How diesel-electric propulsion saves fuel

For most boaters, improved fuel efficiency ranks pretty high on the list when they consider the advantages of diesel-electric propulsion. While it's clear that the technology can improve fuel efficiency (this is, after all, one of the main drivers pushing commercial vessels to diesel-electric), few people in the pleasure boat industry understand how it does so. Is it like a hybrid-electric car? Is "electric" horsepower somehow different from diesel horsepower?

It would seem that, if anything, adding a generator and motor between the propeller and engine (no matter how efficient they are) would simply be introducing additional losses which would not otherwise be there. How can adding more power conversions and the losses associated with it improve fuel efficiency? As you will see in the exploration that follows, what diesel-electric propulsion technology does is to create the potential for fuel saving. It does not, in and of itself, automatically provide it. Understanding the technical issues that effect fuel economy is important for the potential buyer since not all diesel-electric systems take advantage of this potential.

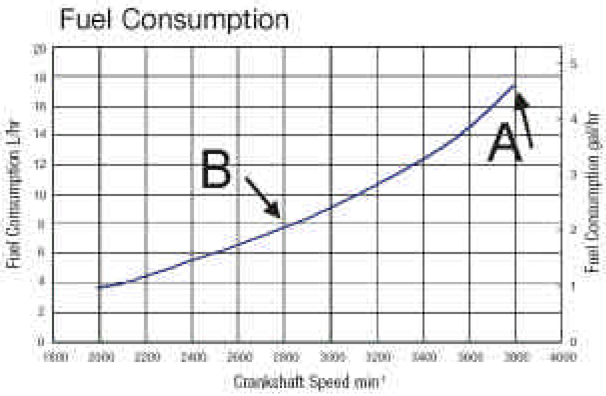
To get started it should be acknowledged that placing a motor and generator between the propeller and diesel engine does indeed introduce new losses into the drive train. These losses can range from relatively minor to very significant and are directly proportionate to the efficiency of the motor, motor controller and generator. Different motor technologies and construction methods result in products of widely varying performance. Using a greater number of thin laminations will result in a more efficient, though more expensive, motor or generator than if they are built using fewer and thicker laminations. Similarly, saving energy in the controller means spending more on the electronic chips that control the flow of power.

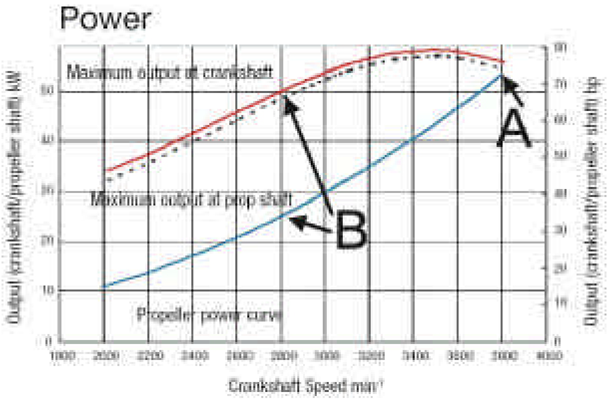
It's not only a matter of spending money, but also one of developing and applying the most appropriate technologies. Some motor designs are quite efficient at one speed/load condition but drop off quickly as soon as the speed or load changes. Others have a much flatter efficiency curve. The collective impact of these differences can be huge with real operational efficiencies varying from better than 98% to as low as 72% for motors and typically between 97% and 84% for generators. This means that for every 100 HP out of the engine you could obtain as much as 95 hp at the propeller shaft or as little as 61 HP. At the high end this compares favorably with the 3% to 5% loss typical of a mechanical transmission (although not all electric motors can be directly connected to the propeller shaft).

Considering these electrical losses, is it really possible to improve energy efficiency? The answer is clearly yes, so long as the basic efficiency of your motor, generator and controller is high. What you are relying on is that you can improve the efficiency of other parts of the system by more than the new losses you have introduced. Fortunately, if the electrical system losses are relatively low, this isn't too hard to do. It turns out that there are many limitations inherent in conventional direct diesel drive that waste fuel. By making more efficient use of the engine and propeller it is possible to more than offset the electrical conversion losses.

The foundation for this saving comes from the fact that, in a well-designed diesel-electric drive system, the power required by the propeller is "decoupled" from the diesel engine speed. In other words, in a diesel-electric system, the engine/generator could theoretically be running at full speed (100% output) while the propeller is only tuning at 50% of peak speed so long as the motor is sized to handle the power. Similarly, if the propeller were lightly loaded, the engine/generator might only need to turn at low speed to provide enough energy to drive the propeller at full speed. This means that diesel-electric systems can be much better at “self-optimizing” to accommodate varying loads than are conventional systems. At sea, load conditions change by the trip (number of passengers), by the hour (wind and tide) and by the minute (going up a wave or surfing down it). These variations provide a significant opportunity for fuel savings.

To better understand how this works lets first take a look at the fuel efficiency of a typical diesel marine engine.





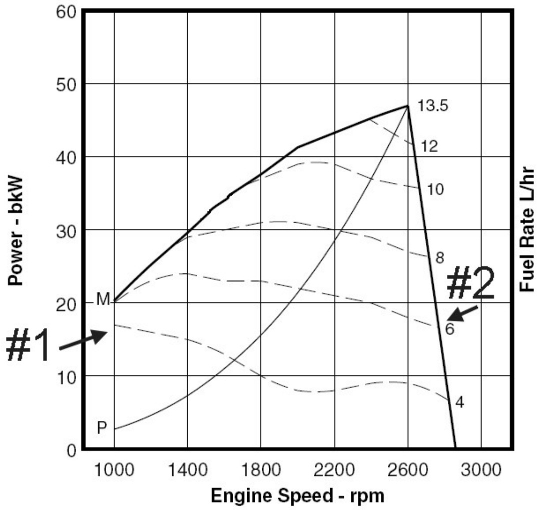
The chart on the right shows the peak power output of the engine at various speeds (top line), the peak power output minus the transmission loss (dotted line) and the amount of power that the propeller is capable of harnessing from the engine (bottom line).

The chart on the left shows the amount of fuel consumed by the engine at various speeds. What is not immediately apparent is that this reflects the fuel consumption it takes to produce the power shown in the propeller curve, not the peak power output of the engine. At maximum rpm (point “A”) it doesn’t matter as both are the same. For general motoring, most boaters would back the throttle down to about 2,800 rpms (point “B”). At this rpm the engine is producing 68hp but only 35hp are being used so point “B” on the fuel curve is for the 35hp not 68hp.

Referring to the left chart, at point “A” the engine is consuming 17 liters of fuel per hour. In terms of fuel efficiency, this translates to 0.25 liters of fuel for every hp produced. When the throttle is backed off to point “B” the propeller is no longer placing a full load on the engine and fuel consumption is 8 liter per hour, or 0.22 liters per hp. If we were to continue to throttle back to 2,000 rpms, the engine would be producing more than three times the power required by the propeller and the fuel efficiency drops to .33 liters per HP.

Clearly, in terms of fuel efficiency, point “B” is the “sweet spot”.- but why? Is it because the engine speed is lower and the fact that the engine is no longer 100% loaded? If this was the case you would see further improvement as you backed down to 2,000 rpms – which you do not. This leaves open the question of what other load/speed combinations would improve efficiency. For a conventional direct diesel drive the question is irrelevant since the engine speed/power and the propeller speed/load are directly linked. They are what they are and the only way to change it would be to incorporate a variable-pitch propeller.

To investigate this further, let’s look at the chart produced by a different, but equally well-know engine manufacturer for an engine of similar size.



This chart also compares the total engine power produced ("M") with the load which can be transmitted by a matched propeller ("P"). In addition, it shows the amount of power which can be produced at various engine speeds for a given fuel consumption rate (dotted lines). A quick glance quickly shows that the issue of fuel efficiency is much more complex than the prior charts would indicate. For example, look at point #1 and #2. Both show the engine with 17kw of load. At point #1 the load is applied at an engine speed of 1,000 rpm. At this speed the engine is only producing 20kw so it is almost fully loaded. At point #2, the speed of the engine is 2,800 rpm and only about 1/3rd loaded. At point #1 the engine is consumes 4 liter/hr to handle the 17kw load (.18 liters per hp). However, at point #2 it requires 6 liter/hr for the same load - 50% more than is required at the lower speed.

Now, let's follow this through and apply it to a traditionally outfitted, direct-diesel boat returning home in a following sea. We'll assume that the throttle is set for a quick return back to port and holds the engine at a constant high speed – 2,600 rpm. As each wave passes under the stern of the boat, the load on the propeller is significantly and temporarily reduced (to 17kW for the sake of this example). During this time the fuel consumption of the engine is 6 liters/hr (point #2 on our chart). After the wave passes, the load increases and fuel consumption increases to 13.5 liters/hr. If we assume that the engine is fully loaded 50% of the time and lightly loaded 50% of the time then the average fuel economy on this return trip is 9.75 liters/hr.

If the boat had a well designed diesel-electric propulsion system, the diesel engine speed would be "decoupled" from the speed of the propeller. As the boat surfs down the wave and the load is removed from the propeller, the engine (generator) would respond by slowing down. At this slower speed the engine is operating more efficiently with a fuel consumption of only 4 liter/hr (point #1 on the chart). After the wave passes and the propeller is again fully loaded, the engine (generator) speeds up and the fuel consumption returns to 13.5 liters/hr. With our diesel-electric system the average fuel economy on the return trip is 8.75 liter/hr – a savings of 10%.

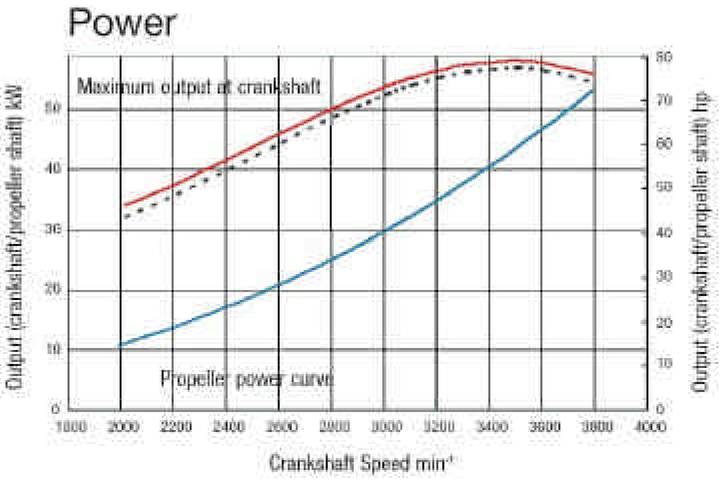
This example illustrates one way in which diesel-electric propulsion can save fuel - by automatically adapting to the constantly chart load conditions characteristic of every sea voyage. However, not all diesel-electric drive systems take advantage of this opportunity. At least one manufacturer claims that their system “improves fuel efficiency by running the generator at a constant speed”. To support this claim they point out that the engines in hybrid-electric automobiles do not vary their speed. What they may not realize is that, in a hybrid-electric automobile, the engine runs only when if and when it will be properly loaded – either by powering the car directly and/or by charging the battery pack. This is not the case in a marine application. Hybrid-electric systems make sense in automobiles where the huge energy fluctuations of accelerating and braking justify the “buffer” of a battery pack. In marine applications, the power fluctuations are present but not as dramatic and they happen on a different time scale. At sea, diesel-electric systems which incorporate generators capable of varying their speed to match the load provide the best fuel efficiency.

The propeller factor –

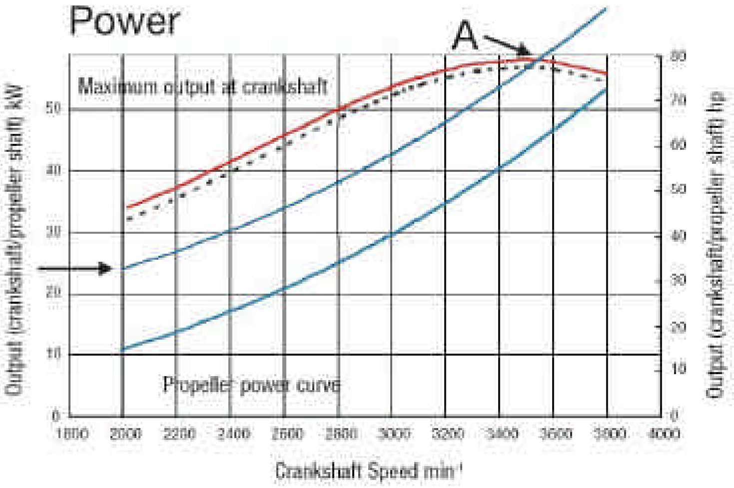
Decoupling the engine speed and power output from the propeller also gives you the opportunity to substantially improve propeller efficiency. It is not unusual for conventional direct-diesel propulsion systems to waste 50% of their power through the propeller. This presents another large opportunity for savings. The details of what makes one propeller more efficient than another is beyond the scope of this paper and, for this discussion, irrelevant. What does matter is that some propellers are indeed more efficient than others. In general, one improves propeller efficiency by (a) increasing the diameter and, (b) turning the propeller more slowly.

So, if it’s really that simple, why are conventional drive systems so inefficient? There are three main reasons. Two of these, engine overloading and poor low-speed control, are easily resolved by switching to diesel-electric propulsion. The third, making room for a bigger prop, can usually be addressed in the design phase once it is known that the other two issues have been addressed.

To gain an understanding of how diesel-electric propulsion allows you to use more efficient propellers, we will again refer the same manufacture’s engine curves that we used earlier this paper.



As previously discussed, this chart shows the disparity between the amount of power produced by the engine and the amount which can be absorbed by the propeller at any given speed. For this particular engine the propeller curve represents the performance of a both a 17”x14” (diameter x pitch) two-bladed propeller and a 17”x12” three-bladed propeller. In the case of the latter, the additional surface area of the third blade reduces “slip” requiring a 2” reduction in the pitch to keep the power curve the same. If the pitch were not reduced the propeller curve would look something like this:

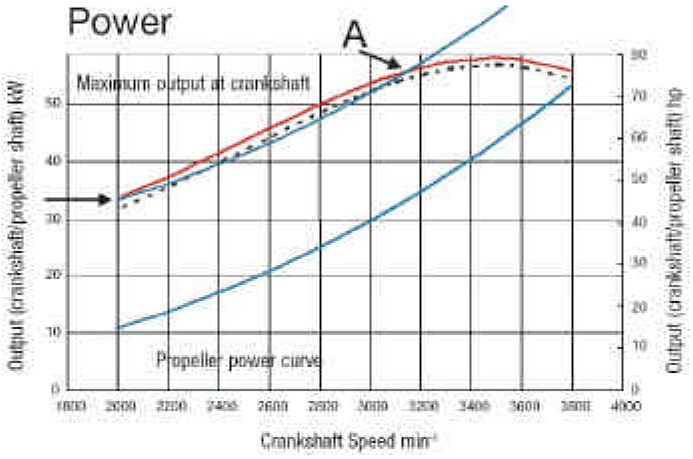


The third blade has improved the grip (reduced the slip) of the blade in the water making it more effective at harnessing the engine power and converting it into thrust. Since the pitch has remained the same, the power curve of the propeller has shifted higher. The propeller and engine curve now meet at point “A” which is 300 rpm before maximum engine speed is reached. The net impact of this change would be:

1. Propeller efficiency would remain the same as with the other two props.
2. The maximum engine speed would be reduced from 3,800 to 3,500 rpm.
3. The engine would not be overloaded since the engine and propeller curves converge after the engine develops peak power output.
4. At mid-range engine speeds the boat speed would be increased since more power would be transmitted to the water.
5. The top boat speed would essentially remain the same since the reduced slip and the lower top engine speed would effectively cancel each other out.
6. The boat speed at idle would be increased which would reduce low-speed maneuverability.

Would fuel efficiency be improved? It is impossible to make a determination based on the information provided on these charts. Since the propeller diameter (and, consequently. the efficiency) remains the same, there would be no improvement here. Throughout the speed range the engine would be operating closer to a full load. This may, or may not result in a better fuel economy. Without having those curves available it is impossible to know.

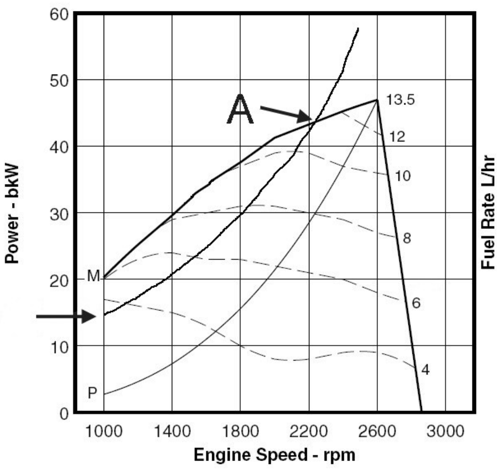
We know that we can increase the efficiency of the propeller by increasing the diameter. Let’s see what happens when we switch from a 17”x14” to a 20”x14”.

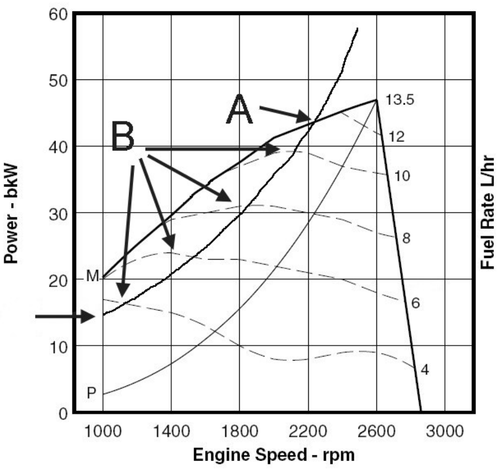


The propeller curve shifts higher still on the power chart. We can see that the propeller and engine power curves now cross (point "A") well before the engine develops maximum power. Putting this propeller on the boat would:

1. Improve the efficiency of the propeller
2. Reduce the maximum engine speed to 3,100 rpm.
3. Overload the engine at full throttle.
4. Fully load, but not overload the engine at mid-range speeds.
5. Increase boat speed at mid-range speeds due to greater power transfer to the water.
6. Reduce the boat's top speed due to the reduced engine rpm (with no increase in pitch).
7. Increase the boat's speed at idle further reducing low-speed maneuverability.

Would the fuel efficiency of the boat be increased? Certainly not a top speed - overloaded engines aren't very efficient. We do know that the larger propeller is more efficient so there is a very good chance that this would translate to better fuel efficiency at the low and mid-range speeds. To determine the fuel efficiency of the new configuration we need to (a) quantify the improvement in propeller efficiency and, (b) calculate the impact that the higher load will have of the fuel efficiency of the engine. We can estimate the propeller improvement at about 7% but to determine the effect on the engine we need to have more detail on the efficiency of the engine changes with load and speed. This information isn't available from this vendor but it is for the maker of our other engine. Let's try applying our new, bigger propeller to their engine chart.





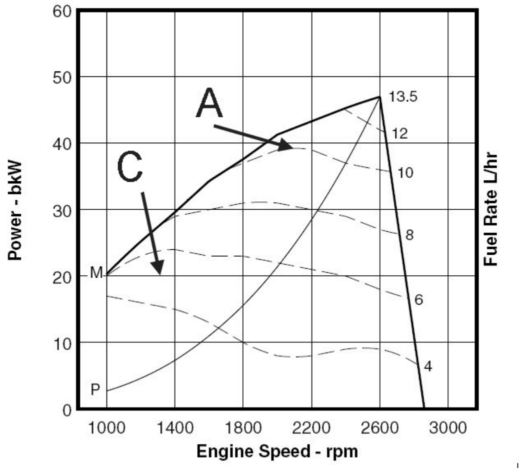
These charts show the original propeller ("P") curve and the new, larger propeller curve in relation to the engine power curve ("M"). The high points on the dotted lines ("B") indicate the engine speed/load combinations that obtain the maximum fuel efficiency from the engine. It turns out that by shifting our propeller curve upward, we operate in the peak efficiency range of the engine over a much greater power range. Comparing the new prop to the original one, we see that the fuel economy of the engine would improve by an average of 13% in the low and middle speed ranges.

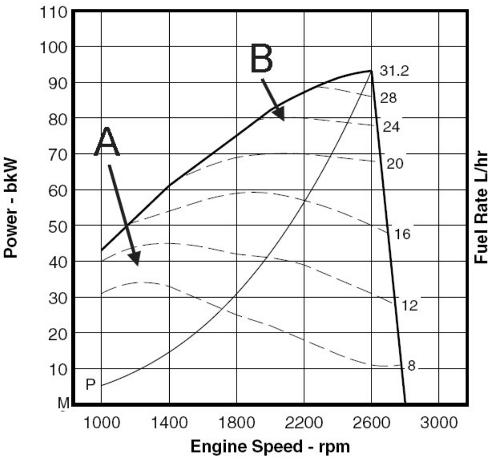
Of course, we can't really use this propeller since we still have the point "A" problem which will not only limit the top speed of the boat, but overload and eventually destroy the engine. One way around the problem would be to switch to a higher gear ratio in the transmission. This would allow you to use the larger propeller but would also require the engine to run at higher rpm in the midrange. This gains you the 7% improvement in propeller efficiency but would wipe out the 13% fuel saving obtained by more efficiently loading the engine.

By using diesel-electric propulsion you avoid this compromise. If this boat were diesel-electric, the full capacity of the engine (in this case, 47kW) would be available regardless of the propeller speed. The engine on our conventionally powered boat overloads because the power required to turn the propeller exceeds the power available from the engine at that speed (point "A"). The engine would have to turn faster to develop full power but can't because it is held back by the high power required to spin the propeller at that speed. In a diesel-electric system, the propeller speed and engine speed are decoupled. The engine speed can be increased to produce full power whenever full power is needed – regardless of propeller speed. The result is a system which allows you to more fully load the engine under all operating conditions and also use larger and more efficient propellers without danger of overloading.

Getting further improvements by using multiple generators –

Many people planning their diesel-electric system will have the choice of using fewer large generators or a greater number of smaller generators. Since all generators feed power into a single buss, any number of generators can be used in any combination to provide the power to the propulsion motors. Factors like redundancy, available space, weight distribution and others will all influence the decision about how many generators should be used. One additional thing to consider is the fact that, by dividing the load between multiple generators, you create the opportunity for even greater fuel economy. The more generators you have, the greater the potential fuel savings. To see how this happens, let's once again refer to our 47kW engine chart and compare it to an engine of twice that capacity from the same manufacturer.





For this comparison we will compare the performance of two diesel-electric vessels operating at a load of 40kW and 80kW. One boat is has two 47kW engine/generators and the other has a single 93kW engine/generator.

In these two charts, point "A" indicates the optimum engine speed and the fuel consumption for each engine/generator when a 40kW load is applied. At this load, both engines consume 10 liters/hr of fuel. On the vessel with two generators, we have the choice of running both engines with 20kW of load (point "C") or, putting the entire on only one and leaving the other at idle or shut down (software control handles this automatically). In both cases, the fuel economy would be the same.

When the power requirement rises to 80kW, the load is split between the two smaller generators on one boat. Each consumes 10 liters/hr for a total fuel consumption of 20 liters/hr. On the vessel using a single large generator, the 80kW of load results in a fuel consumption rate of 24 liters/hr. Having multiple generator gives you the ability to break the load up to better ensure that each engine is optimally loaded. In this case, our two generator vessel maintains the same high fuel efficiency at 20kW, 40kW and 80kW of load. The single generator vessel consumes 20% more fuel at the heavier load.

Doing diesel-electric the wrong way -

In closing, it may be helpful for the reader to have a clear example of how not to set up a diesel-electric system. This is a real system - an effort by a major boat manufacturer to create their own low-cost hybrid-electric propulsion system. Because the system will be outfitted as standard (rather than an option to conventional diesel) it is a primary goal of the manufacturer to provide what it views as the maximum number of benefits at the minimum cost. The system uses standard industrial grade components and a conventional constant-speed 15kW marine AC generator (efficiency is 87%). Power from the generator is sent to an 8.5 kW battery charger (efficiency approximately 78%) and from there to a large 48v battery bank. Power from the batteries flows to a commercial motor control (typical efficiency 93%) and on to a commercial grade 12kw BLDC motor (typical efficiency 89%).

The purpose in describing this system in this paper is not to argue the merit or lack of merit of such a configuration except as it relates to fuel efficiency. While this is a diesel-electric system (hybrid electric to be exact), it should not be expected to provide much in the way of improved fuel efficiency. For every horsepower produced by the engine, only 0.56 hp will be available at the propeller shaft. Combined with the single-speed generator and the limited power available through the battery charger/power supply, it is safe to assume that the boat will be a disappointment for anyone watching the fuel gauge too closely.

Summary –

This paper has used readily available data from a variety of sources to show how diesel-electric propulsion provides an opportunity to significantly increase the fuel economy of power and auxiliary sailing craft. It has shown how these savings are not inherent in the technology but must be part of the overall system design. It has demonstrated that the components of an optimized diesel-electric system include:

1. Motor, controller and generator designs that have a high peak electrical efficiency and maintain that efficiency over a wide range of speeds and loads.
2. A direct-drive propulsion motor that does not incur the additional 3% to 5% loss typical of transmissions and gear reducers.
3. A variable-speed generator that allows the speed and power output of the engine to closely match the load placed on the generator.
4. A propeller optimized for the diesel-electric drive – not a conventional drive.
5. The potential to further optimize performance by splitting the load between multiple generators.

The examples presented and conditions analyzed have shown:

1. A 10% fuel savings achieved by allowing the engine speed to fluctuate along with the load thereby eliminating inefficiencies associated with intermittent high-speed, low-load operation.
2. A 7% fuel savings achieved by using a larger and more efficient propeller than would be possible with conventional diesel drive.
3. A 13% savings achieved by more closely aligning the power required by the propeller and the power produced by the engine and, by doing so, shifting the engine load to a more optimum point on its power curve over a wide range of speeds and conditions.
4. An additional savings of 20% achieved under some load conditions if multiple generator are installed.

The demonstrated fuel savings total 30% to 50% - substantially more than the losses introduced by a reasonably efficient diesel-electric system. Understanding the basis on which these fuel efficiencies are obtained makes it apparent that the efficiency gained over a conventionally powered vessel will vary according to environmental conditions and vessel use and could be more or less than what has been shown here.