vessels to operate in engine-off mode and recharge at sea using their diesel engine. Without shore power, the vessel is still 100% diesel powered, but some load profiles will achieve efficiency improvements with this system as well as the benefits of quiet operation and reduced engine hours. In practice, most vessels with a hybrid system will have access to shore power intermittently, but exploring the potential impact of Case H provides insight into the benefits of a battery hybrid system nonetheless.

In Case G (auxiliary genset hybrid), Equation 3 showed that the efficiency of the auxiliary engine needed to be much greater than the primary engine under light loads in order to overcome the energy losses in the generator, controller and electric motor driving the shaft. In the case of a battery hybrid vessel, the only efficiency improvement (if any) is due to changes in the load profile on the primary diesel engine. The battery propulsion system introduces a battery charge/discharge energy loss in addition to the generator, controller and motor losses inherent to the auxiliary generator hybrid system. In order to result in fuel savings, the inequality of Equation 4 must be satisfied. Equation 4 is an even more challenging requirement than Equation 3.

$$\eta_{primary}(high\ load)\eta_{gen}\eta_{charge}\eta_{discharge}\eta_{controller}\eta_{motor} > \eta_{primary}(low\ load) \qquad 4$$

In Equation 4, *high load* refers to the operating condition of the primary engine in transit, while *low load* refers to the operating condition of the engine while fishing. The battery hybrid system takes advantage of the difference in engine efficiency between low and high load conditions by charging the battery system when the engine is operating near its optimal efficiency for transit, then shutting down the engine during fishing to rely on the batteries.

The best scenario for a battery hybrid vessel without shore power has periods with very low power loads with intermittent transit periods that can be used to recharge the batteries. The more frequent the transit periods are for recharging, the smaller the battery pack can be to support fishing periods. Vessels with refrigeration systems that run continuously are a poor fit for battery hybrid systems due to their increased power demand while fishing. The battery storage system will be expensive, so every reduction in energy consumption while fishing will make battery hybrid systems more affordable.

Similar to Case G, the fuel efficiency trade-off between the additional energy required to charge batteries, discharge batteries, and convert mechanical power to and from electrical power and the inefficiency of a lightly loaded diesel engine can only be determined by quantitatively comparing an existing system with a proposed system. Since the efficiency curves of a primary diesel engine and battery system both vary between installations and engine models, the results of a quantitative analysis will depend on the vessel. The following section provides an example analysis for a gillnet vessel using average engine efficiency curves measured during the FVEEP and several assumptions to specify an operating pattern that is best suited for a battery hybrid system without shore power.

## 5.4 Battery hybrid drive without shore power fuel efficiency example

For this example consider a longline vessel that makes trips with a duration of five days. The vessel transits to the fishing grounds on the first day (12 hours transit). The second through fourth days are spent setting and hauling longlines with baited hooks on the bottom of the ocean for 14 hours per day, and the fifth day is spent in transit back to the vessel's home port. The propulsion, hydraulic and electric loads in fishing and transit are described in Section 3.5. The example vessel uses ice rather than a refrigeration system to store fish and has negligible energy consumption while at anchor.

For a battery-hybrid vessel without shore power, intermittent transit during the day will make the hybrid system more attractive by adding efficient charging opportunities that limit the required battery capacity. For this example assume that the vessel has two one-hour transit periods during each day between different sets. In that case the vessel operates in "fishing mode" for four-hour segments, consuming an estimated 10.4 kWh on a calm day without stabilizers and using only a hydraulic drum to haul and set line. In order to recharge during one hour of transit, the motor would then need to regenerate at a power of 10.4 kW. A 15 kWh battery bank would be sufficient to provide energy for the four hour fishing period on average, and could be supplemented with the diesel engine during fishing periods that required anomalously high power.

*Table 11 Summary of hours in each mode for an example battery hybrid vessel without shore power*

| | Time in fishing mode (hours) | Average total load (kW) |
|---|---|---|
| Transit time | 30 | 37 |
| Fishing time | 36 | 2.6 |
| Anchor time (no load) | 54 hours | 0 |
| Total time | 5x24 hours=120 hours | - |

The total *energy* (kWh) *required* to supply all transit loads is equal to the total transit time multiplied by the transit load (kW): $E_{trans}$ =30 hours x 37 kW = 1110 kWh. Similarly, the total fishing *energy required* is $E_{fish}$ =36 hours x 2.6 kW = 94 kWh. In the hybrid case, the *energy required* must be divided by an efficiency factor $\eta_{hybrid} = \eta_{gen}\eta_{charge}\eta_{discharge}\eta_{controller}\eta_{motor}$ in order to estimate the energy that must be supplied by the diesel engine. Assuming a standard efficiency motor/generator (93%), a 98% efficient controller and a 90% round trip battery charging efficiency, we arrive at an overall efficiency of $\eta_{hybrid} = 76\%$.

Finally, the additional drag ($D_{clutch}$) on the propeller shaft due to the hybrid system must be considered. Depending on how the hybrid drive motor is coupled to the shaft, $D_{clutch}$ could be negligible (for a shaft generator/motor) or on the order of 1 kW (if a belt drive is permanently connected to the shaft). For this example we will assume $D_{clutch} = 1$ kW.

Table 12 shows the equations that can be used to estimate the total fuel consumption over the course of a five day trip with either a traditional system or a hybrid system. $\alpha$ denotes the engine fuel consumption rate with no load, $\beta$ is the increase in fuel consumption rate per kW of additional load and

$T$ indicates the time in transit or fishing mode, Under these assumptions, the total projected fuel savings are 11 gallons per trip.

*Table 12 Fuel consumption calculations*

| | Traditional system | Hybrid system |
|---|---|---|
| Transit fuel | $T_{trans}\alpha + \beta E_{trans}$ | $T_{trans}\alpha + \beta\left(E_{trans} + \frac{E_{fish}}{\eta_{hybrid}} + D_{clutch}T_{trans}\right)$ |
| Fishing fuel | $T_{fish}\alpha + \beta E_{fish}$ | 0 |
| Total fuel consumption (gal) | 117 | 106 |

### 5.4.1 System costs

The costs of the system will be driven by the battery bank, installation costs, hybrid drive coupling system and controller costs. Given the fuel savings estimate above, the fuel savings would take many decades to compensate for the costs shown in Table 13. If a fisher chooses to pursue this type of system, they must recognize that the fuel savings are not commensurate with the cost of the system. However, the additional benefits of quiet operation and reduced engine hours may motivate some fishers to pursue this system despite its limited fuel savings.

*Table 13 Battery hybrid system costs with small capacity*

| Item | Projected cost |
|---|---|
| Battery bank | \$4500-\$12000 |
| Motor/generator | \$5,000-\$15,000 |
| Coupling system | \$1,000-\$10,000 |
| Control system | \$1,000-\$3,000 |
| Installation | \$5,000-\$15,000 |
| Total | \$16,500-\$55,000 |

The battery hybrid system described here may also serve as a first step toward more impactful propulsion system retrofits. Simply expanding the battery bank considered here while keeping the same hybrid coupling system installed would provide enough storage to supply a significant fraction of total vessel energy from shore power. A fisher might develop a small capacity hybrid drive system one year without using shore power and immediately see some fuel savings, then expand the battery bank to charge with shore power and increase fuel savings in future years.

## 5.5 Case I: Battery hybrid drive with shore power

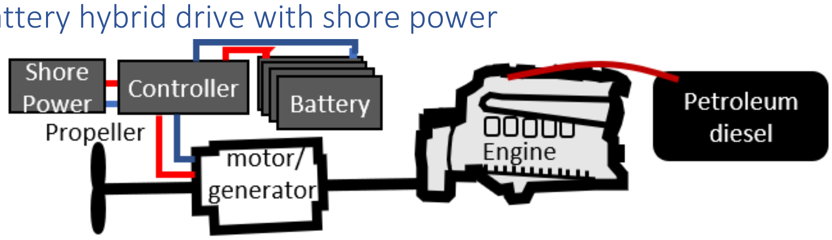


*Figure 13 Battery hybrid drive with shore power*

A battery hybrid drive with shore power is the system that requires least capital to allow a vessel to derive some of its energy from the electrical grid rather than its diesel engine. The system is identical to

Case H, except that it allows the vessel to charge at the dock rather than relying on the diesel engine to supply all of the energy to charge the battery bank. Access to shore power motivates a larger battery bank for this type of system than in Case H in order to store more energy from the electrical grid. If the electricity is produced on shore using renewable resources the avoided emissions from Case I can be much greater than in Case H.

The fuel savings that can be achieved with shore power are determined by Equation 5, where $C$ is the battery storage capacity (kWh), $T_{shorepower}$ is the amount of time that the system is run on shore power, and $\beta$, $\alpha$ and $\eta$ are the familiar engine parameters and efficiency factors. In addition to the fuel savings calculated with Equation 5, the hybrid system will continue to accrue fuel savings after the electricity stored from the grid is consumed through the same mechanism described for a system with no access to shore power.

$$F_{saved} = \beta C_{battery} \eta_{discharge} \eta_{motor} \eta_{control} + T_{shorepower} \alpha \quad (5)$$

The battery system should be used when the diesel engine would be lightly loaded and operate inefficiently. This observation is supported by Equation 5 because deploying the battery system when the total load is small will maximize $T_{shorepower}$ for a given amount of battery capacity. The first term in Equation 5 accounts for fuel savings due to using shore power rather than diesel as an energy source, and the second term accounts for fuel savings due to the overhead fuel consumption associated with keeping the engine running.

The best scenario for a hybrid drive system with access to shore power requires low loads while fishing and frequent access to charging. The more frequently the vessel's batteries can be charged, the greater fraction of total energy on the vessel can be supplied from shore power and the smaller the battery bank can be. While the fuel savings from the battery hybrid system without shore power in case H could only save fuel due to the difference in efficiency of a lightly loaded and optimally loaded diesel engine, Case I saves fuel by introducing an energy source other than diesel fuel to the vessel.

### 5.5.1 Battery hybrid drive with shore power example

For this example, consider a gillnet vessel that makes a three-day fishing trip. Transit to and from the fishing grounds is two hours one way, and the vessel actively fishes for 15 hours per day. For this example, we will also assume that the vessel transits for 30 minutes to anchor at the beginning and ending of each day, with no transit time during the day. Finally, we will assume that the hybrid system uses a motor/generator capable of regenerating at 15 kW. We will consider the loads from the Status Quo scenario in Table 3, and the hours in each mode and the associated total loads are listed in Table 14.

*Table 14 Hours and loads for each operating mode in the battery hybrid with shore power example.*

| | Time in operating mode (hours) | Average total load (kW) |
|---|---|---|
| Transit time | 6 hours | 53 |
| Fishing time | 45 hours | 3 |
| Anchor time (no load) | 21 hours | 0 |
| Total time | 72 hours | - |

With a hybrid drive system, the vessel owner could install any amount of battery storage capacity they choose. For this example, we imagine that the owner installs 60 kWh of battery storage and only uses the batteries while in the fishing mode. The fuel consumption in the traditional mode is given by Equation 6, where $L$ indicates a load (kW) and $T$ indicates the time spent in a particular mode (hours). Plugging the values from Table 14 into Equation 6 yields a total fuel consumption estimate of 57 gallons.

$$F_{traditional} = \beta(T_{transit} \times L_{transit} + T_{fish} \times L_{fish}) + (T_{transit} + T_{fish})\alpha \qquad 6$$

To calculate fuel in the hybrid case, we need to specify times when the vessel is powered using energy from the shore-side electrical grid, energy directly from the propulsion engine, and energy from the battery power system after charging with the motor/generator on the propulsion shaft. Table 15 shows which parts of the trip can be battery powered, and how much energy can be supplied to recharge the battery from the diesel engine. With 60 kWh of battery storage, the battery will run out of charge during the second day of fishing. The analysis assumes that the batteries are recharged from the diesel engine during the second day of fishing.

*Table 15 Summary of loads, fuel use and battery use for the battery hybrid with shore power example*

| Operating segment | Time (hrs) | Battery charge at end of segment | Load after efficiency factors and including battery recharge (kWh) | Fuel consumption (gal) | Battery usage (kWh) |
|---|---|---|---|---|---|
| Transit harbor to fishing | 2 | 60 | 53 | 8.4 | 0 |
| Fishing day 1 Battery power | 15 | 8 | 3.5 | 0 | 52 |
| Transit to/from anchor | 1 | 23 | 70.3 | 5.42 | -15 |
| Fishing day 2 battery power | 6.6 | 0 | 3.5 | 0 | 23 |
| Fishing day 2 diesel engine | 8.4 | 52 | 9.5 | 9.8 | -52 |
| Transit to/from anchor | 1 | 52 | 53 | 4.21 | 0 |
| Fishing day 3 Battery power | 15 | 0 | 3.5 | 0 | 52 |
| Transit fishing to harbor | 2 | 0 | 53 | 8.4 | 0 |

Summing the fuel consumption from each segment listed in Table 15 yields a fuel consumption estimate of 36 gallons with the hybrid system compared to 57 gallons with the traditional system.

With shore power, increasing the storage capacity of the battery system continuously increases the fuel savings. However, using shore power to allow the engine to be shut down during fishing saves more fuel per kWh of battery storage capacity than using shore power to shut down the engine during transit. Furthermore, investing in a motor and connecting system with enough strength to supply transit loads will add to the capital cost significantly. Figure 14 shows how much fuel would be saved if all of the assumptions in the above example were maintained, but the battery storage capacity was changed. Even a small battery bank that makes little use of shore power can result in some fuel savings, as explained in Case H if the diesel engine is cycled on and off to recharge the batteries. As the battery capacity is increased so that shore power can offset more and more engine power while fishing, the savings increase steadily (with small changes in the slope depending on whether the batteries are recharged while the vessel is fishing or while the vessel is in transit to anchor). The rate of fuel savings decreases once the battery capacity is sufficient to offset all fishing hours with shore power. Once the vessel is displacing transit fuel consumption, the marginal fuel savings for every increase in kWh storage capacity remains constant until the batteries have enough capacity to power the vessel for the entire trip.

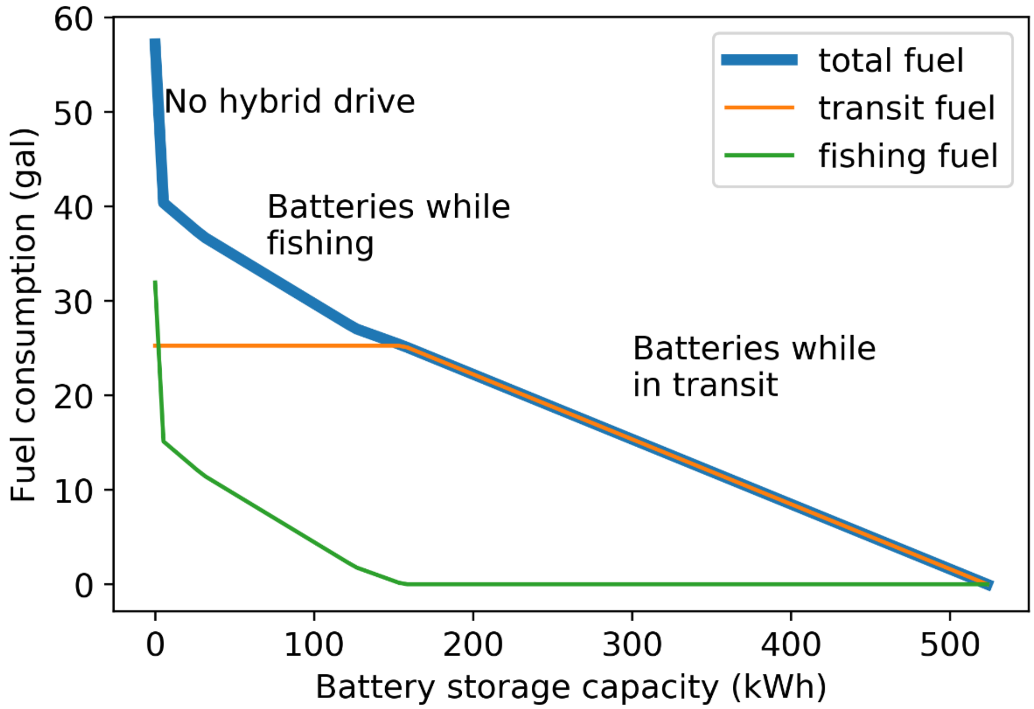


*Figure 14 Fuel consumption dependency on battery storage capacity in a hybrid drive system with shore power.*

### 5.5.2 Comparison of electric drive with hybrid drive

The scenario described above begs for comparison with the battery electric system described in Case E. Both systems use shore power to charge batteries, and rely on a diesel engine for propulsion once the batteries lose their charge. The difference is that the hybrid system provides a mechanical coupling between the diesel engine and the propeller, while the battery-electric does not. Since the hybrid system avoids losses in the generator and motor when operating under diesel power, it will consume less fuel **if** the diesel engine used in the hybrid vessel is equivalent to the engine used to power the generator in the electric vessel.

In practice, the unique engines and fishing scenarios relevant to a particular vessel would need to be considered to determine whether the hybrid drive or battery-electric with diesel genset would be more fuel efficient. If an existing propulsion engine is inefficient under its vessel's operating conditions, a new diesel electric system may reduce fuel consumption.

With respect to cost, the hybrid vessel requires a coupling system and clutch to join the electric motor to the existing propeller shaft, while the battery-electric with genset system requires purchase of a genset. The coupling system is expected to cost $1,000-$21,000 (see the Hybrid Drive Section for an explanation of the range). A genset is expected to cost  $15,000-$30,000 depending on the capacity required. Other equipment costs are expected to be similar in both cases for a given battery capacity.

Non-equipment costs are not estimated in this report, but labor for removing existing equipment, building mounts for new equipment, wiring and welding will be significant. System design to ensure that all components fit in the engine room will also be critical. The hybrid and battery-electric with diesel genset systems differ in both of these respects. The hybrid system makes use of the existing primary diesel engine and propeller shaft. It requires the batteries to be fit in the engine room around the engine. In contrast, the battery electric system requires the primary engine to be removed. The genset replacing the primary engine will likely be smaller and will not need to be placed in line with the propeller shaft. This may result in additional space for battery storage.

# 6 Conclusion

The dramatic decline in battery costs coupled with an increase in battery energy density has created new opportunities in the fishing fleet. While a fully battery-electric fishing vessel remains difficult to realize due to the cost and volume of batteries required, new systems that supplement diesel engines with battery storage are feasible.

Any amount of energy generated onshore from renewable sources and brought to sea will displace fossil fuel consumption. Using the batteries during operating conditions when the diesel engine is lightly loaded will result in the greatest fuel savings for a given amount of battery storage.

In addition to displacing diesel with energy from shore, hybrid systems can also improve operating efficiency if the batteries are charged by the main propulsion engine during transit and then used to reduce main engine hours while fishing. This result extends the impact of battery storage beyond the time that they supply the vessel with energy delivered on shore.

In order to reach net-zero emissions within the practical limitations of cost and space on a small fishing vessel, alternative technologies must be considered. Hydrogen storage for fuel cells shows promise, as the cost per kilowatt-hour of storage are projected to be lower than battery storage by the Department of Energy, although the availability and infrastructure requirements of the technology need to be investigated further. Alternative fuels produced from renewable organic material or synthesized using renewable energy may also provide a viable net-zero emission propulsion system. These concepts should be explored further in future work.

In addition to the alternative power systems considered here, there are numerous opportunities to reduce energy demand through efficiency measures beyond those considered in the above examples. Efficiency measures reduce diesel fuel consumption in conventional systems and have even greater value in battery-electric systems: by reducing the amount of energy required for a fishing trip, efficiency measures reduce the amount of battery storage that must be purchased and installed on the vessel. Implementing aggressive energy efficiency measures in a vessel—or building a new highly efficient vessel—would expand the feasibility of battery-electric vessels.

# 7 References


[1] B. Gauvin, “Alabama River ferry reborn with electric propulsion - Professional Mariner - February 2020,” *Professional Mariner*, 2020. http://www.professionalmariner.com/February-2020/Alabama-River-ferry-reborn-with-electric-propulsion/ (accessed Sep. 10, 2020).

[2] “Hybrid SPORTSMAN 38 HUCKINS YACHT CORPORATION,” 2020. Accessed: Sep. 10, 2020. [Online]. Available: huckinsyacht.com/img/Huckins-Sportsman-38-Brochure.pdf.

[3] K. Aarsaether, “Energy Savings in Coastal Fisheries,” *IEEE Electrification Magazine*, no. September, pp. 74–79, 2017.

[4] F. Grutter, “Personal Communication,” 2020.

[5] C. Kemp, “Vessel Energy Analysis Tool Model Documentation,” 2018. https://www.afdf.org/wp-content/uploads/2018_11_28_FVEEP-Data-Model.pdf

[6] “Torqeedo Single Deep Blue 100 kWib Quote.” Torqeedo, 2020.

[7] “Batteries | Department of Energy.” https://www.energy.gov/eere/vehicles/batteries (accessed Sep. 10, 2020).

[8] B. Nykvist and M. Nilsson, “Rapidly falling costs of battery packs for electric vehicles,” *Nat. Clim. Chang.*, vol. 5, no. 4, pp. 329–332, 2015, doi: 10.1038/nclimate2564.

[9] E. Skjong, E. Rodskar, M. Molinas, T. A. Johansen, and J. Cunningham, “The Marine Vessel’s Electrical Power System: From Its Birth to Present Day,” *Proc. IEEE*, vol. 103, no. 12, pp. 2410–2424, Dec. 2015, Accessed: Sep. 10, 2020. [Online]. Available: https://ieeexplore-ieee-org.proxy-harrisburg.klnpa.org/stamp/stamp.jsp?tp=&arnumber=7329674.

[10] K. Moe, “Battery-operated ferries in Norway: A study of the possibility for electrification of ferry routes in Norway,” University College of Southeast Norway, 2016.

[11] “Flagships project for hydrogen vessels in France and Norway,” *Fuel Cells Bulletin*, 2019.

[12] “Flagships,” 2019. https://flagships.eu/ (accessed Sep. 10, 2020).

[13] J. Trillos, “HySeas III Market Potential Analysis of RoPax Ferry Market in Europe Final Report - Deliverable 6 . 1,” Oldenburg, Germany, 2019. [Online]. Available: https://cordis.europa.eu/project/id/769417/results.

[14] A. Molland, S. Turnock, and D. Hudson, *Ship Resistance and Propulsion*. Cambridge Universty Press, 2011.

[15] J. D. van Manen, “The Choice of the Propeller,” *Mar. Technol. SNAME News*, vol. 3, no. 02, pp. 158–171, 1966, [Online]. Available: https://repository.tudelft.nl/islandora/object/uuid:1b22b6f9-43a4-4c6e-a788-42b46fc86d04/datastream/OBJ/download.

[16] A. Mahmoudi, W. L. Soong, G. Pellegrino, and E. Armando, “Efficiency maps of electrical machines,” *2015 IEEE Energy Convers. Congr. Expo. ECCE 2015*, no. 2015, pp. 2791–2799, 2015, doi: 10.1109/ECCE.2015.7310051.

[17] “EP-100 Electric Inboard,” 2020. https://www.elcomotoryachts.com/product/ep-100-electric-inboard/ (accessed Oct. 12, 2020).

[18] "Electric Motors - Torqeedo," 2020. https://www.torqeedo.com/us/en-us/technology-and-environment/electric-motors.html (accessed Oct. 12, 2020).

[19] "Transfluid Industrial and Marine Permanent Magnets Electric Machines," 2020. https://www.transfluid.eu/wp-content/uploads/2020/07/700_gb_20.07_lq.pdf (accessed Oct. 12, 2020).

[20] PDG, "Powerhouse Diesel Generators," 2020. https://www.pdgenerators.com/copy-of-keel-cooled (accessed Oct. 19, 2020).

[21] JP, "CitiMarine Budgeting Estimate." Dora, FL, 2020.

[22] K. Beard and T. Reddy, *Linden's Handbook of Batteries*, 5th ed. New York: McGraw Hill, 2019.

[23] T. Simms, "Single Deep Blue 100kWib System w/i3 160 kWh total," 2020.

[24] "Cost and Price Metrics for Automotive Lithium-Ion Batteries." Accessed: Oct. 12, 2020. [Online]. Available: https://www.energy.gov/sites/prod/files/2017/02/f34/67089 EERE LIB cost vs price metrics r9_0.pdf.

[25] Samsung SDI, "Samsung SDI - Energy Storage Technology." EV West, San Marcos, CA, 2020, [Online]. Available: https://www.evwest.com/catalog/product_info.php?cPath=4&products_id=486&osCsid=go9tb0s3neblvjiqp54h3v9a96.

[26] "Batteries," *Office of Energy Efficiency and Renewable Energy*, 2020. https://www.energy.gov/eere/vehicles/batteries (accessed Sep. 10, 2020).

[27] "KraftPower Hybrid & Electric Technology," *Kraft Power Corporation*, 2020. http://www.kraftpower.com/wp-content/uploads/2019/07/Transfluid-Hybrid-Electric-Technology.pdf (accessed Sep. 10, 2020).

[28] "NetGain HyPer9 HV AC Motor X144 Controller Kit 144 Volt, EV West - Electric Vehicle Parts, Components, EVSE Charging Stations, Electric Car Conversion Kits," *EVWest*. https://www.evwest.com/catalog/product_info.php?products_id=482 (accessed Sep. 10, 2020).

[29] "Pod drive Cruise 10.0 fixed pod for motorboats / sailboats," *Torqeedo*, 2020. https://www.torqeedo.com/us/en-us/products/pod-drives/cruise-10.0-fp/1252-00.html (accessed Aug. 17, 2020).

[30] Torqeedo, "Sail drive quote." Crystal Lake, Il, 2020.

[31] M. Barth, G. Scora, and T. Younglove, "Modal Emissions Model for Heavy-Duty Diesel Vehicles," 2004.

[32] ASTM D975-15b, "Standard specification for diesel fuel oils," *ASTM Int.*, pp. 1–25, 2015, doi: 10.1520/D0975-12A.2.

[33] "GREET 1 Series (Fuel-Cycle Model)," *Argonne National Lab*. https://greet.es.anl.gov/index.php?content=download1x (accessed Jul. 30, 2002).

[34] E. C. Tupper, *Introduction to Naval Architecture*, 4th ed. New York: Elsevier, 2004.

[35] F. White, *Fluid Mechanics*, Sixth. New York: McGraw Hill, 2008.

# Appendix A. How to estimate energy requirements for existing vessels based on fuel consumption

If we are considering an alternative energy system—that is, an energy system that does not rely on diesel fuel—we need to know how much energy is required to meet all of the loads on the vessel. This is distinct from the amount of energy used by the diesel engine due to the efficiency of the engine. For example, one gallon of the #2 diesel fuel used in Southeast Alaska fishing vessels typically contains 138,000 British thermal units (btu) of chemical energy that will be released during combustion[3]. A diesel engine might convert that energy to useful work with an efficiency of around 33%. So, if we knew that achieving some task required one gallon of fuel, we could conclude that the work required was 0.33x138,000=45540 btu. We can then convert that measure of energy to kilowatt-hours (kWh) by dividing by 3412 to finally conclude that a job that consumes a gallon of diesel fuel requires 13-14 kWh of energy.

We can improve the accuracy of the energy consumption estimate by modeling diesel engine efficiency as a function of load. During the FVEEP, fuel consumption and power delivered to the propeller shaft were measured over a broad range of conditions, as shown in Figure 15.A. As an example, the fuel consumption curve measured in sea trials on a fishing vessel are shown in Figure 15.B. In this case, the vessel was operated from idle-ahead up to full throttle in three separate sea trials under different drag conditions. Dots indicate measured data points and the line is the best linear fit to the data. Figure 15.B shows that the fuel consumption rate for this engine can be well approximated by a linear function of engine load. Manufacturer specifications, measurements made on dozens of other engines for the FVEEP and published diesel engine fuel consumption models show that fuel consumption generally increases linearly with increasing output power [31].

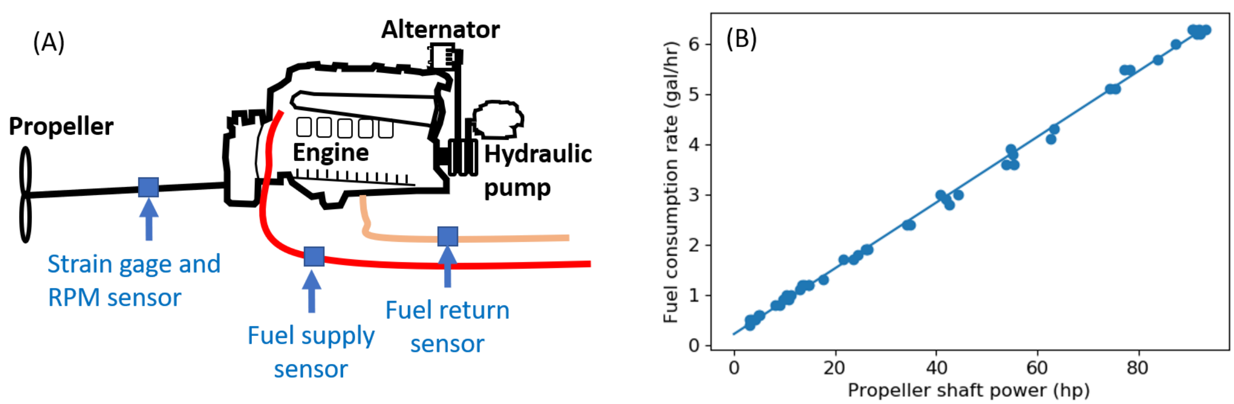


*Figure 15 Engine fuel consumption measurement. (A) Schematic of measurement arrangement. (B) Measured data in three different sea trials conducted with the same engine and vessel.*

[3] Diesel fuel is specified by ASTM D975 [32]. The standard does not specify fuel energy density directly. Rather, it specifies the distillation temperature of the fuel which is strongly correlated with energy density. Fuels that satisfy ASTM D975 standards for #2 diesel typically have a Higher Heating Value (HHV) of 137,000-139,000 btu/gallon [33].

A basic linear model of fuel consumption is provided by Equation 7, where *P* is the power produced by the engine (horsepower) and *F* is the fuel consumption rate (gal/hr), $\alpha$ is the fuel consumption rate when no useful power is delivered by the engine, and $\beta$ determines how much the fuel consumption rate increases as the useful power production increases (gal/hp-hr). $\beta$ is characteristic of the engine alone, while $\alpha$ depends on properties of the engine as well as any loads that are placed on the engine that do not deliver useful work. For example, adding a belt drive to an engine will increase $\alpha$ because turning the belt increases the fuel consumption of the engine whether or not it delivers useful work. Engine efficiency ($\eta$) is then given by Equation 8, where HHV is the *higher heating value* of the fuel (btu/gal), and $C_{units}$ is the necessary unit conversion factor. Figure 16 shows the same data as Figure 15 after using Equation 8 to calculate the engine efficiency.[4]

$$F = \alpha + \beta P \qquad (7)$$

$$\eta = \frac{P}{F \times HHV \times C_{units}} \qquad (8)$$

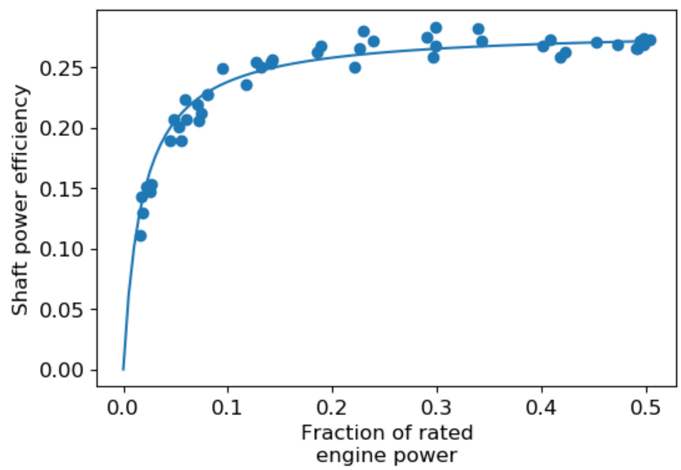


*Figure 16 Efficiency of the example diesel engine in delivering energy to the propeller shaft.*

Figure 16 shows that while using a single efficiency value is accurate for loads above ~20% of rated engine power, the efficiency falls by more than half when this engine is loaded to 5% of rated power. In addition, the data show that the maximum power delivered to the propeller during the sea trial was much less than the engine's rated power. These three characteristics were common in sea trials conducted for the FVEEP:

1. Fuel efficiency stabilizes above approximately 20% of rated engine load
2. Fuel efficiency decreases dramatically below 10% of rated engine load
3. At maximum throttle, the power delivered to the propeller is less than the engine's rated power.

[4] All useful loads (except propulsion) on the engine were eliminated during the sea trial, with the exception of the alternator. The alternator continued to deliver current to the DC power system during the sea trial, which causes the efficiency shown in Figure 16 to be an underestimate. However, the magnitude of this error is expected to be small compared to the range of loads measured on the propeller shaft.

The maximum efficiency value that an engine can achieve—and the precise load at which engine efficiency begins to decline significantly—varies by engine and application but the general trends described by 1 and 2 are expected in all diesel engines. Results from the FVEEP provide a method for estimating $\alpha$ and $\beta$ in order to calculate energy efficiency for a range of engine sizes. However, using the average values measured across all vessels included in the FVEEP, yields a useful rule of thumb given by Equation 9.

$$Power\ [kW] \approx (Fuel\ [gal/hr]\ - 0.5) \times 14 \tag{9}$$

The amount of energy consumed by the propeller at any RPM depends on the propeller pitch and vessel drag characteristics. In some cases the power consumed by the propeller at maximum RPM may be much different than the rated engine power. This situation was observed frequently during the FVEEP, and must be appreciated in order to understand the amount of energy storage and power required for an alternative propulsion system.

In order to estimate useful power delivered by your engine in kilowatts, subtract 0.5 from the fuel consumption rate in gal/hr and multiply by 14.

Before investing in a new system, existing vessels can directly measure the propulsion power delivered to their propeller using the strain gage installation shown in Figure 15. The strain gage measures the amount of strain put on the shaft in order to turn the propeller. Combining the measured strain with known properties of the shaft material (or calibrating the gage with a known torque) yields a measurement of torque placed on the shaft. The shaft rate of rotation can be measured with a magnetic pick up, and the product of rotation rate and torque is the delivered power. The Alaska Fisheries Development Foundation owns the equipment required to make this measurement.

# Appendix B. Components of vessel drag

## a. Friction and pressure drag

Vessel drag is a result of both friction and pressure differences between the bow and stern. Friction drag results from the viscosity of water: a vessel passing through water drags some water along with it, dissipating energy in the process. Friction drag force on vessels is approximately proportional to the square of the vessel speed[5]. The power required to propel the vessel is equal to drag multiplied by speed, implying that the power required to overcome friction is proportional to the cube of vessel's speed.

Wave-making drag accounts for the energy dissipated as waves in a vessel's wake. Vessels typically have a low-pressure trough at their stern, and a high-pressure wave peak near their bow. Waves may also emerge along the hull. The relationship between speed and wave-making drag is more complex than for friction drag because the bow, stern and other waves may interfere with each other, and also because

[5] Friction drag is given by $D_f = \frac{1}{2}\rho U^2 C_f$, where $\rho$ is the density of water, $U$ is the vessel's speed and $C_f$ is the friction drag coefficient. $C_f$ has a week dependence on $U$, making friction drag imperfectly proportional $U^2$ [14], [34], [35].

the waves affect the trim of the vessel. Interference results in the phenomenon of hull speed: when the trough of a bow wave aligns with the trough at the stern of the vessel, the pressure difference between the bow and stern is maximized and the vessel will be out of trim. The power required to accelerate a displacement hull increases dramatically as the vessel approaches this speed due to the increasing pressure gradient from bow to stern and the change in trim.

### b. Propulsion power required for troll, longline and gillnet vessels in Southeast Alaska

Optimal design of an alternative propulsion system depends on the power required to deliver the desired cruising and fishing speeds of a vessel. Given the variety of factors that significantly impact vessel drag, accurately estimating propulsion power requirements is a formidable challenge. Here, we will summarize key concepts that will be useful for discussing alternative propulsion systems and refer the reader to textbooks and peer reviewed literature for a more quantitative and in depth discussion of the propulsion power requirements. We will also present results of sea trials on 29 vessels in the Alaska fishing fleet and a correlation between vessel length, beam, speed and propulsion power (as well as limitations to this correlation). Finally, we will describe a method for measuring propulsion power on board vessels.

Figure 17 illustrates key terms that will be used to discuss propulsion power. **Calm water resistance** is the drag force due to both water and air that must be overcome to maintain speed under calm conditions. The calm water resistance is ideally determined by towing the vessel and measuring the required tow force. As long as the speed is constant, the tow force must exactly equal the calm water resistance. **Sea margins** account for the difference between calm water drag and drag under real operating conditions. Sea margins typically allow for a 15-30% increase in drag over the calm water resistance [14]. **Effective power** is equal to the thrust required to push the vessel forward multiplied by the vessel's speed. At constant speed, thrust must be equal to drag. **Delivered power** refers to the power delivered to the propeller shaft. Delivered power is equal to the torque on the propeller multiplied by the rate of rotation. Delivered power ($P_D$) is related to effective power ($P_E$) by propeller efficiency ($\eta_P$): $P_E = P_D \eta_P$. The "propeller efficiency" referred to here is also known as the quasi-propulsive coefficient, and includes the open-water efficiency, hull efficiency and relative rotative efficiency of the propeller installed on the vessel. **Rated power** is the power developed by the engine or motor before any transmission inefficiencies or auxiliary loads reduce the available power. Engines and motors may have separate maximum and continuous power ratings. Unless otherwise specified, "rated power" refers to the continuous power rating in this work.

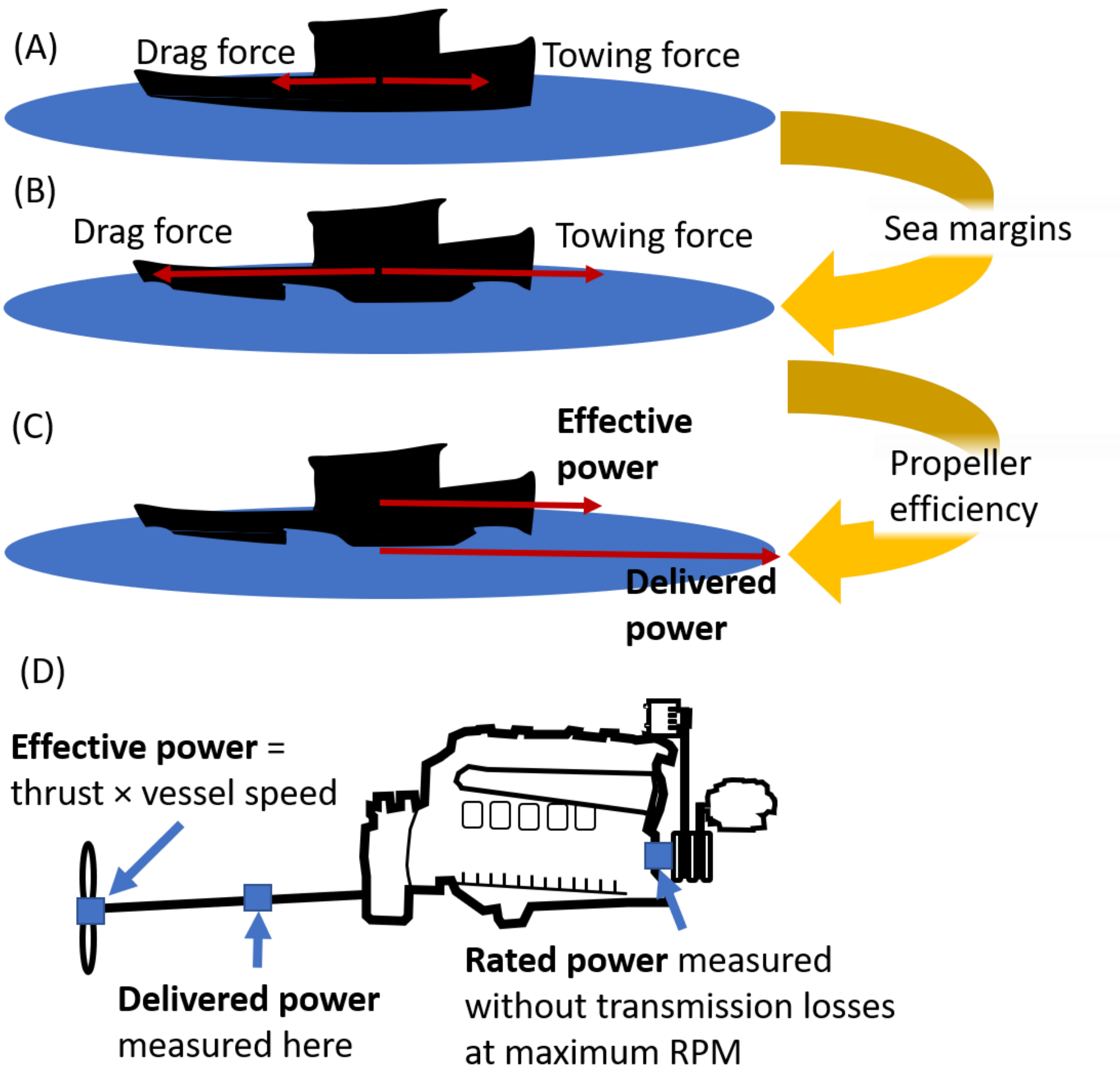


*Figure 17 Visualization of the various terms used to describe propulsion power. A.) Calm water restistance is equal to the force required to tow the vessel in calm water. B.) Sea (and wind) conditions cause the drag under realistic conditions to differ from calm water drag. C.) The "effective power" that propels the ship forward is less than the amount of power delivered to the propeller. D.) "Effective power," "Delivered power," and rated power refer to distinct performance metrics of a vessel propulsion systems.*

## Appendix C. Components of hydraulic loads

As with propulsion systems, there are several efficiency factors that affect hydraulic load. Figure 18 illustrates a basic hydraulic schematic and four types of power that could be measured related to each other by efficiency factors. Using similar terminology to the propulsion section, **delivered power** ($P_D$) is the power delivered to the hydraulic pump. **Hydraulic power** ($P_H$) is the power delivered to the hydraulic fluid by the pump. Hydraulic power and delivered power are related by the pump efficiency ($\eta_P$—accounting for both volumetric and mechanical efficiency): $P_H = \eta_P P_D$. **Delivered hydraulic power** ($P_{D\text{-}H}$) is the power delivered to the hydraulic load after transmission and valve losses accounted for in a transmission efficiency ($\eta_T$): $P_{D\text{-}H} = \eta_T P_H$. Finally, **effective power** ($P_E$) is the power used by the load itself. Effective power is related to delivered hydraulic power by the hydraulic motor efficiency ($\eta_M$): $P_E = \eta_M P_{D\text{-}H}$.

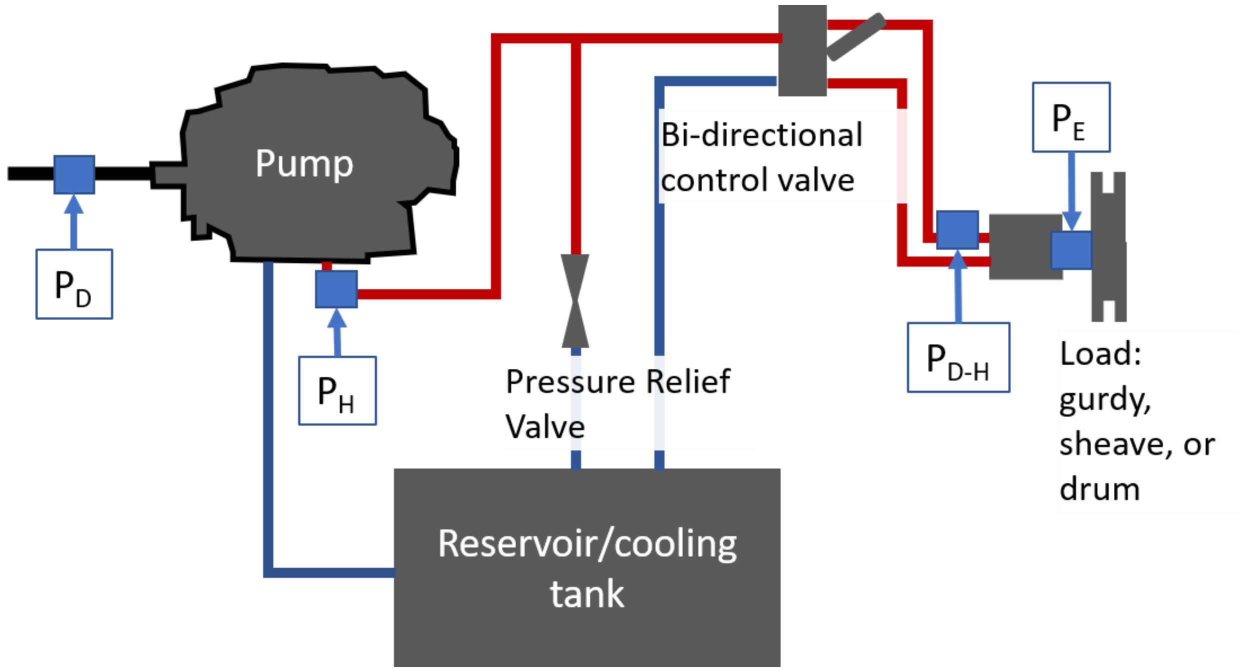


*Figure 18 Hydraulic schematic. Blue squares indicate locations where various types of power could be measured.*

In considering the energy storage requirements to power a hydraulic system, delivered power is the correct figure to consider.

## Appendix D. Details of the auxiliary genset hybrid drive example

Table 16 summarizes the equations used to calculate fuel consumption for the auxiliary and main engines in the auxiliary genset hybrid drive scenario (Section 5.2.1). $\alpha$ is an engine overhead fuel consumption rate, and $\beta$ is a marginal brake specific fuel consumption. Standard efficiency motors and generators achieve 93% efficiency, while controllers are approximately 98% efficient, implying an overall conversion efficiency of 85%. In practice, $\beta_{aux}$ may be greater or less than $\beta_{main}$. For this example we assume both the auxiliary and main engines have $\beta$ values equal to the average observed in the FVEEP: $\beta_{aux} = \beta_{main}$ =0.07 gal/kWh. We estimate $L_{fish} = 6.2$ kW (including 2.5 kW for propulsion and 3.7 kW for hydraulics). Therefore, fuel savings are reduced by $90 \times 6.2 \times 0.07(1/0.85 - 1) = 6.9$ gallons. Assuming $D_{clutch} = 1$ kW, additional drag from the hybrid systems reduces fuel savings by an additional 2.5 gallons. Therefore, the total fuel savings estimated for this 1 week troll trip example is 36 gallons. An efficient hydraulic system that did not run continuously while in the fishing mode could increase fuel savings by approximately five gallons, while implementing a hybrid system on a vessel with a better than average $\alpha_{main}$ would reduce the achievable fuel savings.

*Table 16 Auxiliary genset hybrid drive fuel savings example calculation*

| | Traditional system | Hybrid system |
|---|---|---|

| | | |
|---|---|---|
| Auxiliary generator fuel (gallons) | $168 \times (\alpha_{aux} + \beta_{aux} L_e)$ | $168 \times (\alpha_{aux} + \beta_{aux} L_e) + 90 \frac{\beta_{aux}}{\eta_{all}} L_{fish}$ |
| Main engine fuel (gallons) | $(35 + 90)\alpha_{main} + (35L_{trans} + 90L_{fish})\beta_{main}$ | $35\alpha_{main} + 35(L_{trans} + D_{clutch})\beta_{main}$ |
| Fuel savings (gallons) | 0 | $90\alpha_{main} - 90L_{fish}\left(\frac{\beta_{aux}}{\eta_{all}} - \beta_{main}\right) + 35D_{clutch}\beta_{main}$ |