Saving Money with Fishing Vessel Energy Audits

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"Follow the money—that's energy management." —Mike Gaffney

This report describes phase 1 of a project on fishing vessel energy audits. The long term goal of this project is to provide vessel owners new resources for evaluating fuel efficiency that will help them **reduce overall operation costs** of their vessels. Objectives of the first phase of the project are to provide the vessel owner a **format for understanding a vessel's fuel energy use** and how much each system of the vessel and its operations consumes, and to **gather baseline data** for doing energy cost analysis. Creating a baseline energy use profile is essential for helping fishermen understand how fuel energy is being used on board before going on to succeeding steps.

In the first stage of an energy audit an engineer uses sensitive instrumentation to record parameters such as fuel flow, shaft speeds, torque, AC and DC electrical current, electrical power and quality, and radiated heat. Resulting data are compiled and analyzed and a final report is drafted detailing results and recommended **Energy Conservation Measures** (ECMs). Measures can include application of energy-saving equipment or technologies, as well as operational behaviors. An energy audit typically includes a financial analysis to determine cost effectiveness, as measured by return on investment.

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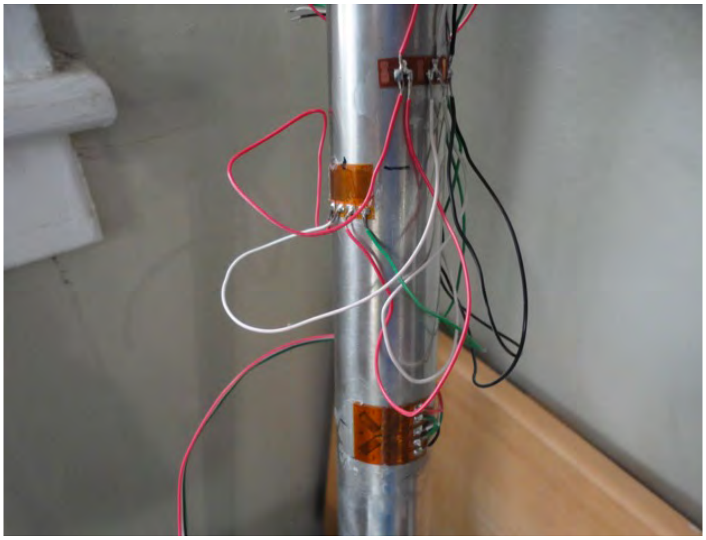


Wiring that is part of a strain gauge to measure prop shaft torque.

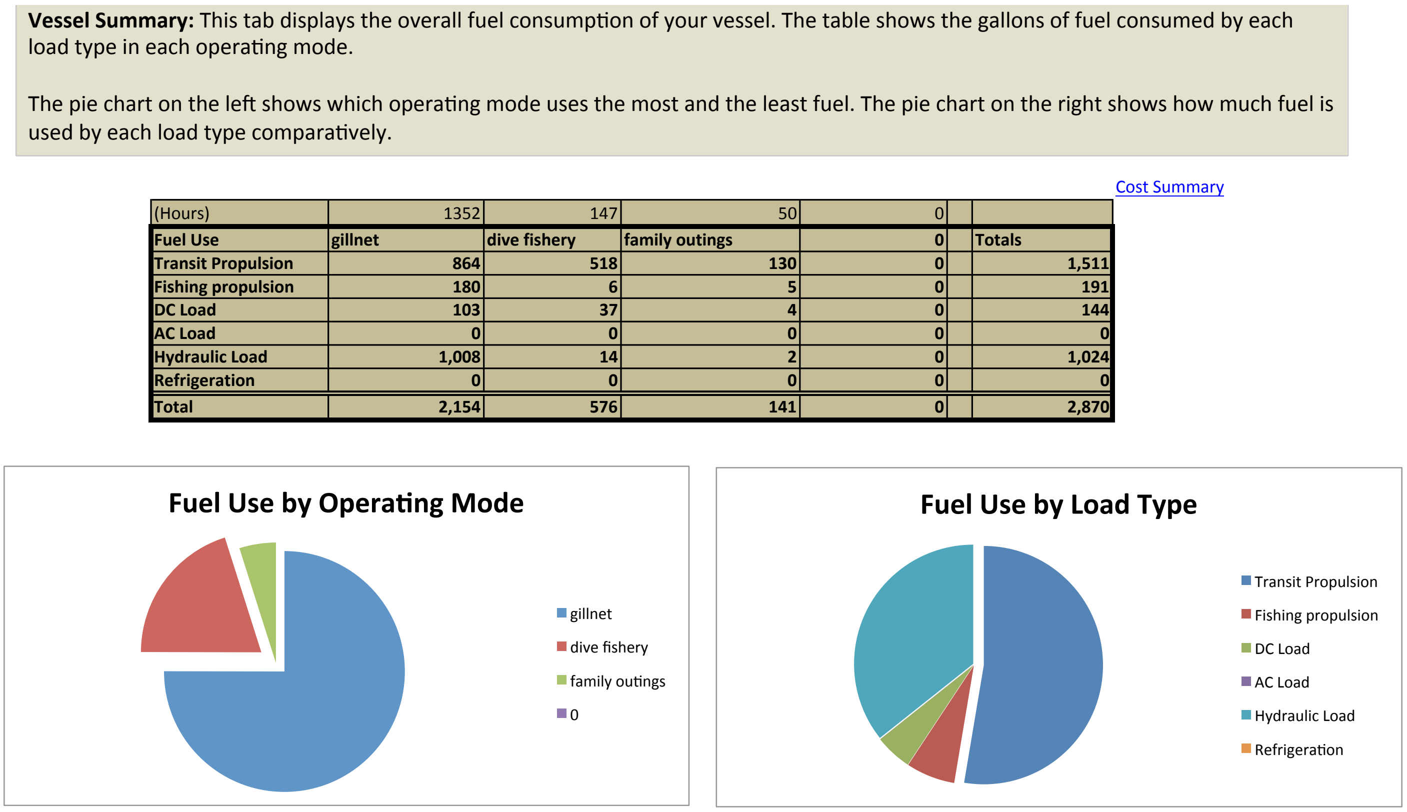
As the Alaska Fisheries Development Foundation obtains funding, future phases will identify ECMs that are practical and cost-effective for Alaska fishing vessels, and will calculate dollar savings to be realized through application of ECMs. Though the first phase was not structured to do so, results do suggest some ECMs and some savings estimates that are described in this report.

Background

In 2013 the Alaska Fisheries Development Foundation (AFDF) secured State of Alaska funding, entered into collaboration with Alaska Sea Grant Marine Advisory Program (MAP), Alaska Longline Fishermen's Association (ALFA) and individual vessel owners, and contracted Alaris Companies LLC to conduct phase 1 of the Fishing Vessel Energy Efficiency Project. The project evolved out of a MAP energy efficiency program dating back to the fuel price spike in 2008. Earlier work had, among other things, developed a vessel self-audit template for fishermen, but it became clear that much could be gained by having audits done professionally. In phase 1 Alaris engineer Mike Gaffney collected operational data from 12 displacement hull diesel-powered fishing vessels ranging in size from 36 to 89 feet and then analyzed results. The data were compiled into a vessel data library.

ALFA staff, working with Alaris, developed a Microsoft Excel worksheet called the **Energy Analysis Tool** (Tool) designed to provide a vessel owner with the necessary context for understanding a vessel's fuel energy use and how energy conservation measures could improve efficiency. It uses the library of data collected from the vessels in the Alaris study. It allows a vessel owner to enter vessel specifications, fishing modes, operating hours, and other operational performance measures associated with the propulsion, electrical, hydraulic, and refrigeration systems of his or her own boat. Where actual loads are unknown, loads can be estimated from calculators within the Tool or the owner can use data from the library to estimate loads. Loads are assigned to an engine to determine load factor and used to estimate fuel consumption. The Tool then calculates baseline energy use, expressed as gallons or dollars, and presents summary data in tables and charts to illustrate the relative fuel consumption of each vessel system and operating mode. The vessel owner can change data in cells of the Tool, making "what if" scenarios and displaying the results.

Alaris engineer Mike Gaffney at work on the energy audit project.



Vessel Summary: This tab displays the overall fuel consumption of your vessel. The table shows the gallons of fuel consumed by each load type in each operating mode.

The pie chart on the left shows which operating mode uses the most and the least fuel. The pie chart on the right shows how much fuel is used by each load type comparatively.

Cost Summary

(Hours)	1352	147	50	0		
Fuel Use	**gillnet**	**dive fishery**	**family outings**	**0**		**Totals**
Transit Propulsion	**864**	**518**	**130**	**0**		**1,511**
Fishing propulsion	**180**	**6**	**5**	**0**		**191**
DC Load	**103**	**37**	**4**	**0**		**144**
AC Load	**0**	**0**	**0**	**0**		**0**
Hydraulic Load	**1,008**	**14**	**2**	**0**		**1,024**
Refrigeration	**0**	**0**	**0**	**0**		**0**
Total	**2,154**	**576**	**141**	**0**		**2,870**

This sample page from the Energy Analysis Tool shows fuel use by load and operating mode.

Vessel Energy Use Overview

None of the power used aboard a fishing vessel is free. Mechanical, electrical, and hydraulic power all come at a fuel cost, even if taken from a propulsion engine that is already running for another purpose, and the energy costs of these parasitic loads can be measured. Only sail propulsion and solar or wind electricity generation do not consume fuel, though they have other costs.

All conversion of fuel energy into useful work has **inherent inefficiencies**. Energy is lost as heat, noise, vibration, smoke, and friction. Over 60% of the fuel energy delivered to a marine engine escapes as heat through cooling jacket water, oil, radiation from the block, and exhaust. Another 3-5% is lost through friction in the transmission (reduction gear) and bearings. Propellers are only 55-65% efficient in converting shaft torque into propulsion thrust due to slip and cavitation. Hulls are subject to wind resistance, skin friction, and wave-making drag. Generators and alternators waste energy in converting mechanical to electrical power; hydraulic lines and valves have friction; and electric motors, compressors, and pumps are less than 100% efficient at converting electrical power to mechanical work. Most of these losses are unavoidable but some can be minimized.

Measuring Engine Fuel Efficiency

Brake specific fuel consumption (**BSFC**) is a measure of thermal conversion of fuel to work through an internal combustion engine, expressed as units of fuel (grams, pounds, or gallons) per unit of power (kW or hp) produced at a given power setting (see Units, Definitions, Conversions, Rules of Thumb section in this publication). BSFC is a function of engine type, condition, air temperature, and loading. Typically a diesel engine is relatively inefficient (has high BSFC) at low power settings (below about 30% of its rated horsepower, depending on engine type), becomes more efficient in the middle and upper part of its power band, and becomes less efficient again as power approaches the engine’s wide open throttle (WOT) rating.

BSFC for some engine models is published in the manufacturer's performance data tables, but those tables are not always available. Furthermore, the operator commonly does not know the actual horsepower (or kW) output of the engine during operations. In the pilot project, engine output (kW or hp) was calculated from torque measured by strain gauges installed on the propeller shaft, and shaft rpm, the results of which were applied to measured fuel consumption to calculate BSFC through a range of engine loads.

The pilot project took measurements on two-stroke naturally aspirated (NA), four stroke NA, and four stroke turbocharged engines. All engines in the tests have mechanically controlled injection; no electronic injection ("common rail") engines were sampled. Two- and four-stroke NA engines displayed similar results, except that two-stroke efficiency proved to be poorer than four-stroke at very low power settings (trolling speed, for example), as expected. Turbocharged four stroke engines proved to be somewhat more efficient. Measurements were not taken in the upper part of the power band on any engines because those higher outputs were not applied during the regular fishing and transiting operations in which the testing was done. See following section.

The authors believe that the BSFC curves for electronically controlled diesel engines would be somewhat different from those obtained in the study. Published data indicate that electronic engines generally are more fuel efficient at low power settings, and this is explained by the fact that the onboard computer exercises more precise control of injection volume and timing. Unfortunately no vessels with electronic engines were selected for testing in this study.

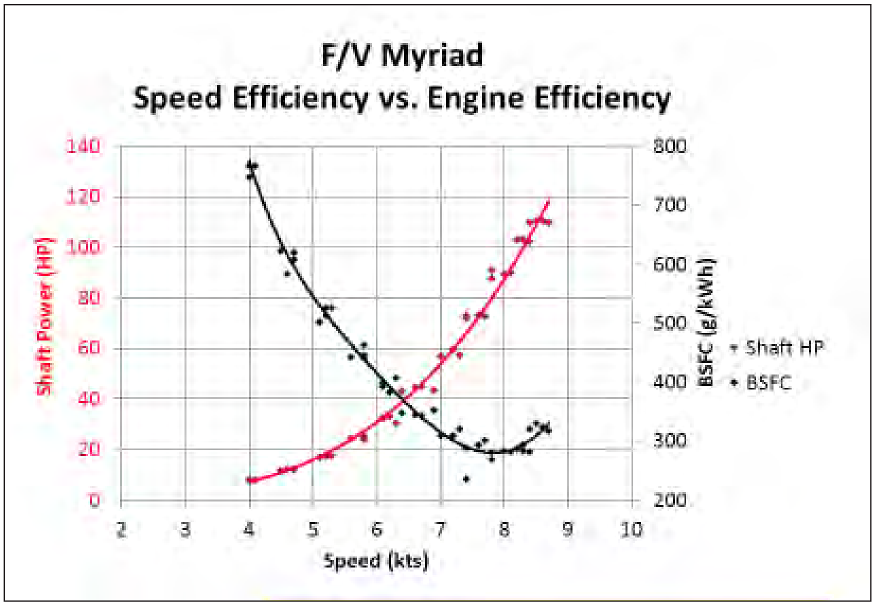
Propulsion Efficiency

Engine efficiency and propulsion efficiency are not the same. Running an engine in the upper part of its power band produces horsepower more efficiently but unless that power is optimally matched to the propeller, and to the hull in terms of displacement and length, much of that power is wasted. This is due mainly to the factor known as **wave-making resistance**, which occurs when a hull pushes aside a bow wave and drags a stern wave. The faster a displacement hull is pushed through the water the greater the distance between the bow and stern waves, and the bigger those waves become. Pushing and dragging those waves consumes a large part of the propulsion energy, and the energy consumed increases exponentially with speed. A vessel also loses energy to hull skin friction. Each hull has a nominal "hull speed," which is the theoretical maximum it can be driven without a huge increase in power. Hull speed in knots is calculated by multiplying 1.34 times the square root of the waterline length in feet. Above that speed the propulsion cost increases sharply, although measured performance data generally show an increasingly steep power demand curve rather than a precise break point.

Nearly every vessel Alaris sampled in the project is powered by an engine that, if run at its most efficient power setting, would push the boat faster than hull speed, wasting a great deal of fuel. In other words, **virtually every boat in the pilot project is over-powered**, that is, its propulsion engine is rated to produce substantially more power than the boat can efficiently use for driving the hull. This not only wastes fuel, but also entails greater engine size and weight, and greater purchase and operational and maintenance costs.

The easiest way most vessel operators can save fuel is by throttling back, reducing wave-making losses. There is a point, however, where engine efficiency becomes so low that the fuel cost per mile increases. The energy audit analysis identified the minimum speed for most efficient operation on several types of vessels, which the BSFC curve illustrates.

Naturally skippers consider many factors when selecting boat speed, including the desire to beat inclement weather, get the catch to processor promptly, maximize crew time ashore, and maximize fishing time on the



Trend curves drawn through data points, taken from measurements on a 47 foot longliner, illustrate that the fuel efficiency (BSFC, black line) is poor at low loads.

grounds. With the data on the fuel costs of various speeds skippers can make those decisions based on an understanding of the fuel costs.

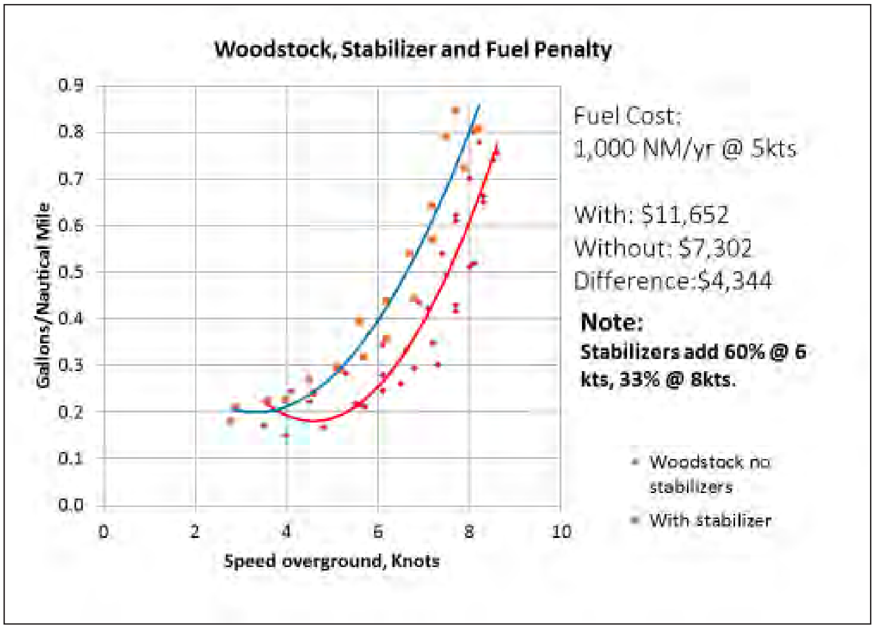
Pushing a hull efficiently through the water isn't the engine's only job, of course, and owners intentionally over-power for many reasons: to ensure sufficient reserve power for punching into head seas, racing against current or other vessels in competitive situations, driving electrical or hydraulic equipment, or simply in the belief that running a bigger engine slowly is more economical and promotes greater longevity than running a smaller one at close to its rated output. The last reason technically is invalid, as verified by many diesel engine authorities, but is not addressed in the pilot project. Numerous published sources and statements by engine authorities explain that underloading an engine can cause cylinder glazing, carbon build-up on valves, and other issues that reduce engine life. The other reasons are valid but data collected in the pilot project illustrate that most fishing vessel applications are oversized by a greater margin than necessary. In short, low speed operation achieved by running a large engine at low output results in high brake specific fuel consumption, which means high cost for the amount of power produced. It also means high capital and maintenance costs and can shorten engine life.

A typical **propeller converts to thrust only about half of the horsepower** that the engine can deliver. Improperly sized or non-optimal design props are even less efficient. **Fixed-pitch propellers usually are optimized for transiting** and are even less efficient during low-speed fishing operations. Even a small amount of marine growth or a rough surface on propeller blades decreases propeller efficiency.

Underwater appendages, including struts, transducers, rolling chocks, and stabilizer fins, increase drag and reduce fuel efficiency. Operating factors such as comfort and safety may outweigh fuel considerations but vessel operators should be aware and make conscious choices.

Maintenance Cost Factor

When maintenance costs are factored in, the picture changes slightly. Most vessel maintenance cycles are based on engine operating hours; for example, oil changes done on 150 engine hour intervals. If a boat travels more slowly it typically takes more hours to cover the same distance, so over a season more maintenance cycles may occur. In theory this means that total costs (fuel and maintenance) can be minimized by running at a speed where the least number of maintenance cycles is required while keeping fuel consumption as low as is practical. Cost of maintenance that is done on annual rather than engine hour intervals, of course, does not increase with slower running speed. See



Note that fuel consumption (gal/nm) ranges from 33% to 60% higher, depending on speed, when stabilizers are deployed.

accompanying graphs that compare dollars per mile traveled at various speed settings when maintenance costs are or are not factored in.

Some of What the Data Show about Engine and Propulsion Efficiency:

- **Each fishing vessel uses energy differently**. Typically transiting constitutes half of vessel energy use, but the range in the study was 8% to 55%. Propulsion while fishing ranged from 10% to 33% of fuel use.
- **Most main engines are oversized** for efficient propulsion. At transiting cruise speed, audited vessels were using only 13% to 33% of available horsepower, averaging about 20%.
- An **underloaded engine burns fuel inefficiently.** The data tables show that a typical naturally aspirated four-stroke diesel engine operating at 10% of its rated horsepower burns about 0.13 gallon of fuel per hp per hr but at 30% load it uses only 0.08 gal/hp/hr, or about 40% less.
- **Turbocharged engines typically are more efficient** than naturally aspirated, at least at the lower loads where the testing was done. Comparison with NA engines showed that turbocharged engine BSFC averaged as much as 37% less at lower speeds, while efficiency of both types improved at higher loads.
- At very low power output the two-stroke diesel is less efficient than four-stroke but at higher power settings the **two-stroke can have similar efficiency to** most naturally aspirated four-strokes in the study.
- At **very low engine and vessel speeds fuel efficiency decreases** due to the increased BSFC noted above. One vessel in the audit was just as efficient at 6 knots as at 4 knots, with the lowest gallons per nm at 5 knots.

AC Electrical Systems

AC electrical power aboard fishing vessels may come from a dedicated diesel-powered generator, an inverter drawing DC current from batteries, or from shore power when the vessel is tied to the dock. Diesel gensets provide most of the AC power aboard fish boats that is used to run hydraulics, refrigeration, electronics, "hotel" service in the living accommodations including galley refrigeration and domestic water and cabin heating, as well as pumps and motors that perform a variety of tasks onboard. Electric heaters are big AC power consumers on some boats.

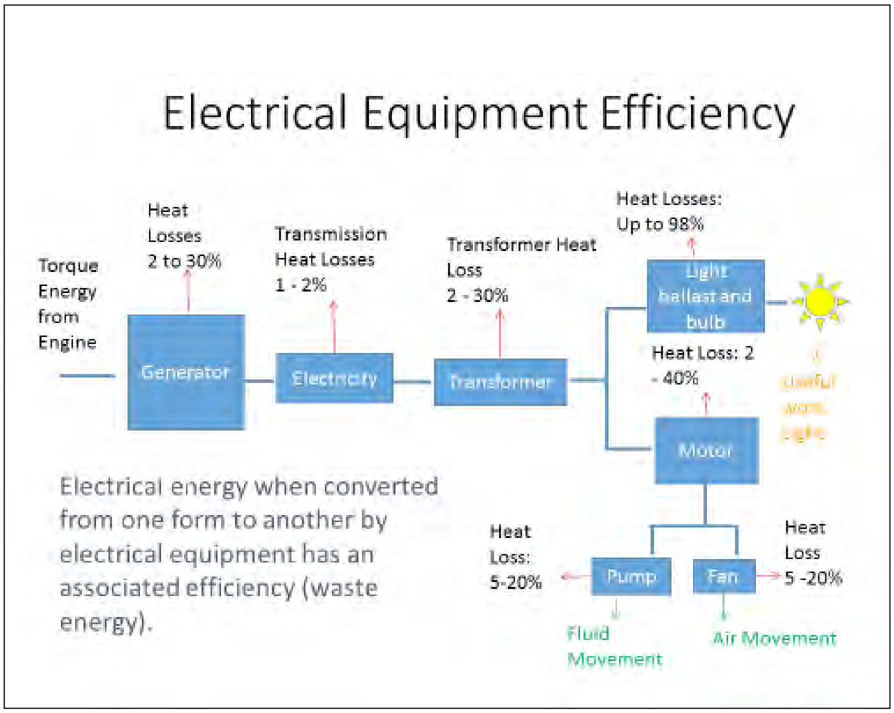
Diesel **genset engines suffer the same inefficiencies** as propulsion engines. More than half of the fuel energy supplied to a properly loaded diesel generator is lost to heat. In addition, the generators to which they are coupled are not totally efficient at converting engine power to useable electrical current. One shaft horsepower of engine output is equivalent to about 0.75 kW and while the efficiency of an optimally loaded large (municipal or industrial) generator is about 98%, a smaller unit is only about 75% efficient so it takes about two diesel horsepower to produce one kW of 120 volt AC power if the system is properly sized and loaded.

As with propulsion systems, **underloaded gensets are significantly less efficient.** A diesel generator run at 10% of its rated output consumes at least 40-50% more fuel per kW than when run at full load. Results of the pilot project indicate that fishing vessel generators are typically run at well below rated loads.

Energy losses (and safety concerns) can be considerable if electrical systems are not **properly sized, installed, and maintained**. Undersized wiring, improper or poorly maintained terminals and connections, inadequate grounding, and other errors generate heat that robs energy, causes devices to operate inefficiently, and can cause fires and other damage.

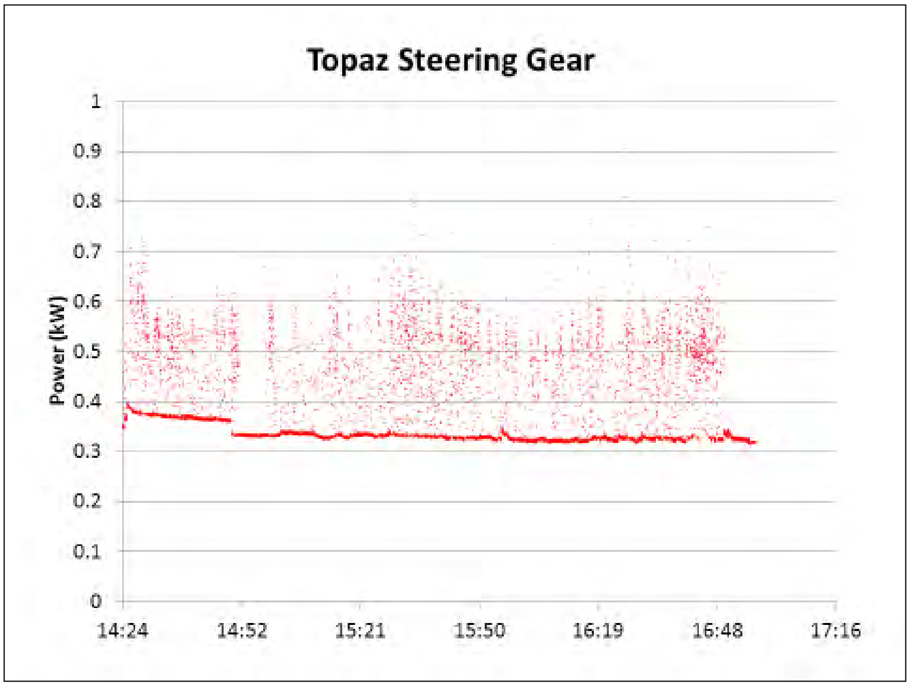
Onboard generation typically costs two to four times as much per kW/hr as shore power at the dock, depending on local electricity rates.

An inverter can eliminate the need to install and run a diesel generator for light loads (generally less than 2-4 kW), saving weight, noise, and cost. However, the batteries from which the inverter draws its DC power are charged by engine alternators that have their own energy efficiency issues (see the DC Electrical Systems section that follows).



Electrical Equipment Efficiency

Electrical energy when converted from one form to another by electrical equipment has an associated efficiency (waste energy).



AC-powered hydraulic steering on this trawler draws 0.3 to 0.4 kW on standby. Specks represent values when steering is actuated; draw is 0.6 to 0.7 kW when rudder is turning.

All electrical devices also have inherent inefficiencies, often detectable as radiated heat. Pumps, fans, and other electric motors experience 5-40% energy losses to heat. Modern premium efficiency motors waste less energy.

Each electrical device has a nominal amperage draw, and **induction motors have a much larger start-up surge demand,** as much as eight times their operating amperage. Nameplate amperages can be entered in the Energy Analysis Tool along with the percent of total time it is powered up, and whether there is a transmitting or full-power demand that is far greater than the standby usage. Radios and radars, for example, use a lot more power when transmitting than when on standby.

Over the 10 year life span of an AC electric motor, around 93% of total cost is energy; the remaining 7% is purchase price and installation.

Old technology electric motors are only about 50-70% efficient at lower horsepower ratings, compared to 80-95% for IE3 grade motors. All types become more efficient at higher power outputs and the differential diminishes but modern motors are more efficient at all loads. Over time a premium efficiency motor will save about 20% in energy cost. **Variable frequency drive** (VFD) motor controllers save as much as 70% in energy by eliminating standby power draw and smoothing out start-up surges.

What the Pilot Project Revealed about AC Electrical Systems:

- Installed diesel generators tend to be oversized for the actual demand, and significantly underloaded most of the time.

- Many fishing industry vessels still use old technology motors, pumps, fans, and compressors that have high start-up surge, typically six times the current that the unit draws when running. Premium efficiency motors can have a slightly greater start-up surge.

- Each kW costs 12-15% more when produced by a generator running at around 40% of rated output than one running at 80% when powered by a non-electronic diesel engine. Electronic engines have a flatter curve, and are much more efficient at the low end. At low loads the difference can be as much as $.10/kW/h but the differential diminishes as output increases. A small genset running at rated capacity can save as much as 20% from the cost of running a large one when only light loads are anticipated. Systems such as AC-powered hydraulic steering have high standby current draws. On a tender in the study the steering system uses 1 kW when no steering movement is occurring.

- Old technology switching prevails. Variable frequency drive is rare in the Alaska fishing fleet.

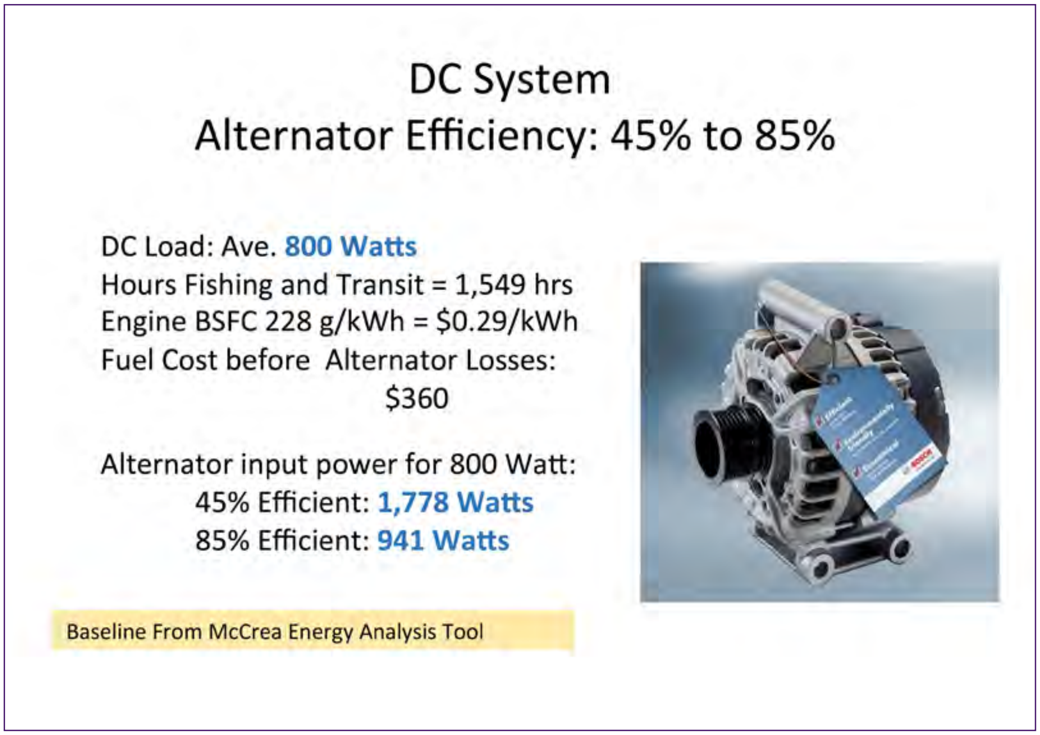
DC Electrical Systems

Onboard DC electrical power normally is supplied by one or more alternators driven by the main engine(s). Nominal 12 and 24 volt are most common although other voltage systems may be found. Important uses include engine starting, powering wheelhouse electronics, lighting, bilge pumps, and other light-duty electrical loads. DC alternators also feed batteries that may be used for running AC loads through inverters.

Alternators draw power off the propulsion engine so indirectly they consume fuel. The efficiency of a DC power system is a function of the BSFC of the engine, the efficiency of drive belts, alternator temperature, alternator pulley rpm, and the design efficiency of the alternator. The energy consumption can be calculated by measuring the increase in fuel flow to the engine as the system is engaged.

A DC alternator typically takes about 1 hp from the engine for every 25 amps at 13.5 volts, or 337.5 watts per hp, or 3 hp per kW.

Common engine-driven **DC alternators are 45-55% efficien**t in converting engine mechanical energy into DC electrical current. **Premium efficiency alternators** are as much as **75-85% efficient**. A standard V-belt loses about 7% of the energy it transfers from engine pulley to alternator; V-rib and synchronous belts are more efficient.



DC System
Alternator Efficiency: 45% to 85%

DC Load: Ave. 800 Watts
Hours Fishing and Transit = 1,549 hrs
Engine BSFC 228 g/kWh = $0.29/kWh
Fuel Cost before Alternator Losses:
$360

Alternator input power for 800 Watt:
45% Efficient: 1,778 Watts
85% Efficient: 941 Watts

Baseline From McCrea Energy Analysis Tool

What the Pilot Project Revealed about DC Electrical Systems:

- Small boats in the audit have DC electrical costs ranging from $388 to $1,040 per season. **Incandescent lighting, galley refrigerators, and autopilot pumps** are major uses of DC power.
- Nearly a kilowatt of 12V power is not unusual during transiting and fishing operations.
- Most vessels are running standard technology belts and alternators that are producing DC current at a fuel energy cost of nearly $.70/kW/hr.
- Installed alternators are not always matched to actual electrical demand (may be too small or too large) or to battery acceptance rate.

Hydraulic Systems

Hydraulics perform many tasks on small Alaska fishing vessels, from steering to powering gurdies, drum drives, and anchor winches. On some vessels refrigeration is powered hydraulically, as is some electricity generation. Hydraulic systems may be powered by a belt- or gear-driven pump off the main engine, by a dedicated auxiliary engine or by an electric motor.

Hydraulics drawing power from the main or auxiliary engines operate at a wide range of efficiencies depending on manufacturer of pump and motor, size of system, and load, with efficiency of optimized systems about 98% when operating at full capacity, and 0% efficiency when operating at no load. Wherever a hydraulic system makes **noise or heat it is wasting energy**. Proper sizing of components, and assuring that plumbing allows unrestricted flow, minimize heat.

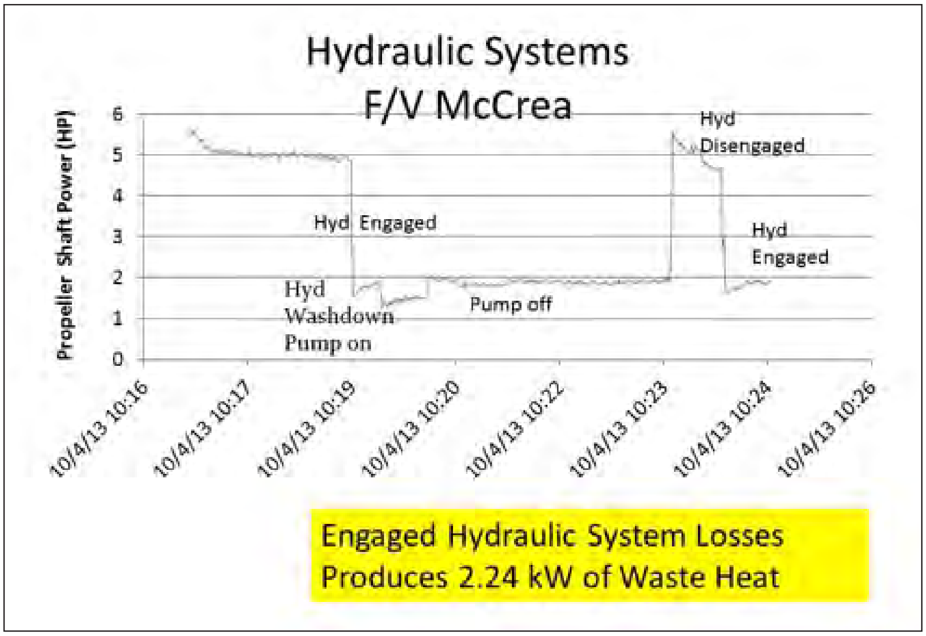
Continuously running hydraulics waste energy when the machinery they serve is not engaged. **Hydraulic power demand can be** calculated from pump displacement, pressure and flow rate. If good hydraulic system data are entered in the energy Analysis Tool it will show the fuel cost in gallons and dollars per year.

Hydraulic power **efficiency can be optimized** by keeping line runs as short and straight as possible with gradual rather than abrupt corners, by keeping fluid and filters clean, and by using the lightest grade hydraulic fluid permitted by manufacturers.

Dirty oil wears out pumps and causes sticky valves and heat build-up. Hydraulic oil from the manufacturer is clean only down to 50 microns, and should be filtered to 3 microns with additional filtration.

What the Pilot Project Indicates about Hydraulics:

- Small Alaska fishing vessels have substantial hydraulics operation fuel costs. On some vessels in the study, hydraulic power demand accounted for more than half of total fuel energy use.
- One 50 footer is spending almost $2,000 in fuel per season for hydraulic power.
- Some boats are configured to have power-takeoff (PTO)–driven or belt-driven hydraulics running whenever the main engine is running, which wastes energy and may necessitate the additional cost of a hydraulic oil cooler.
- One gillnetter in the audit was found to have an energy penalty of almost 2 hp off the main engine when hydraulics were in standby, with the energy converted into waste heat.



The hydraulic pump on this gillnetter uses 2 hp when machinery is on standby. The washdown pump uses 5 hp.

- A troller in the study was consuming an additional quarter gallon or $1 worth of fuel per hour at trolling speed when the hydraulic pump was engaged but the gurdies not turning. Over a season the cost was $1,200 in fuel energy just while trolling with the hydraulic pump on standby and gurdies disengaged.

Refrigeration

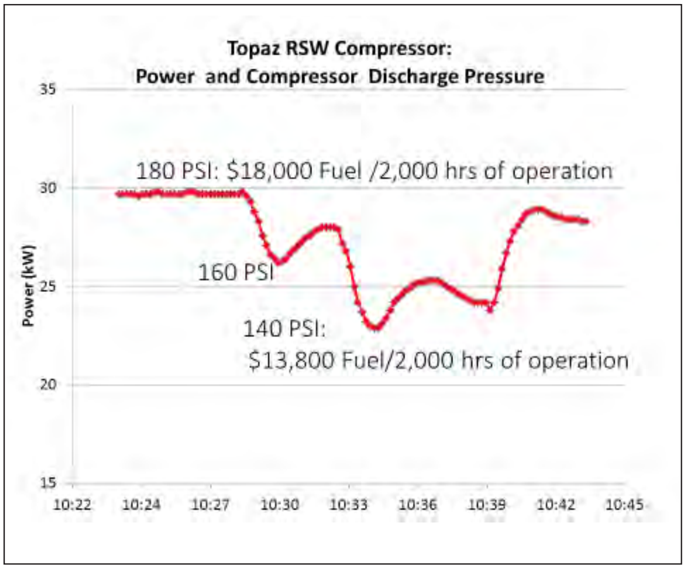
Refrigerated sea water (RSW) and blast freezer systems may be run mechanically, electrically, or hydraulically, usually off a dedicated auxiliary, sometimes off the main engine or off a multipurpose electrical generator. The **biggest energy demand in both types of refrigeration is the compressor**; lesser energy inputs power the seawater pump for the condenser and the circulation pump (RSW) or the fan (blast freezer).

Both types of refrigeration are most **energy efficient under heavy load**. At full load RSW refrigeration typically requires about 1.6 hp per ton of capacity, and blast freezer about 4.6 hp per ton of compressor rating.

By entering blast freezer compressor capacity, evaporator fan, and saltwater condenser pump, the Energy Analysis Tool can calculate horsepower use. Likewise, with RSW load rating (in tons) the program will calculate hydraulic power refrigeration demand in horsepower.

Refrigeration compressor technology has advanced over the decades and new designs use as much as 30% less energy than older models. Proper maintenance and sufficient insulation are essential for refrigeration efficiency.

Compressor head pressure can be adjusted, and maintaining too much head pressure wastes energy. The same pertains to cooling water flow to the condenser, which can be reduced by slowing the pump.



Lowering compressor head pressure on the "reefer" system of this trawler from 180 psi to 140 can save thousands of dollars a year.

What the Pilot Project Reveals about Fish Hold Refrigeration:

- Most of the vessels in the audit did not have onboard refrigeration. Those that did had refrigeration-related fuel costs as high as $15,000 per season.
- Vessels with refrigeration tend to have older technology, including compressors and pumps. Owners stated that component purchases were based on what was offered by local dealers rather than what was most efficient.
- A few refrigeration systems were found with head pressure settings well above that necessary for system requirement.
- One data analysis indicates that the vessel could save 23% in refrigeration cost by reducing head pressure.
- One trawler in the audit could save $4,200 in just 2,000 hours of operation simply by reducing head pressure from 180 psi to 140 psi.

Energy-Saving Technologies

LED lighting—Incandescent light bulbs consume up to 10 times as much energy as LED lights and up to four or five times as much as compact fluorescent lights. Efficiency varies significantly by manufacturer, output, and service. LED lights also have longer service life, which is not diminished by turning them on and off frequently. LED units produce more light useable to the human eye than incandescent, they don't wear out from repeated switching on and off, are not affected by vibration, and don't abruptly fail; they just get gradually dimmer.

Premium efficiency alternators—Alternator technology is advancing but even the best experience significant magnetic, electrical, and mechanical losses in conversion of rotating mechanical energy from the pulley to DC electrical output to the batteries. Standard alternator efficiency is 50-55%, and the best—known as premium efficiency—is around 70% to as high as 80%. There is nothing radically different between the various designs; improved efficiency is obtained through special bearings, density of windings, and better heat dissipation. Financial analyses show that an efficiency differential of 20% (for example, from 50% to 70%) can save several hundred dollars in fuel consumption over the course of a 2,000 hour operating season, with payback of one to three years.

The problem is that there is no official standard for premium efficiency alternators (unlike premium efficiency motors, see below) and it's hard to determine the efficiency of the various brands and models. Some companies, like Delco Remy and Bosch, tout their premium efficiency models and publish spec sheets that state efficiency percentages. Other major marine alternator manufacturers like Balmar don't. So it's difficult to do comparison shopping. Note that "high performance" and "high output" refer only to total current output, not to alternator efficiency.

Premium Efficiency Motors—Like alternators, electric motors have become more efficient over time. The national Energy Policy Act of 1992 mandated improvements and the National Electrical Manufacturers Association (NEMA) set voluntary efficiency standards. Manufacturers have met the standards through advanced materials and design, and through higher manufacturing standards. More recently the International Electrotechnical Commission established a revised set of efficiency standards. Standard efficiency motors (IEC1) post efficiencies in the low 80% range, while NEMA Premium motor (IEC3) efficiency runs as high as 95%.

Keep in mind that motor efficiency depends on motor size and motor load. Fully loaded motors are more efficient than low loaded motors and larger motors tend to be more efficient than smaller motors. For example: a ½ hp IE3 motor has an efficiency of 82.5% and a 5 hp IE3 motor has an efficiency of 90.2%.

Note that if a NEMA Premium motor is selected to replace a standard motor it is important to select one rated for the same or lesser full-load speed; a faster motor would consume more electricity than the one it replaced.

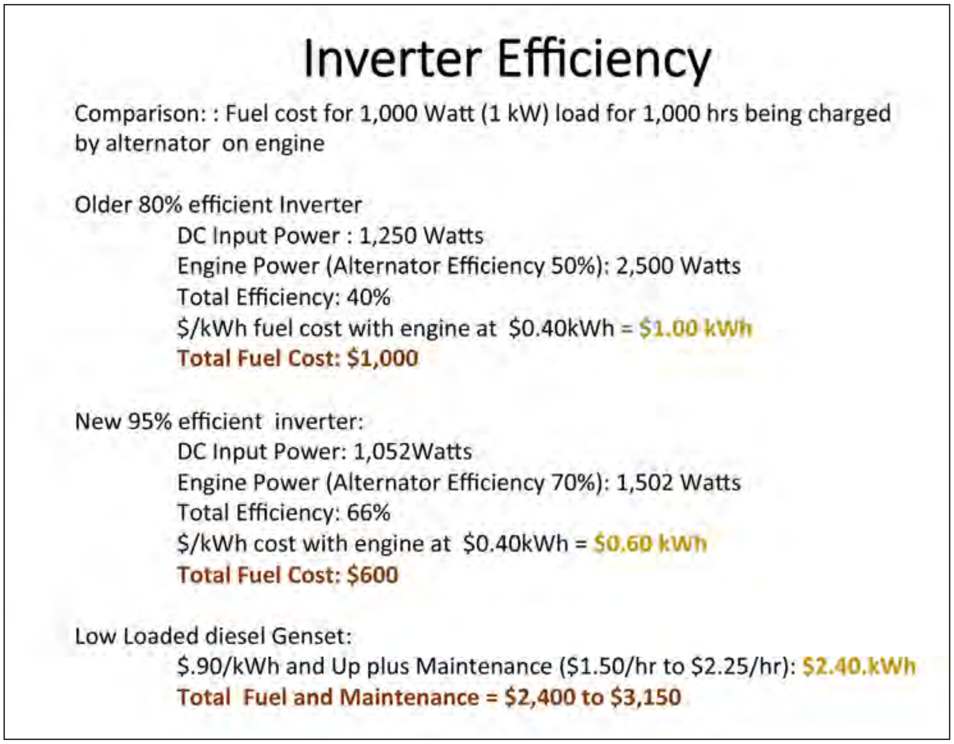
The typical life cycle of AC motors is 15 years of year-round use, and electricity comprises about 97% of life cycle costs with purchase price the remaining 3%. That is based on shore power electricity costs, and onboard generated electricity typically is two to four times as costly or more. Studies show that in industrial applications a payback time of three years or less is achievable, and while service hours on a fishing vessel likely would be less, the increased cost of electricity would balance that out.

True sine wave (TSW) inverters—True sine wave inverters (otherwise known as pure sine wave) are more energy efficient than the less expensive modified sine wave (MSW) models, although the latter's relatively greater surge response to inductive loads such as power tools is slightly superior. A more important consideration may be that MSW inverters are not as effective at charging and powering electronic devices, and may even damage delicate electronics and battery chargers due to harmonic distortion. Since so many electrical devices, from sound systems to refrigerators, are controlled by microcomputers, TSW power usually is more cost effective even when taking into account higher purchase price. TSW inverters are about 20% more energy efficient than MSW because they produce higher power quality and lose less energy to heat from harmonic distortion. TSW inverters tend to cost about twice as much as MSW of equivalent output.

Turbocharging—Many diesel engines are equipped with turbochargers because they provide better power-to-weight ratios or more total horsepower than a naturally aspirated engine of the same size. Results of the data collection show that turbos can also produce lower BSFC or improved fuel efficiency. The data show the most dramatic differences at lower loads: for NA engines the average BSFC value when operating at 30% of rated power range was 239.35 g/hp/h, while the turbo engines averaged 151.9 g/hp/h, or 37% less. The difference likely would decrease at higher loads, and not all engines will produce these results.

A prospective buyer may wish to balance reduced fuel costs against higher purchase price and increased maintenance/repair costs, if such data are available, when considering whether to power or repower with a turbocharged engine.

Variable frequency drive (VFD)—VFD, also known as adjustable frequency drive or variable speed drive, is a device that controls AC power flow to fixed-speed three-phase induction motors such as those that power fans, compressors, and pumps. It adjusts motor speed and torque by regulating current frequency and motor voltage. A VFD



Inverter Efficiency

Comparison: : Fuel cost for 1,000 Watt (1 kW) load for 1,000 hrs being charged by alternator on engine

Older 80% efficient Inverter

DC Input Power : 1,250 Watts
Engine Power (Alternator Efficiency 50%): 2,500 Watts
Total Efficiency: 40%
$/kWh fuel cost with engine at $0.40kWh = $1.00 kWh
Total Fuel Cost: $1,000

New 95% efficient inverter:

DC Input Power: 1,052Watts
Engine Power (Alternator Efficiency 70%): 1,502 Watts
Total Efficiency: 66%
$/kWh cost with engine at $0.40kWh = $0.60 kWh
Total Fuel Cost: $600

Low Loaded diesel Genset:

$.90/kWh and Up plus Maintenance ($1.50/hr to $2.25/hr): $2.40.kWh
Total Fuel and Maintenance = $2,400 to $3,150

contains a solid-state power conversion system with an operator interface, mounted apart from the motor it controls, which allows the user to set operational parameters for that motor. Sensors can be programmed to measure air or refrigerant temperature, for example, to control the speed of fans, seawater condenser pumps, and compressors.

Since energy can be saved by using the lowest available speed setting that meets output requirements of an AC motor, a VFD reduces the operating speed of a normally fixed speed motor when demand is less than the rated horsepower of the motor. For example, once an RSW system is down to temperature, the compressor and condenser pumps can be throttled back. The saving is greater than the reduction in flow because the power required to run a three-phase AC motor is proportional to the cube of its speed. That means that slowing a motor by half reduces its energy requirement by about 87.5%. A VFD also can reduce mechanical and electrical stress on pumps and fans by smoothing out starting surges, thereby reducing maintenance costs and extending motor life, and can likewise reduce wear of impellers, bearings, and so on. However, VFDs produce harmonics that can cause bearing failure through electrolysis if the shaft is not grounded as well as insulation failure from voltage spikes and extra heat produced. When a VFD is used it should be matched with a VFD rated motor. Although some non-inverter duty motors can be operated on a VFD, it may shorten their life.

A soft starter, also known as a soft start motor controller, can achieve a similar reduction in starting surge by reducing initial voltage, but cannot control running speed in response to demand.

Research by the Military Sealift Command indicates VFD energy savings of 15-65% on different kinds of engine room and refrigeration equipment. Energy efficiency of the VFD itself is 95-98%. VFDs in the size required to control small onboard pumps and fans cost $200-500.

ECMs Suggested by Project Results

Propulsion—Transiting and Fishing:

- **Slow down**. Audit results illustrate that from a vessel's theoretical "hull speed" an 11% decrease in speed reduces fuel consumption by 43%, and a 25% decrease in speed by as much as 75%.

- **Use stabilizers only when needed**. Paravane stabilizers impart significant drag and increase fuel costs. One test on a 38 foot troller showed that the fuel cost per nautical mile increased by 63% with stabilizers deployed. Or, to put it differently, for the same fuel consumption the boat would go about 30% faster without stabilizers deployed (see graph on page 6). Devices such as gyro or anti-roll tanks do not impart significant drag.

- **Install a fuel-flow meter** and use it. If wired to the GPS it can indicate gallons per mile rather than per hour. Simple arithmetic will get the same result over a measured distance but not minute-by-minute. A flow meter helps the operator adjust speed to optimize fuel efficiency in real time.

- **"Right-sizing" main engines**. Bigger is not better; the correct size is most efficient. When doing a new-build or re-power select engines only powerful enough to do the job efficiently.

- It may save money to **use a small auxiliary engine** with a second prop shaft, or with hydraulic or electric drive for low speed operation. A diesel-electric hybrid drive could be the solution.

AC Electrical Systems:

- **"Right size" generators** to match the load. It may be more efficient to install a second, smaller genset for "hotel" loads rather than to run a large unit underloaded.

- **Use a true sine wave inverter**, where possible, in place of diesel generator for "hotel" and other light loads. TSW power is up to 20% more energy efficient and less harmful to delicate electronics than modified sine wave.

- If lights, pumps, refrigeration compressors, or other high demand electrical units are required at dockside, **use lower-cost shore power** rather than run an onboard diesel generator.

- When replacing pumps, motors, etc., select **premium efficiency** models. A rule of thumb is that if a motor is used 2,000 hours per year or more it pays to upgrade to premium efficiency.

- **Heat domestic water and living spaces with waste engine heat** via a cooling circuit water heater and a Red Dot–type space heater installed on the engine's cooling circuit.

- Install **variable frequency drive controllers** on variable-demand electrical equipment.

DC Electrical Systems:

- **Turn off** lights, fans, pumps, and other devices when not needed.

- **Switch to V-rib or synchronous** drive belt for alternator.

- **Maintain proper belt tension.**

- **Switch to a premium efficiency alternator,** which can save 30% in DC generation cost.
- **Match alternator to load,** or to battery bank acceptance rate**.**
- Select motors, pumps, and fans by **power rating. Replace incandescent lights** with CFL or LED, which can save 75% in lighting cost.

Hydraulics:

- **Declutch hydraulics** when not in use, if possible. Consider installing a dedicated **small auxiliary engine** to run hydraulics.
- Install **variable frequency drive** (VFD) controls on electrically driven hydraulics and hydraulic steering to save energy.
- In some applications more efficient **electric power** could replace hydraulics. There is no friction in electrical wiring and no standby energy consumption. Electric motors provide very high torque at low rpm and many large workboats and tugs use electric winches and other machinery.

Refrigeration:

- When buying compressors, fans, or circulating pumps, **select premium efficiency** rated models.
- **Reduce compressor discharge pressure** (head pressure). An interpretation of data from a Kodiak trawler indicates that decreasing head pressure from 180 psi to 140 psi would reduce refrigeration energy consumption by 23%.
- Ensure thorough **insulation of fish hold** and refrigeration system coolant plumbing, and door or hatch **seals are tight**.
- Install **VFD controls** on compressor and condenser pumps, circulating pumps, and freezer fans.

Additional ECMs:

- **Variable pitch or controllable pitch propellers** can compensate for the changing loads and power demands of fishing. Propeller ducts, nozzles, or tunnels can improve propeller efficiency, as can more advanced propeller and drive train design. Data on propellers were not collected during the pilot project, but consequences of sub-optimal engine loading were clearly illustrated and properly matching propeller diameter, pitch and blade design are key in correctly loading the engine.
- **Ensure that steering is properly adjusted and tight**. Steering pumps use a lot of energy, and a vessel zigzagging through the water is traveling much farther than if going straight. Ensure the autopilot is tuned to minimize yaw.
- Where possible, select modern high efficiency **Energy Star certified** light fixtures and bulbs, fans, entertainment devices (TVs, stereos), vacuums, cordless power tools, and other tools and appliances. The US Department of Energy issues Energy Star certification.
- **Keep alternators cool** with adequate ventilation, and ensure pulleys are sized so that the alternator runs at optimal rpm. Check documentation for correct speed.

- Supply engine air intakes with **cool outside air** from natural air ducts or supply fans.
- Keep hydraulic **fluid and filters clean** to reduce back pressure and wear.
- Use the **lightest grade hydraulic fluid** recommended by equipment manufacturers, and use synthetic fluid if allowed. Filter to 3 microns, using bypass filtration if necessary to minimize back pressure. Hydraulic oil goes bad over time—viscosity decreases and it absorbs water.
- Ensure the hydraulic **lines run smoothly** without tight bends or obstructions.

Conclusion

This is a preliminary report. Work toward increasing energy efficiency on fishing vessels continues as funding is secured. The Energy Analysis Tool is still in the beta-testing phase undergoing further refinement to make it more accurate and user-friendly. Fishermen are encouraged to try out the current version with a project team member, and provide their data and comments on the experience to help craft refinements. Request a jump drive from ALFA at ALFAstaff@gmail.com. The team welcomes questions, comments, and additional operational data from readers. For more information on the project see the ASG/MAP vessel energy audit website at http://seagrant.uaf.edu/map/fisheries/fishing-vessel-energy-audit/index.php.

Units, Definitions, Conversions, Rules of Thumb

Abbreviations, Acronyms, Definitions, Initials

BHP: brake horsepower, equal to 550 ft lbs per second

BSFC: brake specific fuel consumption, fuel consumed divided by BHP or kW produced

Btu: British thermal unit (heat required to raise 1 lb of water by 1 degree F)

Btuh: British thermal units per hour

CFL: compact fluorescent light

DAR: disc area ratio, percentage of the area of a circle circumscribed by the arc of a propeller that is filled by the combined areas of all the blades

Displacement: weight of water displaced (pushed aside) by the hull

EBSFC: electrical brake specific fuel consumption, used to rate genset efficiency, calculated as fuel consumed divided by electrical power produced

ECM: energy conservation measure

ECO: energy conservation opportunity

FO: fuel oil, usually referring to diesel fuel

GRT: Gross registered tons, a mathematical calculation of the volume of the vessel

Hotel service: electrical network in support of living accommodations—galley, berthing areas, etc.

hph: horsepower hour

Hull speed, in knots: square root of waterline length in feet x 1.34

IEC: International Electrotechnical Commission

kW: kilowatt, equal to 1,000 watts

kWh: kilowatt hour

LED: light emitting diode

Sources for Units Section

Clean Technica

Corey Manley, Schneider Electric, Xantrex

Dave Gerr, The Propeller Handbook

Diesel Service and Supply

Elliot Bay Design Group

Energy Star

Mike Gaffney, Alaris Companies

Numberfactory

Rapid Tables Online Reference & Tools

US Department of Energy, Energy Efficiency & Renewable Energy

Long ton or metric ton: 1,000 kg or 2,200 lbs

MGO: marine gas oil (any of several petroleum distillates including but not limited to diesel fuel)

MSW, TSW: modified sine wave, true sine wave

NA: naturally aspirated (diesel engine)

NEMA: National Electrical Manufacturers Association

Net tons: GRT minus qualifying accommodation and machinery space

Power factor (PF): The ratio between real power (kW) and apparent power (kVA). The amount of fuel that a genset burns is directly related to the kW the generator produces. Apparent power is the product of the volts times amperage. The amperage is the sum of both active and reactive current components and is what the typical AC amperage gauge reads on a vessel. It is the active current that consumes fuel. By knowing the power factor, the real power can be calculated (kW = volts x amps x PF). The differential between real and apparent power is the reactive power that activates the magnetic field in the motor, and does not perform any work. Ideally PF should be as close to 1:00 as possible. PF tends to be low when the motor is underloaded (<70%) and highest when the motor is operating at close to design load (80-85%).

Propeller curve: graph line indicating amount of horsepower used by the propeller through the engine power band, as opposed to engine bhp curve.

Propeller designations: diameter (inches), pitch (inches), direction of rotation, number of blades

ROI: return on investment

Short ton: 2,000 lbs

SHP: shaft horsepower

SMCR: specified (specific) maximum continuous rating

ULSD(O): ultra low sulfur diesel (oil), 15 ppm sulfur or less

VFD: variable frequency drive

Conversions and Rules of Thumb

AC watts single phase = volts x amps x power factor

AC watts three phase = volts x amps x power factor x square root of 3 (approx. 1.732)

DC amperes = watts divided by volts

DC watts = volts x amps

Engine room air supply = 1.5 x combined air consumption of all engines, boilers, etc., at max SMCR

Engine room air temperature: for each 10 degree F increase/decrease in air temperature, fuel consumption will increase/decrease by about 0.7%

1 gallon MGO = 3.785 liters

Heat generated by hydraulic fluid: 1 hp = 2,545 Btu/hr, 1 btuh = 1.5 x psi x gpm

1 hp = 745.7 watts

1 hp supplied for hydraulic drive = approx. 1 gpm @ 1,500 psi

Hydraulic power hp = psi x gpm divided by 1,714

1 hydraulic power hp = 1 gpm @ 1,500 psi

1 kilowatt = 1,000 watts

Kilovolt amps (kVA) = volts x amps divided by 1,000

1 kW = 1.341 hp

MGO density = approx. 840 grams/liter

MGO density = approx. 3,179 grams/gallon

1 ton of refrigeration = 12,000 Btuh

1 ton of refrigeration = 3.52 kW

Mechanical and Electrical Efficiencies

Note: These are approximations based on current technology and may not encompass the full range of variation between makes, models, load, and many other factors. New developments may make these numbers obsolete at any time. Do not make purchase decisions based on these numbers alone.

Diesel engines	40% (up to 50% with electronic injection)
Gasoline engines	25-30%
Generators	95%
Small engine alternators	40-80% (speed dependent)
Small engine alternators	45-55% at rated speed (standard efficiency)
Small engine alternators	55-85% at rated speed (premium efficiency)
Lead acid batteries	85-95%
Inverters	85-95% (MSW and TSW)
Small electric motors (1-50 hp)	80-90% standard efficiency
Small electric motors	82-95% NEMA Premium
Centrifugal pumps (<200 gpm)	40-70%
Hydraulic pumps, motors	85%
V-belts	95%
Cogged belts	97%
Flat belts (including serpentine)	98-99%
AC motor efficiency @ 75% load:	
5-10 hp	70 PF
15-30 hp	75 PF
40-75 hp	80 PF
100-125 hp	84 PF
Lighting efficacy (amount of light usable by the human eye):	
Incandescent	13-18 lumens per watt
CFL	55-70
LED	60-120

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