A practical, hands on manual for designing, building and owning an electric boat.

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1. ELECTRIC AND HYBRID PROPULSION

Today’s boat owner’s requirements for clean and quiet propulsion with high energy house systems are being met by Electric and Hybrid technologies.

Electric and hybrid technologies offer quiet, clean, efficient propulsion. Operation is significantly easier with more finesse. Diesel engine runtime can be decreased or completely eliminated. Diesel start and stop can be automated or run at opportune times. Diesel engine use can be optimized for peak load efficiency resulting in less diesel engine run time.

The electric experience is more synonymous with sailing, and consequently, the market is expanding quickly.

Higher voltage, more complex systems are requiring new training and new standards, many of them yet to be ratified.

The Electric Drive industry is experiencing a renaissance after 120 years of quiet operation in pleasure launches, trolling boats, and submarines. Battery technology is now available to make all-electric boats applicable for daysailors and hybrid boats for cruisers. Solar Electric Boats are capable of sustained, continuous operation and have circled the world on solar power alone. My solar sailboat Kapowai, has not seen a fuel station in over 8 years and has not been plugged into shorepower for over three years.

It is now possible for sailboats to become energy independent with almost limitless range and significantly improved capability.
The Electric Boat

This book aims to encourage the technology by providing up to date information on how to design the right electric or hybrid drive for your boat, installation tips and tricks, safety issues, and how you will be enjoying your boat now and many years from now.

This e-book details how to design, install and use electric drives on monohull sailboats and displacement powerboats up to 40 feet long and drives up to 100 volts. Future editions of this book will include chapters on multihulls, planing boats, and higher voltage systems for larger sailboats.

2. DESIGNING A PROPULSION SYSTEM FOR HOW A BOAT IS USED.

Most boats today are outfitted with a small diesel and 12 to 20 gallons of fuel which gives the boat a 100 to 200 mile range. Most boats are used primarily for daysailing. Most motoring is done from the slip to the sea. Many boats fill up once a year or even less. Many boats run more often at their slip than out at sea. Often times fuel goes bad before it is used.

I hope that one day someone does a study on how boats are used. My observations indicate that 90 + percent of all sailing is daysailing, 99% of a boat’s life is spent in the harbor, and that the primary use of a sailboat is a home away from home on the water. I’ve quoted these numbers many times without any argument from anyone. If you think differently or know of a study that can shed light on this, please let me know. In the meantime, we can proceed with these assumptions as we design propulsion systems for how boats are used.

When a client is inquiring about an electric drive, my first question is “What is the range at speed requirement and what are the conditions?” Some inquiries require a long range at high speed, say 50 or 100 miles at 6 knots, in which case I suggest that the customer buys a diesel. Diesels are designed to work for 10,000 hours at 75% of peak torque. Perfect for the customer who wants to motor around endlessly.

For the majority of us, this is not the case. Most of us are daysailers and occasionally we venture out of our local cruising area, usually not more than 50 miles round trip, and most of the time we are sailing. It is this group of people that electric drives are perfect for.

The majority of boats are not designed for how they are used. The diesel engine is just not appropriate, is excessive and high maintenance. The diesels are not used at their peak operating conditions and usually fail due to lack of use rather than too much use. Many diesels are run more at the dock than they are at sea, as the owner seeks to preserve the diesel by running it frequently. This creates a pollution problem for neighboring boat owners who inadvertently breathe the exhaust.
As more of us realize this design mismatch, and communicate our requirements for cleaner energy aboard, boat builders will start offering electric propulsion as standard equipment aboard recreational sailboats.
I predict by 2025 Electric Propulsion will become the primary source of propulsion for recreational sailboats up to 40 feet long.

Boat builders build for demand, and the demand is not there, because the customer is not aware of the current technologies that are available. There is a growing number of boat owners that are looking closely at how they use their boats, and realizing that electric propulsion is exactly what they need.

Even though it is more difficult to retrofit a boat with electric propulsion than build it from new, the technology is taking off.

As sales of new boats remain stagnant, one can only ask if electric and hybrid models could jump start sales. As sure as the Prius has become a best seller because it makes sense, so will electric and hybrid propulsion for boats.

Ultimately it is the customer who creates the change. It is the customers who contact the dealers and ask for a hybrid or electric boat. In turn the dealer talks to the manufacturer, and when the manufacturer gets inundated with requests for better boats, they adopt new technology or get left behind while new manufacturers spring up to satisfy the demand.

But just building an electric boat and putting it on the market is not the solution either. Boats need to be built for how they are used. Not only is it a functional requirement, it is a safety issue too. Boat builders need to know how to translate the customers requirements into designs that work.
With diesel it is easy for the boat builder. Drop a $5,000 diesel motor into the boat, fill up with fuel, and you won’t run out of fuel as long as you keep the tank full.

With electric boats that formula is vastly different. Boat designers, builders and owners can now learn the basics of electric propulsion so they can accurately communicate the features, benefits and limitations of any particular system.

Education is key to adoption of this technology. ‘The Electric Boat” aims to provide the necessary information for boat owners to decide how they should choose a propulsion system that is right for their boat and how they use it.

**Boat builders with Electric and Hybrid options can achieve higher sales from a larger pool of potential customers.**

### 3. PHYSICS OF MONOHULL SAILBOAT PROPULSION

#### SIZING AN ELECTRIC DRIVE

I recommend 1 KW per ton of displacement for inshore sailing vessels and up to 2 KW per ton of displacement for offshore cruising sailboats. Sailboats with high freeboard should have larger motors due to the increased windage.

One KW per ton yields up to 90% of hull speed in calm conditions with no wind and no waves. We choose to use calm conditions as a benchmark because it is the only way to establish a baseline. For most weather, this is plenty of power.

There will always be situations out in the ocean where more power is desirable. Good seamanship is all about using whatever resource is available to achieve the desired course. With an electric boat, the sails are the primary source of propulsion, and the electric motor backed by batteries or a generator is the secondary. Those wishing to have the motor as the primary should utilize a diesel engine with large diesel fuel reserves.

The advantage of the electric drive is being able to provide small amounts of power to enhance the sailing attributes of the boat. Small amounts of power can create apparent wind while traveling upwind or on a broad reach. In low wind conditions, this enables a boat owner to continue sailing, where a traditional diesel powered boat would have to stop sailing and turn on the diesel engine.

Small amounts of power can provide directional stability or control instability, by acting like a drogue. Electric sailors can utilize their motors in ways that a diesel sailor is
incapable of doing. Increased functionality of the electric drive is where the appeal comes from.

The important part of sizing an electric drive is making sure that the drive has a sufficient continuous rating, and at what internal motor temperature that rating was made at. Many electrical components are over-rated. Rating conditions are dissimilar to what is found on a sailboat, plus all boats are different, and operate in different temperatures. Since every vessel and its operating environment is unique, it is important to find out the maximum continuous power output of the boat when the boat is commissioned with the new electric drive.

What determines the maximum power output of an electric motor is physical size, efficiency and ability to dissipate heat. Ambient temperatures in the engine compartment affect the ability to cool an air cooled motor. Water temperature and flow rate determine the ability to cool a water cooled motor.

All electrical components are more powerful and efficient when operating in cooler temperatures. Water cooling is more effective and necessary for larger electric drives. For solar and electric sailboats you can use a large fresh water tank as a heat sink (systems over 50 volts nominal require ground fault monitoring). For hybrid, we recommend the heat exchanger be cooled by seawater.

ESTIMATING POWER AT SPEED

The basic physics of a boat reveals that for each knot you increase in boat speed there is roughly a doubling of the power requirement.

As you can see in the following graph, at low boat speeds it takes very little power to push the boat. It is at these speeds that electric propulsion really shines. Small amounts of power make huge differences while motor sailing. Small amounts of power can make the difference of whether the sails are luffing or not and whether the boat has directional stability or not.
Because of the excessive amounts of power required to run at high boat speeds, it typically is not done with an electric boat. But remember that it is not done regularly with diesel boats either, because as you approach hull speed the sound and vibration of the diesel gets excessive and the boat ride becomes uncomfortable. For this reason I typically think that a boat has a natural speed for motoring, whether diesel or electric, at around 75% of hull speed which can be obtained by taking the square root of the waterline length.

The best advice for anyone considering an electric boat is to keep the boat bottom in racing condition. Through hulls should be eliminated if possible, and faired in flush. Any gouges, scrapes or dents in the bottom should be faired. The keel should be faired. The bottom and propeller should be cleaned regularly. There is a huge difference in performance for a boat that is ignored and dirty, compared to a boat that is clean and racy.

The chart predicts power consumed at speed by halving power required for each knot decrease in speed, starting with 2 KW per ton for hull speed (1.34 x the square root of the waterline length).

Actual results are listed for comparison purposes. As you can see, this is a fairly accurate method of predicting the power requirement of a monohull sailboat.

Remember that the estimate is for calm conditions with no wind and no waves. Down weather performance will be increased, while up weather performance will decrease. There is no way to predict power requirement as you head into weather, as all weather is different. These predictions include a clean bottom and propeller.
ELECTRIC PROPULSION POWER VS. SPEED - PREDICTED VS. ACTUAL : CATALINA 30

<table>
<thead>
<tr>
<th>SPEED</th>
<th>POWER</th>
<th>Catalina 30</th>
<th>Predicted</th>
<th>Actual</th>
</tr>
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<tr>
<td>HULL SPEED</td>
<td>2 KW PER TON</td>
<td>6.7 knots</td>
<td>12 KW</td>
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<tr>
<td>90 % of Hull Speed</td>
<td>1 KW PER TON</td>
<td>6 knots</td>
<td>6 KW</td>
<td>6 KW</td>
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<tr>
<td>90 % of Hull Speed less 1 knot</td>
<td>500 watts per ton</td>
<td>5 knots</td>
<td>3 KW</td>
<td>3.2 KW</td>
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<tr>
<td>90% off Hull Speed less 2 knots</td>
<td>250 watts per ton</td>
<td>4 knots</td>
<td>1.5 KW</td>
<td>1.48 KW</td>
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<tr>
<td>90% of Hull Speed less 3 knots</td>
<td>125 watts per ton</td>
<td>3 knots</td>
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<tr>
<td>90 % of Hull Speed less 4 knots</td>
<td>62 watts per ton</td>
<td>2 knots</td>
<td>375 watts</td>
<td>262 watts</td>
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POWER COMPARISON WITH DIESEL

We have found that 1 KW per ton moves the average electric boat at 90% of hull speed in calm conditions with no wind and no waves. With diesel boats we find that 3+ KW per ton moves a boat at close to hull speed in calm conditions with no wind and no waves. Why such a discrepancy between power levels? The Electric motor can run a big propeller due to the flat torque curve. A diesel motor is limited to running a small, fast turning propeller due to the limited torque available to a diesel at idle.

The big, slow turning electric propeller gets traction, while the small fast turning diesel propeller spins and slips. Additionally, the diesel must turn parasitic loads including the alternator and two water pumps. The diesel must be sized for full load on the alternator while powering the vessel. This contributes to the excessive power formula for diesels.

It must be noted that when a 3 KW / ton diesel boat encounters wind and waves, it will decrease less in speed than its 1 KW / ton electric counterpart. This is because of the torque curves of the two different systems. A diesel’s torque curve meets the propeller’s torque curve at maximum rpm. At lower than maximum rpm, the diesel has
available torque that is not ordinarily used. At slower boat speeds the diesel can call upon the extra torque at the lower rpm and keep the boat moving into weather.

The slower boat speed (caused by beating into weather) increases the torque requirement of the propeller. If a 3 KW per ton Diesel would keep a boat going into weather at 5 knots continuous, the 1 KW per ton Electric would keep the boat going at 4 - 4.5 knots continuous.

How often you are out in heavy weather? If you are frequently sailing in heavy weather then it is advisable to get a diesel or hybrid.

An electric system is designed so that maximum power output occurs at maximum rpm. The torque of the electric motor is close to a flat line from 0 to maximum rpm which enables the use of huge, highly efficient propellers. There is additional torque that the electric motor can call upon in the mid range, just not as much as what is available to a diesel on a continuous basis.

On an intermittent basis, an electric motor can create enormous amounts of torque - often two to three times the continuous rating of the motor.

At full rpm, the load on the propeller is highest when the boat is sitting still (a bollard pull) In Kapowai’s case the motor is drawing 175 amps doing a bollard pull. Motoring at 6 knots, the motor is drawing 120 amps. As the boat speeds up, there is less demand on the motor, so the current drops.

A diesel minimum speed at idle is usually around 600 rpm. Taken through a 2:1 gearbox, the diesel driven propeller has a minimum speed of 300 rpm. Due to the lack of torque at low rpm’s, the diesel must utilize a small propeller with minimum pitch. By contrast an electric motor has similar torque at all speeds, and can drive a comparatively huge propeller at 50 rpm or less. The low speed capability of the electric motor results in huge efficiency gains that the diesel is not capable of. This makes for long range motor sailing qualities and enhanced control while maneuvering and docking.

REGENERATION

When I first installed an electric drive in my Catalina 30, Kapowai, I had high hopes for regenerating power through the propeller. I figured I could obtain 1 KW of regen power. I was disappointed to find out that at 6 knots sailing speed, I could regen at about 120 watts. Upon closer examination of the physics of the boat, I found out why.

When the propeller is in regen mode it is turning at around 150 rpm. Taken through my 2.2:1 gearbox yielded a motor rpm of 330 rpm. Permanent Magnet AC motors are synchronous machines, so at 330 rpm the motor was generating about 8 volts. To
regen, the controller provides reverse torque to the motor. This creates an inductive spike in voltage above the voltage of the battery pack, which is necessary for regeneration. (electricity always flows from high voltage to low voltage) So right off the top the process is not that efficient because of the energy required to boost the voltage.

The amount of energy that the Catalina 30 requires to push it through the water at 6 knots is 6 KW. In regen, the amount that the propeller can capture is proportionate to the size of the propeller, as a fraction of the size of the boat. So if 1 square foot of propeller, is 2 % of the cross sectional size of the boat, we get 2 % of 6 KW at 6 knots, about 120 watts, and not the 1 KW I was dreaming of.

Regen on a boat is affected by the slip of the propeller. Its not like a car where the wheel speed is proportionate to the car’s speed all of the time. The slip reduces the propeller rpm significantly. Slip occurs both in propulsion and in regen, so compared to a car, a propeller suffers from two forms of slip while regenerating.

Larger boats fair far better because of higher boat speeds. The amount of regen power that a propeller can produce is proportionate to the cube of the boat speed, so simply going from 6 knots to 7 knots can produce huge gains. Catamarans fair very well in this game and regen on a Cat can be considered a formidable source of power, as high as 10 KW!

For the smaller boats I consider regen to be a good source of house power, but not a source of propulsion power.

Regen can be further optimized by locating the propeller parallel to the hull at the most horizontal point. Regen is better on boats where the propeller is located in clear water and not in an aperture.

Regen usually starts at around 5 knots of boat speed and increases exponentially from there.

RANGE

Range was never much of an issue with diesel or gas boats. Most boats had a 50 to 200 mile range and most boats use their motors for 5 or 10 miles at a time. There was lots of range to go around. Range is not an issue with hybrid boats either. At lower speeds, range is greatly increased with the use of hybrid technology. Range is not an issue with electric boats that predominantly electric motor sail. Motor sailing range is far greater than any other form of propulsion range.
As a rough rule of thumb, when drive motor rpm is less than 2,000 rpm, a hybrid boat will have more range, and above 2,000 rpm a diesel boat will have more range. For each boat and system, this cutoff number will be different, but for all boats, hybrid range will be greater at low boat speeds and diesel range will be greater at higher boat speeds. Once again we have to ask how do we use our boats? When was the last time that you were using your engine at greater than 2,000 rpm and for how long? My guess is not very often and for not very long because the sound and vibration pollution gets excessive with diesels above 2,000 rpm - but once again that is different for every boat and every owner.

When range is an issue is when you are deciding whether or not you can re-power with an electric system without a generator and if your battery only range will be great enough for how you use your boat.

In the Battery Range vs. Boat speed graph, we see how speed affects range. The rough rule of thumb is for every knot you increase in boat speed, you halve your range. This graph is taken for a Catalina 30 with 22 KWH's of battery pack, in calm conditions with no wind and no waves. Range will increase when going down wind, and decrease when going up wind.

What is vitally important to understand is how battery chemistry affects range. Peukert’s exponent allows us to calculate how much we derate the battery capacity for load. This calculation must be applied to all batteries. Lead acid batteries are derated far more than Lithium Batteries are. (see section on Batteries)

4. DRIVELINE

ELECTRIC MOTORS

Electric motors convert electrical energy into rotational energy plus heat. The heat is created by the inefficiency of the motor. Consider our 92 % efficient, 10 KW Electroprop. 8 percent of the power consumed by that motor will be given off as heat-800 watts at full power. It is a motor’s ability to dissipate heat that partially determines the maximum power capability of the motor. Water cooling is the best way of dissipating heat. And the worlds largest heat sink is only a foot away!

*Heat created is closely related to motor current. Both should be monitored.*

Battery current to the controller is different from controller current to the motor. The gear ratio of the speed reducer changes the ratio between the battery currents and the motor currents. Increasing the ratio of the speed reducer reduces the motor currents for any particular motor rpm.
Magnets in the stator (stationary winding) move magnets in the rotor (the part of the motor which rotates). The magnetic fields alternate at a frequency proportional to the rpm of the motor and the number of poles of the motor.

Induction motors create the magnetic field in the rotor through passing a current by induction to the rotor. Permanent magnet motors rely on rare earth permanent magnets in the rotor. Permanent magnet motors are more efficient and smaller than induction motors because they don’t have to create and maintain the second electromagnet.

Torque is proportional to current and speed is proportional to voltage on a Permanent Magnet AC motor. Permanent magnet motors are directly proportional and have a current to torque coefficient and a voltage to rpm coefficient. Induction motors have some slip in the magnetic fields so the torque / current and speed / voltage ratios change. A motor that has no slip is said to be synchronous. Permanent Magnet Alternating Current and Brushless Direct Current motors are synchronous.

Stators can be positioned next to the rotor axially or radially. Axially arranged stators create an axial force on the rotor. Mounting a stator on either side of the rotor cancel out these axial forces for higher efficiency. Most high power permanent magnet motors have twin stators for this reason.

New motor technology is seeing efficiency claims as high as 98%. Most common AC permanent magnet motors have efficiencies between 88 and 94 %. Efficiency changes with load and rpm so an efficiency map is necessary for a complete understanding of any particular motor.

Motors need to be rated for their continuous output.

I define continuous operation as 1 hour operating time at rated output, with motor windings temperature not to exceed 100 C. Intermittent operation is any operation that does not stall the motor or exceed the allowable high motor temperature.

At very high temperatures the varnish on the winding wires starts to cure which you can smell on an open frame air cooled motor. Controllers monitor winding temperature and cut back as they approach a set temperature. Although the varnish on many motors is rated to 150 Celcius, they are often not cured enough to run at such a high temperature.

DIRECT DRIVE MOTORS

Direct drive motors are desirable for their almost silent operation.
Direct drive motors are three to four times larger and heavier than motors utilizing a power transmission product. For instance, the Mastervolt direct drive 10 KW Electric drive weighs 315 pounds, while the new 10 KW Electroprop weighs 55 pounds.

Direct drive electric motors are limited as to what propellers can be used. The propeller must not be too large for the motor’s maximum current capability.

Direct drive motors lack the ability of tuning the motor to the propeller with a change of gear ratio.

**POWER TRANSMISSION**

Marine power transmission products have three functions, speed reduction, thrust bearing and motor mount

Horsepower is torque (ft lbs) x rpm / 5252

1 H.P. = 746 watts so rewriting the equation we find that
Power in KW = Torque in ft lbs x rpm / 5252 / 746

Power developed is proportional to both torque and rpm.

Electric motors have similar torque over the entire rpm range, so to increase power output, rpm has to increase. This contrasts with the needs of a propeller. Propellers work most efficiently by utilizing high torque at low rpm.

Propellers convert rotational energy into thrust thus requiring the use of a thrust bearing.

The two ways of accomplishing speed reduction are with belts or gears.

BELT REDUCTION is accomplished by mounting a small pulley onto the motor and a larger pulley onto the drive shaft. Different ratios can be accomplished by changing the size of the pulleys. Two or more motors can be used to drive the same output pulley. Belt drives are relatively quiet. Belts need to be periodically inspected. The drive shaft requires a dedicated thrust bearing which needs to be inspected and lubricated regularly. Belt drives have to be tensioned to operate. Cogged belts require less tension than smooth belts. The tension is transferred to the motors bearings and the thrust bearing. Belt reduction efficiency is between 80 and 95 % depending on the type and make of the belt. Belt reduction efficiency does not take into account losses for the radial loads put on the motor or the thrust bearing, and does not include efficiency losses of the thrust bearing.

GEAR REDUCTION is accomplished by mounting an electric motor on a gearbox. There are several different types of gears that can be employed. The most common marine gearboxes employ helical or planetary gears. The motor has no radial loads placed on its bearings so longer bearing life is expected.

Gear reduction is close to maintenance free. Just check the oil annually and change the oil once every five years.

Helical gears are 97% efficient. There are additional losses of 1 to 2 % from the seals on the input and output shafts. The new 10 KW Electroprop gearbox is 96% efficient including losses for the seals and the thrust bearing.
The thrust bearing is located on the output shaft and lubricated by the gear oil and does not require inspection and greasing. Total gearbox efficiency includes the thrust bearing efficiency which changes with load. Typical gearbox efficiency is between 90 and 96% depending on the load.

**COUPLINGS:**

Couplings must be able to take force in both directions - both push in forward and pull in reverse.

Sleeve type couplings can come apart when in reverse and should not be used.

The coupling should be machined slightly larger than the propellers shaft, known as a slip fit, and then it can be easily serviced.

Two set screws should be tightened into recesses ground into the propeller shaft and tied together with binding wire.

The coupling on the gearbox side should include a center bolt into the middle of the output shaft of the gearbox, installed with a thread locking compound and a lockwasher to prevent rotation of the bolt caused by accelerating rotation of the propeller shaft.

**FLEXIBLE COUPLINGS:**

Use of a flexible coupling provides protection for the thrust bearing in the gearbox from the affects of misalignment.

A flexible coupling provides a means to accurately align the drivetrain. A flexible coupling provides flexibility in the drive train for any left over misalignment.

Flexible couplings are not advisable when using the Kiwi Prop and may be problematic with some feathering or folding propellers. Sympathetic vibration in the driveline can occur when there are two or more points of flexibility. This can lead to an enormous vibration in the driveline.
THRUST BEARING

Smaller gearboxes can utilize ball bearings to absorb thrust. Larger gearboxes utilize tapered roller bearings with opposing races. Thrust bearings in a gearbox are lubricated by the gear oil.

Externally mounted thrust bearings need to be lubricated periodically with grease.

PROPELLERS

Electric drives are capable of turning larger propellers with higher pitch and cupping. Utilization of these high efficiency propellers enable large system efficiency gains over propellers turned by fossil fuel engines. Electroprop propellers have a higher pitch than diameter, cupping, and a high blade area ratio for maximum efficiency.

Slip is the difference, as a percentage, between how far the boat moves and how far the propeller turns. How far the propeller turns is calculated by multiplying the pitch by the number of revolutions in any given time period. Decreasing the slip increases the efficiency. A large propeller turning slowly has less slip than a smaller propeller turning quickly.

We replaced Kapowai’s Atomic 4 gas engine with a 5.5 KW Electroprop. The 35 h.p. Atomic 4’s propeller turned at up to 3,000 rpm. Our 7 h.p. Electroprop turns at 700 rpm. The Electroprop propeller has more traction or bight on the water so is more efficient and more powerful than the Atomic 4. Things have come a long way in 75 years!

Excessive slip is like spinning tires on a car - most of the energy is wasted and only a small amount of energy is used to propel the car.
Most sailboats now use diesels and the propeller turns at 1250 rpm after a 2:1 reduction. The standard Catalina 30 comes with a 16 KW (21 h.p.) diesel motor. Our Electroprop achieves 6 knots using 6 KW (8 h.p.) Most of these gains come from the increased efficiency of the slow turning propeller.

Cupping is another way of increasing the efficiency of a propeller. The forward surface of the blade is longer than than the aft surface. This creates a low pressure in front of the propeller which adds to the propulsive force of the propeller. Cupped propellers have more power in forward than in reverse.

Braking force is set up on commissioning by adjusting the rpm in reverse. Too much reverse speed can cause cavitation, especially if the propeller is too close to the hull. Propellers are optimized for forward, so reverse speed should be set up lower. Most feathering propellers have the same thrust in forward as reverse due to the rotation of the blade.

Propellers should have adequate clearance from the hull which should be maximized. A minimum of fifteen percent of the propeller diameter is recommended.

The closer the propeller is to the hull, the more the boat will walk sideways in reverse. This is caused by the difference in water pressure above and below the blade, due to the proximity of the propeller to the hull.

**CAVITATION:**

Cavitation first appears in reverse while braking. When the propeller is starved for water it pulls dissolved gases out of the water and ignites them at temperatures as high as 700 degrees F. This can cause pitting of the propeller. It is also very noisy.

**MARINE GROWTH**

For peak propeller performance, check to see that the propeller is clean. If even the smallest marine organism has attached itself the propeller will have lackluster performance, vibrate and make noise while turning.
5. BATTERIES

SIZING THE BATTERY BANK

Maximizing the size of a battery is beneficial in terms of range and longevity. A larger battery bank doesn't have to work as hard as a smaller battery and will consequently have longer cycle life.

Minimizing the size of the battery decreases weight and cost.

I recommend a minimum of 1 kilowatt hour of battery capacity per kilowatt of motor power when using Lithium or 2nd Generation AGM batteries (TPPL) and 2 KWH’s of battery for each KW of Motor Power for AGM and GEL Batteries.

To find out the Kilowatt hour rating of your battery, multiply the amp hour capacity by the nominal voltage. For example, if you use four 4D batteries @ 200 amp hours per battery in series at 48 volts, you would multiply 200 x 48 to get 9.6 KWH’s.

When batteries are assembled in series, the voltage increases, and the amp hour stays the same. (Most modern diesel boats assemble the batteries in parallel and we are used to the voltage staying the same and the amp hour capacity being added together.)

The size of the battery required is ultimately determined by the range requirement of the vessel at speed. Increasing speed decreases range. As a rough rule of thumb, for each knot increase in speed, the power requirement doubles and the range halves.

To figure out how large a battery you require, you will need to know the power requirement of the vessel at the speed you need. Take the range requirement, divide by the speed to get the number of hours operation requirement, multiply by the power requirement at that speed in KW, to get the number of kilowatt hours used for that range at speed.

To avoid depleting a battery to less than 20% capacity, multiply your KW requirement by 1.25 to find out the kilowatt hour capacity of the battery bank you require.

All batteries must be derated for loads using a formula developed by Peukert, known as Peukert’s exponent. For AGM and GEL, I recommend batteries at least twice as large in amp hours as the loads they are servicing to minimize this deration. The larger the battery is for a given load, the less it is derated by Peukert’s exponent. Add another 15% capacity for AGM or GEL Batteries an extra 2 % for Lithium to account for Peukert’s exponent.
Divide the Kilowatt hour rating of the battery bank by the nominal voltage of the battery bank (ie. 48 volts) to get the amp hour capacity of the batteries.

BATTERY CHEMISTRIES

The 5 different types of battery chemistry being commonly used on boats today are flooded lead acid, Gel, Absorbed Glass Matt (AGM), Advanced AGM (TPPL) and Lithium Iron Phosphate.

LEAD ACID

AGM, GEL, and FLOODED batteries all use the same basic Lead Acid Chemistry - Lead plates with a Hydrogen Sulphate Electrolyte. The major differences between these chemistries are the viscosity of the electrolyte and the thickness of the plates.

All Lead Acid Batteries can off-gas and all Lead Acid Batteries should be ventilated to prevent the buildup of explosive hydrogen gas. Off gassing increases throughout a batteries life. A sealed battery has a vent that release gases at a certain pressure, otherwise they are recombined into the electrolyte. Sealed Batteries are more likely to vent at the very end of their life, where they should be monitored most closely for this condition.

FLOODED LEAD ACID

Due to the high currents involved, Flooded Lead Acid batteries are not recommended. (I feel so strongly about this, that if FLA batteries are used with an Electroprop, it voids the warranty.) They have to be derated to 47 percent at a 1 C load which is borderline damaging to the battery. FLA batteries emit hydrogen gas while charging and discharging. The slightest spark from a loose connection can cause these batteries to explode. I have personally witnessed a battery exploding and have repaired 10 exploded batteries in 10 years working as a marine electrician in the Santa Barbara
Harbor. This is a very real danger and on electric boats even more so because of the loads involved. Gassing off increases as the battery ages and at end of a battery’s life, gassing off can be constant while charging.

Flooded lead acid battery terminals build up acidic corrosion from the vaporized electrolyte depositing on the terminals. This leads to a bad connection with possible thermal condition.

Flooded lead acid batteries can dry out and if charged in that state will create a thermal condition.

*Avoid the use of flooded lead acid batteries on an electric boat and be very wary of them on any other boat.*

![Battery Comparison Chart](chart.png)
Peukert’s Exponent: Derating for load by Eric Dysart

When you purchase a flooded lead acid, AGM or Gel battery for a high current application you do not get what you bargained for. Lead acid battery capacity is derated for high currents.

For Flooded Lead Acid (FLA), the derating is highest at 1.25
At 1.0C, the delivered capacity is 47% of 20hr rated capacity. (the typical maximum listed by manufacturers) 1C will damage an FLA battery.
At 0.5C, the capacity is 56% of 20hr rating.
At 0.25C the capacity is 65% of 20hr rating.
At 0.1C the capacity is 84% of the 20hr rating.

For AGM, I'll use a 1.1 PE, typical for Odyssey and other quality AGM.
At 1.0C, the capacity is 74.1% of 20hr rating
At 0.5C, the capacity is 79.4% of 20hr rating
At 0.25C, the capacity is 85.1% of 20hr rating
At 0.1C, the capacity is 93.3% of 20hr rating

Lithium batteries are derated very little for high load applications.
Peukert’s constant is 1.03 PE for LiFePO4,
At 1.0C, the capacity is 91.4% of 20hr rating
At 0.5C, the capacity is 93.3% of 20hr rating
At 0.25C, the capacity is 95.3% of 20hr rating
At 0.1C, the capacity is 97.9% of 20hr rating

You get what you bargained for with Lithium Batteries!

"My Lithium batteries are now three years old on my Electroprop powered Cheoy Lee. They have worked flawlessly. I have a small generator on board just in case, but have never used it - Lithium is simply amazing battery technology."

Eric Dysart,

Cheoy Lee Electroprop conversion
SEALED LEAD ACID

GEL and AGM batteries are the most affordable and consequently the most common battery technology used on electric boats. GEL batteries are rated up to 2,000 cycles at an 80% depth of discharge. AGM batteries are rated at 400 cycles at an 80% d.o.d. AGM batteries are capable of higher currents than GEL batteries.

We recommend AGM and GEL Batteries to be sized at twice the amp hour capacity of the highest current.

Sealed Lead Acid batteries are about 75% efficient meaning that only 75% of the energy used to charge the batteries is actually stored by the batteries.

Sealed lead acid batteries can be charged at slow charging rates like solar or with smaller chargers, providing that the charger is large enough to be able to take the battery through a complete charging cycle.

Sealed Lead Acid batteries should be custom ordered from the battery manufacturer to make sure they are both the freshest and that they are from the same manufacturing lot with the same date stamp. This helps the batteries stay at the same voltage when charged in series.

The batteries need to be monitored and protected from over-charging and under-charging. These batteries are the most forgiving to accidental deep discharges, though it does shorten a battery’s life. Contrary to popular belief, these batteries should not be held in float for extended periods of time, for it shortens battery life. The best charging profile includes a forth stage that allows the battery to fall out of float, drop to 12.5 to 12.7 volts, and then restart the charging algorithm.

The Electric Boat
Sealed Lead Acid batteries charged in series need to be monitored for voltage and balanced as necessary. If one battery starts failing in a string, it looses its capacity and becomes spongy. When a charging source is present, the weak battery will increase in voltage faster than the other batteries. When the battery string is under load, the weak battery will have a lower voltage than the others in the string.

When the string of batteries is being charged together, and one battery has a voltage higher than all the rest, then this battery will overcharge and all the rest will be undercharged and the problem will keep getting worse until you can have a thermal. Sealed Lead Acid batteries should be charged individually from time to time to keep their voltages similar.

Sealed Lead Acid batteries should not be held in parallel unattended especially near the end of their life. An internal short in one battery will be driven by the other battery in parallel and can cause a thermal, fire or explosion. Even though a sealed lead acid battery is sealed, there are pressure relief valves on every cell and these batteries will also gas off if overcharged, and consequently should be vented. Gassing off increases near the end of battery’s life. Explosive hydrogen gas is emitted during a gassing off event.

Sealed Lead Acid Batteries should be stored fully charged and recharged every 3 months.

THiN PLATE PURE LEAD - TPPL

Thin Plate Pure Lead (TPPL) batteries are also known as Advanced AGM or AGM 2. They are made of many thinner smaller plates and have a lower internal resistance than traditional AGM, allowing for higher currents.

TPPL batteries can be sized at the same amp hour capacity as the highest load.

TPPL batteries are 85% efficient.

TPPL batteries are high current batteries and need high current charging. Typically a 200 amp hour TPPL battery needs at least a 40 amp charge to stay healthy. TPPL batteries should be charged at 1 amp minimum for each 5 amp-hours, for maximum life.

Higher capacity TPPL battery banks may have difficulty getting a fast enough charge from limited shore power.

TPPL batteries are not suitable for boats charged primarily with solar power because of their need for a high current charge. A work around to the need for higher current charging is to extend the absorption time period to as much as 8 hours if lower currents are used, but this is a work around and will still result in reduced battery life.
My favorite TPPL battery is the Odyssey PC 1800 rack mount battery. It holds an impressive 218 amp hours at 12 volts nominal. The PC 1800 has a high energy density. The rack mount shape allows a lot of energy to be stored in a small area.

TPPL batteries are sealed but still have pressure relief valves and can emit explosive hydrogen gas when over charged or at the end of their life.

TPPL batteries are intolerant to accidental deep discharges which will ruin the battery. House loads should have automatic low voltage shutoff to protect the battery. Batteries returned with low voltages are not covered by warranty.

When using solid busbars it is important that the battery cannot move around, or the terminal can crack the battery.

TPPL batteries should be stored fully charged and recharged every three months.

LITHIUM IRON PHOSPHATE (LiPo4)

Here’s a few interesting facts about Lithium, Iron and Phosphorous.

Lithium is the third lightest element. Lithium has one electron in its outer valence shell, making it electrically active. Lithium is an alkali metal.

Iron was forged in the supernova’s core that created the Milky Way. Iron makes up the majority of the core of the earth. Iron is capable of storing, transporting and changing energy by converting energy to magnetic fields.

Phosphate is made up of Phosphorous and Oxygen. Phosphorous is present in the molecule ATP, which all living cells use for energy. Alone it glows in the dark, a phenomenon we are familiar with in algae blooms.

Oxygen is already famous. Its what we need to live, and what plants produce which makes life possible. It wasn’t until massive algae blooms occurred on earth millions of years ago that provided the oxygen for people and animals to breathe.

Combined these elements make an exceptionally compact, lightweight, powerful battery. Lithium Iron Phosphate (LiPo4) was invented in the United States. Over the last 10 years this technology has been widely adopted by electric car enthusiasts. LiPo4 batteries have a great safety record and can last 2,000 cycles at an 80% depth of discharge.
The marine industry primarily uses the Prismatic Lithium Iron Phosphate batteries because of the inherent safety of their design. Prismatic means they are enclosed in a rigid plastic container. Lithium Iron Phosphate batteries can come in cell sizes as high as 1,000 amp hours. Lithium Iron Phosphate batteries come in prismatic or pouch configuration. The marine industry is using Prismatic cells due to their ease of installation and safety concerns with the pouch cells.

LiPo4 Safety

At the time of this writing we could find only one failure of a Lithium Iron Phosphate Battery causing fire on a boat. The cause of the fire was overcharging with an unregulated charger. There are thousands of failures of lead acid battery technology, many of them catching on fire or exploding. Lithium Iron Phosphate is the safest battery technology available for the marine industry and are increasingly being used in ships, tugs, ferries and pleasure boats.

Lithium Thermals

Lithium Batteries are less likely to have thermal conditions arise than lead acid batteries because of their high efficiency. Even under loads of 4C or more, the batteries stay relatively cool. Lead acid batteries by contrast get very hot under high load conditions.

There are four ways a Lithium Iron Phosphate battery can fail:

- after a complete discharge, the cell inverts, and charges up with reverse polarity after which all the energy put into the battery is dissipated as heat.
- overcharging in which a thermal can be created. Excess energy gets burned away as heat, which can create a thermal in a neighboring cell.
- discharging at too high a rate of discharge thus creating a thermal at or around the battery. Lithium batteries can sustain a complete short from dropping a wrench across the terminals. The wrench will glow red yet the battery will still be functional. We are more concerned about surrounding wiring than the batteries themselves.
- charging at very low temperatures.

A cell experiencing a thermal can contaminate an adjacent cell.

If a thermal gets hot enough, the battery can catch fire. If the fire reaches the ignition temperature of the electrolyte, then the fire has be starved of oxygen and cooled before the fire is out. All commercially available Lithium Batteries have flammable electrolyte.
Lithium Battery Management Systems

Battery Management Systems (BMS) prevent thermal conditions from occurring plus extend the battery life by balancing the cells. The BMS allows charging in series, while listening to the conditions of each cell. The BMS prevents individual cells from over-charged or over-discharged conditions.

The Battery Management System is a small computer hooked up to sensors that measure temperature and voltage on every cell. There are two different wiring configurations available - distributed or centralized. On a distributed system, smart cell boards are mounted on each individual cell and connected together into a local area network which is then optically isolated at the battery to eliminate voltage on the wires. Distributed systems have less wires and provide a simpler looking system with less spaghetti. On a centralized system, each battery has a temperature sensor and a fused wire going to the BMS. Both systems work well and which BMS to choose should be based on functionality and user friendliness.

All Battery Management Systems function in the same way. As a cell approaches its top voltage a resistor is triggered to burn off excess current from that cell. At the same time, the charging source is either reduced to the value of the current that the resistor can burn off, or the charging source is disconnected from the load to prevent the cell from going over voltage. CAN controlled chargers are superior because of their ability to continue charging at the lower current and thus balance the battery. Other chargers are controlled by either disconnecting the AC feeding a shorepower charger, disconnecting the DC coming from a solar or wind source, or disconnecting the field wire going to an alternator.

Work is being done on shunting excess current from one cell to another. Shunting from cell to cell is the next evolution of BMS systems.
Lithium Wiring

Lithium Iron Phosphate batteries have high energy density that can be delivered quickly. Wiring on LiPO4 systems has to be to the highest standard. They hold three times more energy by weight and have 10 x more current potential. Look after them, and they will look after you. Have the highest respect for these batteries when designing and installing your system. Use circuit protection exactly to code with no exceptions.

Lithium Iron Phosphate Performance

Lithium Iron Phosphate batteries are 98 % efficient - almost all the energy coming from the charging sources gets captured by the battery. Lithium Batteries can be charged at any charge rate. This makes Lithium the choice for solar installations.

Lithium Iron Phosphate Batteries charge much faster than lead acid batteries. If a battery is only cycling the top 20% of energy, a lithium battery can charge up in as little as 4 minutes whereas a lead acid battery will take 4 hours to be fully charged. That is sixty times faster. In applications that are cycling 80% of the energy, a Lithium Battery can charge up in 20 minutes while a lead acid battery will take a minimum of 4 hours - 12 times faster. The limitation for Lithium Charging is the charging source, whereas the limitation for a lead acid battery is the battery’s acceptance rate. This makes Lithium Iron Phosphate the ideal choice for hybrid applications utilizing a DC generator.

Lithium Iron Phosphate batteries have an almost negligible Peukert’s exponent so do not need to be derated much under load. Under a 1 C load, they retain 98 % of their energy - see insert on page 23.

In some performance applications, Lithium Iron Phosphate batteries can replace 3 or 4 x the amp hour ratings of Lead Acid batteries and consequently be as little as one tenth of the weight aboard.

Lithium Iron Phosphate batteries have higher energy densities. Lithium Iron Phosphate batteries are lighter and smaller per amp hour capacity so more energy can be stored in the same amount of space as lead acid. With electric boats this means that the batteries can be mounted with less concern for boat trim than lead acid batteries. This improves overall performance of the boat.

On Kapowai, I have 1200 lbs of AGM batteries which will someday be replaced with 400 lbs of Lithium with no loss in capacity.

Lithium Iron Phosphate batteries experience less voltage droop than lead acid batteries. This allows installation at a lower voltage than a comparable lead acid battery installation.
Lithium Iron Phosphate Construction

The sides of a Lithium Iron Phosphate Battery can swell over time if not contained. The cells should be mounted in a structure that prevents swelling from occurring.

Since the BMS functions by measuring voltage across the cell, it is vitally important to get an accurate voltage reading. After installing a cell board on a cell, it is important to check the voltage reading to make sure the cell board is accurate. Additionally, busbars should be tinned to prevent corrosion which will alter the voltage measurement.

The tinned busbars should be mounted with alloy bolts and washers to provide another current path. Stainless is not a good conductor and can gall the anode and cathode materials. Military Grade Alloy Bolts should be installed with conductive grease and lock washers. Cell boards should be installed with conductive grease. It is important that the conductive grease does not spill on the cell board, which would damage the cell board. Thread locker should not be used on the battery bolts.

**Each battery should be fused.** Lithium Batteries have a short circuit current potential of 10 x the amp hour rating of the battery. A 400 amp hour battery therefore has a short circuit current potential of 4,000 amps. Shorting a 12 volt battery, would yield an astounding 48 KW. Fusing at 200 amps knocks this down to a reasonable 2.4 KW.

For ultimate protection from a battery fire, each battery should be contained in a sealed metal box to prevent fire by starving the battery from oxygen. Small drain holes need to be provided to remove any moisture buildup from condensation.

The Dreamliner battery failure was probably caused by charging at sub freezing temperatures, perhaps when the battery was
at altitude. This caused dendritic growth inside the battery. When the Dreamliner fire occurred, the temperature of the battery exceeded the ignition point of the electrolyte which made the fire very difficult to extinguish. By containing these batteries in a metal case, the battery is deprived of oxygen, which makes any fire self-extinguishing.

It is important to note that the Dreamliner was using a more exotic Lithium formulation for higher power to weight than Lithium Iron Phosphate. Lithium Iron Phosphate is known as the safest Lithium chemistry. Lithium Iron Phosphate is the choice of NASA for use in space suits.

**Lithium Iron Phosphate Operation**

When stored for long periods of time, the batteries should be discharged by 25 to 50%.

Lithium Iron Phosphate batteries are best at mid charge for long periods of time. Chargers should be set up to re-bulk at the nominal voltage of the battery so the battery is living a majority of its life at mid charge. Prior to making a long voyage on a Lithium battery that is set up to rebulk at nominal, be sure the batteries get a full charge at the dock before leaving. This may be accomplished by turning the shorepower or the BMS off then on, which reboots the charger and puts the charger into bulk mode. Allow the necessary time to get a full charge.

Charging should not be attempted below about 36 degrees Fahrenheit - a couple degrees above freezing.

Lithium Iron Phosphate Batteries should not be discharged lower or charged higher than manufacturers specifications. This is typically between 3 and 3.6 volts per cell.

**SOLAR**

**Voltage**

Panel voltage must be higher than battery voltage unless a boosting charge controller is employed. Panel Voltage should be between 20 and 30 percent higher than battery voltage, depending on the type of charge controller used. Check the panel for maximum power voltage. This voltage should be higher than the batteries absorption voltage (lead acid) or the maximum voltage of a Lithium Battery. When using MPPT charge controller, the Maximum Power voltage should be 10 to 20 percent higher than the battery absorption voltage (lead acid) or maximum voltage of a Lithium Battery to give the MPPT circuitry room to function.
Orientation

The solar panel installed on Kapowai can change angle and bearing to focus on the sun to increase output. This is most noticeable at dawn and dusk where output can increase tenfold. One evening when the panel was horizontal I noticed the output was down to 20 watts. This increased to 200 watts when I focused on the sun.

The solar panel has to revolve around two axis to be able to focus on the sun. One axis of operation, a hinge, is still a big benefit to the overall output of the panel.

Shading

Shading decreases output of a solar panel and is an issue on a sailboat. The panels are subject to shading from the mast and rigging. Shading can be eliminated by changing the orientation of the sailboat. To a lesser extent shading can be eliminated or minimized by moving the panel. Find the best orientation of the sailboat when choosing your anchorage to maximize solar energy.

The effects of shading can be decreased by wiring the panels in parallel instead of series. This can only be done if the voltage is high enough to charge the battery bank. Voltage boosting charge controllers can be employed if the voltage is not high enough.

Charge Controllers

Maximum Power Point Tracking (MPPT) Charge controllers allow the panel voltage to operate at a higher voltage than the battery. Solar Panels are constant current devices that produce the same amount of current whether operating at a low voltage or at a high voltage. Power in watts is voltage x current, so allowing the panel to operate at a higher voltage produces more power. An MPPT Charge Controller constantly monitors the power equation to choose the voltage that produces the most power. The panel
can’t operate at the open circuit voltage because it would not have a load on it. Electricity always flows from high voltage to low voltage hence the charge controller is operating at slightly lower voltage than the panel. Most MPPT charge controllers work in Buck Mode, that is the panel voltage is higher than the battery voltage. The optimum voltage for the panel voltage for Bucking Charge controllers is about 20 percent higher than the battery voltage.

Shunt style Charge Controllers hook up the battery directly to the solar panel and don’t let the solar panel voltage float above battery voltage. Shunt style charge controllers produce about 25% less energy than MPPT charge controllers. Shunt style regulators cycle on and off many times as the battery becomes close to full and do not benefit from the taper charge capability of MPPT Charge Controllers.

**Solar Poles**

Large arrays mounted on solar poles produce the highest output. Windage is the major concern. The pole must be able to withstand the wind forces so should be braced above the base. A 100 pound wind load at the top of a pole is a 1,000 pound side load 1 foot above the base.

Windage can be reduced by horizontal orientation of the panel.

Panels can be folded together to reduce wind loading.

Solar poles can be operated manually, by joystick or automatically. Automatic operation can be done by looking for increasing current as the pole turns and then stopping at that point, or by sophisticated computer programs that know where the sun is.

On Kapowai we are using a joystick with great success. We have plans for solar tracking using the increasing current method. I plan to develop horizontal tracking as well for minimizing windage.

**Solar Stanchions**

The most common method of mounting solar panels is on the stanchions. If the panels are wired in series to increase the voltage, they are going to only be as effective as the highest output panel.
DC GENERATORS:

HYBRID ELECTRIC BOATS EMPLOY DC GENERATORS WHICH ARE FAR MORE EFFICIENT THAN THEIR AC COUNTERPARTS OR DIESEL DRIVEN ALTERNATORS.

DC generators with a Battery Pack run a fraction of the time of an AC generator when used for house loads. The DC generator runs only long enough to recharge the batteries, then shuts down, while many AC generators run 24 hours a day.

AC Generators are sized for the maximum starting current on the boat. Typically a starting current of a motor can be twice the operating current. Most AC generators run unloaded most of the time.

DC Generators require less maintenance than AC generators because they are simpler and run at optimum load all the time which is easier on the diesel.

DC generators with inverters are far superior than AC generators for providing clean and reliable power because the power comes from an inverter from a stable DC power source. There are no spikes or brown outs when starting or stopping. A hybrid’s DC generator runs a fraction of the time of a traditional diesel which utilizes the diesel’s alternator for house loads. A 30 h.p. diesel will commonly employ a 100 amp alternator, which utilizes about 5 h.p. or 16% of the engines power while charging at anchorage. An alternator’s efficiency is about 50%. Total system efficiency of an alternator is thus only 8% while recharging batteries at anchor. In comparison, a DC genset has up to 40% efficiency.

A DC generator burns one fifth of the fuel while charging than an alternator powered by a diesel engine! That is one fifth of the pollution for you and your neighbors on anchor to breathe.... and one fifth of the diesel runtime.
6. ELECTRIC BOAT WIRING

Wiring on an electric boat should be done to a higher standard than traditional diesel wiring. The systems are more complex with a greater number of circuits operating at higher voltages and currents. Electric boat systems need to work flawlessly over time so there is no room for error on the installation.

The most noticeable feature of an electric boat is the large, higher voltage battery. The large battery serves both the house and propulsion loads of the boat. Having a high energy house battery has many advantages, the most notable being the extended duty cycle at anchorage.

All batteries, regardless if they are paralleled or in series, should be monitored for temperature and voltage and, if possible, equipped with audible and visual alarms.

Dissimilar voltages in a string should be corrected. (A String of Batteries means several batteries connected in Series) A string of batteries is only as good as its weakest cell. Charging at the cell level is best, followed next by charging at the battery level.

No batteries should be left unattended in parallel without automatic disconnect in the event of a battery failure. This is to prevent the good battery driving a short in the bad battery which can lead to a thermal and possible fire. Lead acid batteries at the end of their life are particularly susceptible to this fault condition.

It is vitally important for an owner of an electric boat to know his batteries and how they work in both the charging and discharging cycles.

Properly installed and maintained batteries last a long time. Conversely, a sloppy installation will cause premature failure. We have a saying “Batteries don’t die, they are killed”

All batteries should be fastened to a boat so they cannot move - they should be part of the boat. If the boat turns turtle (upside down), the batteries should not move at all. Mount your batteries firmly as if you were attaching them to the ceiling, not the floor.

All wire connections are fused at the battery. All connections are torqued down to manufacturers specifications. Beware of lead connectors as they fail over time.

It is better to use batteries with lug connections and not posts. This eliminates a complete connection and point of potential failure. If you do use posts, choose a high quality, zinc plated bronze battery clamp and avoid the lead clamps as they fail over time.
A thin covering of grease, or electrical protection spray on the terminal will prevent corrosion. Try to prevent the grease, which is dielectric (non-conducting), from creeping into the current carrying joint.

Of primary concern for all battery chemistries is detecting and preventing thermal conditions which can result in explosion and fire. This applies to all boats and is most prevalent in lead acid battery technology without control systems.

*Cells* can be permanently paralleled. Batteries consist of one or more cells in series. If batteries are installed in parallel, they should be wired through diodes or have a sufficient battery management system that can automatically separate them in the event of a thermal fault.

*It's Best to Look after your Batteries so they can Look after You.*

Batteries should not be left unattended in parallel. Diodes should be used when combining the second battery in parallel. One battery needs to be hooked up directly to the controller. If a diode is between the controller and the battery, then the system cannot regenerate, and the capacitors and mofsets inside the controller can rise in voltage and then fail. There is a half volt drop across a diode, so under load, the main battery bank will be half a volt higher than the second battery. On the other hand, charging sources can be isolated by diodes on both batteries. The lower main battery will charge up until it has an equal voltage to the secondary battery, after which both batteries will start charging at the same rate.

Each battery should be independently monitored for temperature. All batteries should be monitored for voltage.

Battery Positive and Negative should float above ground. Batteries over 50 volts should be monitored for ground faults by checking the insulation value between the ground plane and both the positive and negative of the battery. Battery positive and negative should be located in the same sheath or sleeve to prevent electromagnetic interference. Compasses should be located far away from any loop of wire.

In the event that there are two strings of batteries being held in parallel without diode isolation, then switching should be rated for the highest current sustained when combining a full battery with an empty battery. Occasionally resting voltages of the two strings should be observed when the batteries are uncombined. Combining dissimilar voltages can be accomplished by placing a load on the high battery or a charge on the low battery until both batteries are at the same voltage. The batteries can then be combined and the load or charge removed. In any event, whenever there are batteries in parallel, the batteries should be monitored, (and even more so at or near the end of their projected lifespan.) *Lead Acid Batteries should not be held in parallel and left unattended, especially when there is a charging source present. If there is a cell short on one of the batteries, the other battery will drive that short up to temperatures which can cause explosion or fire.*
House loads get their power through DC to DC converters. A good idea is to add a voltage sensitive relay to the DC to DC converter that shuts the load off in the event of a low battery. On Lithium Systems the BMS looks after under voltage load switching.

All shipboard metals should be tied together in a ship’s ground plane and tied to seawater potential at a dynaplate or propeller shaft. Metal through hulls should be avoided because in the event of corrosion the boat can sink. There is risk to grounding on the propeller shaft because if electricity starts to leak to ground through the propeller, then the propeller can corrode. A dynaplate is the best solution. On more complicated systems, two dynaplates are recommended - one for all shipboard metals and one for the electronics system. The electronics dynaplate can be further electrically cleaned by the use of a filter.

All electric boats should have an isolation transformer if shorepower AC is used on the boat.

A battery charger qualifies as an isolation transformer if there is no other AC used on the boat, and the charger is in a sealed, electrically isolated compartment and the main shorepower breaker has a non conductive switch mounted on a non conductive panel.

All electric boats should have an Equipment Leakage Circuit Interrupter Breaker (ELCI) on shorepower protecting the entire boat.

Loads operating in excess of 100 volts should simultaneously switch both the positive and negative of any load with one double pole breaker. Loads operating under 100 volts can switch only the positive in an isolated circuit panel.

All wiring should be clearly labelled. All wires on busbars should be clearly labelled. Negative wires on a busbar are just as important to label as positive breakers. Without labeling troubleshooting can be laborious.

All troubleshooting should be considered to be done at sea, with high winds and high waves and the boat bouncing around like a cork - the worst possible conditions. Imagine trying to fix something in these conditions and you will quickly see why labeling makes a huge difference!
I recommend a circuit breaker box to consolidate all wiring into a small highly organized area. This eliminates an electrical mess which is hard to work on and hard to troubleshoot.

There should be no bare current carrying metal showing. All conductors should be insulated and preferably double insulated with split loom. Be creative with the split loom. Large split loom can be opened up and zip tied to completely cover the end of any cable or connection or battery terminal.

All wiring should be fused at the battery or anywhere the wire size decreases in size.

Every connection should have adequate surface area for conducting current.

All charging sources should be self regulated. Charging sources for Lithium Batteries should be controlled by the BMS or hooked through a voltage sensitive relay.

Intelligent switching of charging sources by first reducing current should be employed wherever possible - ie. disrupting the field wire of an alternator prior to disconnecting the battery, or shutting the AC off to the charger instead of the DC.

All components should be rated for continuous duty with internal temperatures not exceeding 100 C. Components that fail their continuous duty rating should be derated and marked as such.

All electric motors should have thermistors communicating with their controllers and thermal cutbacks programmed into the controller.

All Electric Propulsion Drives should have a display which monitors motor voltage, current and temperature, battery voltage and current, and controller temperature.

All Electric Boats should employ Smartplug Shorepower cords. Smartplug systems are more capable of handling the high continuous loads experienced while charging a large battery bank. These systems are completely sealed and have a better connection with less chance of thermal condition arising from high continuous loads while charging.
APPENDIX 1: 100 REASONS TO OWN AN ELECTRIC BOAT

Electric boats have been in existence for over 100 years. At the turn of the 20th century, there were more electric runabouts than gasoline or diesel. All submarines are hybrid electric boats.

In the last 20 years there has been a resurgence of electric boats, mostly by hobbyists, though several notable manufacturers offer electric options. Advancements in battery, motor and controller technology have made electric boats a viable option for many sailors.

There are many different options available to power an electric boat with. It is important that sailors understand the options available, the costs, and the limitations of each different system. A battery powered sailboat is a day sailor. Solar sailboats are capable of extensive cruising in sunny areas. Most lower latitude areas have enough sun to sustain a solar sailboat. It is really quite amazing to own a solar sailboat. They are always ready to go. Kapowai hasn’t been plugged in or had any maintenance to her energy systems in over 3 years. From a practical point of view, she has become a perpetual motion machine.

The ultimate sailboat is powered by a diesel electric propulsion system. Minimizing engine run time results in more enjoyment for the passengers and crew while providing fuel savings and longer range.

The two main reasons why a person would choose a traditional diesel over an electric boat are lower cost and range under full power. Diesel boats operating at peak power, with very minimal house loads have higher efficiency and range than an electric or hybrid boat.

The ability of an electric motor to produce small amounts of power, much like a sail does, make electric boats better sailboats by providing a noise free motor sailing experience.

Presented here are over 100 reasons why a boat owner would choose electric power over diesel. In the end, it is your budget, and how you intend to use your boat, that determines your choice of propulsion.

ELECTRIC BOATS ARE MORE COMFORTABLE

1) Solar Electric boats have no smell of fuel or exhaust.
2) There is less incidence of sea sickness on an electric boat. Diesel fumes and exhaust contribute to seasickness on diesel powered boats. Hybrid boats can choose when to run the diesel to minimize exposure to exhaust fumes.

3) Batteries can be used for large house loads for extended periods of time before recharging.

ELECTRIC BOATS ARE FUN TO SAIL

1) Keeping an eye on your energy, how it is regenerating or depleting, what your electric only range is, focusing your solar panels at the sun, monitoring power consumption and its effect on motor-sailing - all great fun and intellectually stimulating.

2) Owning an electric boat is a cultural shift in sailing. It is dramatically different and a far nicer experience on the water.

3) An electric boat is more in line with the spirit of sailing ----using natural energy to propel your boat.

4) Small amounts of electric power can act like a mizzen sail. The sail-like qualities enhance the boats sailing attributes by creating apparent wind.

5) Because an electric boat can generate apparent wind, it is rarely, if ever, becalmed.

ELECTRIC BOATS REDUCE POLLUTION

1) Electric boats pollute less and reduce global warming.

2) There is little to no pollution in your local environment.

3) There is no smell of diesel fuel, or of diesel exhaust, on an all-electric boat.

4) There is no grundgy, smelly stuff under the motor of an electric boat.

5) There is no oil in the bilge water.

6) An electric boat smells pure and clean.

7) Electric boats don't vibrate.
8) Electric boats are very quiet with far less noise pollution

ELECTRIC BOATS REQUIRE MINIMAL MAINTENANCE

1) When you are finished building your boat, you are done. There is almost no maintenance after the original purchase.

2) Packing glands, cutlass bearings and engine mounts last longer because electric motors don't shake around.

3) You don't have to run your boat to keep the engine in good shape. An electric boat can sit unused without damaging the motor.

5) Brushless motors require no maintenance.

6) You don't have ongoing, large maintenance costs!

ELECTRIC BOATS ARE VERY RELIABLE

1) The simplicity of an electric drive results in higher reliability. Simply turn the electric motor on and it goes.

2) An electric motor has less things to go wrong with it than a diesel motor does.

3) Temperature sensors in the motor and controller communicate with the controller preventing overheating caused by high ambient temperatures or obstruction of the propeller.
ELECTRIC BOATS ARE SAFER

1) Higher reliability increases safety.
2) Better boat handling increases safety.
3) Higher Acceleration and Deceleration increases safety.
4) Reduction or complete elimination of fossil fuels increases safety.
5) Elimination of sticky shifter and throttle cables increases safety.
6) Electric boats equipped with solar panels never completely run out of energy.
7) Electric boats using Lithium Battery Management Systems monitor battery voltage and temperature on every cell which reduces the possibility of a battery thermal.

ELECTRIC BOATS ARE EASIER TO OPERATE

1) You don't have to remember to turn on through hulls before running your motor.
2) You don't have to change or check the oil before running the motor. You don't have to change the oil filter.
3) You don't have to clean or change the air filter.
4) You don't have to check for water in the fuel.
5) You don't have to warm up the engine.
6) Solar sailors don't have to go to the fuel dock.
7) Solar Sailors don't worry about spilling diesel or gas in the marina and getting a fine.
8) Solar Sailors don't have to worry about managing fossil fuels.
9) You don't have to deal with sludge or microbes growing in your diesel fuel tank and polishing your fuel.
10) You don't have to service the starter, alternator, water pump, belts, injection pump, thermostat, coolant, clutch or transmission on an all-electric sailboat.
ELECTRIC BOATS HAVE ENHANCED SAILING CHARACTERISTICS

1) You don't have to wait for wind. Electric motoring around the harbor is just as pleasant as sailing your boat. In fact, you will enjoy motoring around in calm conditions like never before. **You can take an electric boat out in any weather. Mornings, afternoons and evenings are all good times to go electric boating.**

2) Electric motors complement your sail plan. When motor sailing in low wind conditions, an electric motor acts more like a sail than a motor, by providing just enough energy to the boat to negate the propeller drag.

3) Small amounts of energy on the propeller can add enormously to the performance of a sailboat in light air conditions. Small amounts of power on the propeller can take the luff out of your sail when sailing upwind.

4) Electric motors create apparent wind while sailing upwind or on a broad reach. A one knot breeze can be transformed into a 3 knot breeze and you become a happy sailor!

5) The magic of an electric boat is in low power to the propeller - a diesel cannot idle less than 600 rpm and through a 2:1 gearbox cannot turn the prop less than 300 rpm. An electric boat can turn a propeller at less than 100 rpm allowing amazing motorsailing capabilities at very low power levels for long periods of time.

7) Power tacking. You won't get stuck in irons when you have power on the propeller, without having to start a diesel engine.

8) Raising sails. You can keep pointing into the wind to raise and lower your sails easily, without having to start a diesel engine.

9) Battery weight mounted low and central on a monohull increases the stability and seaworthiness of the vessel, giving better directional stability and less rocking in the trough.
ELECTRIC BOATS HAVE ENHANCED MOTORING CHARACTERISTICS

1) You can hear the environment that you are sailing through when electric motoring --- birds, water lapping on the hull, fish or whales jumping. In foggy conditions this can be a huge benefit.

2) No need to shout at your crew while motoring.

3) No need to warm up the engine --- instant power all of the time.

4) No need to shift into and out of reverse and forward, and no grinding gears. Electric motors turn backwards electrically eliminating the need for separate forward and reverse gears.

5) Electric boats accelerate faster than diesel boats. As a boat starts moving through the water it becomes easier to turn the propeller. Electric motors and gear ratios are chosen for maximum efficiency at hull speed. However, electric motors have very high intermittent ratings, often twice as high or more than their continuous ratings. These power attributes are available for acceleration when the propeller demands more. Electric motors are better suited for the load of a propeller than a diesel is.

6) Improved control for docking. No worries about shifting into reverse on time. Variable, wide range propeller rpm allows for precise control coming into your slip. There is no need to shift into and out of gears multiple times to effect docking your boat.

7) High torque at low rpm allows electric motors to turn larger propellers, known for higher efficiency.

8) Electric boats outfitted with alternative charging sources (solar, wind, hydro) never completely run out of energy as may a diesel boat.

9) Electric boats have an unlimited range when equipped with alternate energy sources while diesel boats have a finite range.

10) Masters of electric boats do not have to chart a course that includes stopping at a diesel dock. Less reliance on diesel allows for greater flexibility in trip planning.

11) An electric controller can be programmed for acceleration and deceleration characteristics to avoid damaging the propeller shaft, couplings and flexible couplings, while giving the right performance characteristics.

12) A diesel motor’s torque curve meets the propeller power curve at only one rpm for maximum power and efficiency. At every other point in the torque curve, the diesel motor is not fully utilized and therefore not reaching peak efficiency.
13) An electric motor’s torque curve tracks the propeller’s curve at maximum efficiency. An electric motor creates only the torque required with no additional overhead and is therefore more efficient at all points on the power curve.

14) In heavy weather conditions an electric boat gives maximum control over the propeller and can act like a variable drogue.

15) There is no lag in the throttle of an electric boat. You get instant power as soon as the throttle is engaged. You do not have to wait for the motor to rev up because electric motors have enormous instantaneous torque reserves to call upon for almost instantaneous propeller acceleration. The motor is not the limitation of the driveline when instant power is called upon.

**ELECTRIC BOATS CAN BE CHARGED FROM MULTIPLE ENERGY SOURCES**

1) SOLAR POWER IS A REPLENISHING RESOURCE ON A BOAT, WHILE DIESEL IS A DEPLETING RESOURCE. Even though a battery stores a fraction of the amount of energy as diesel, it can store it over 2,000 times.

2) Electric boats can be recharged with solar power.

3) Electric boats can be recharged with wind power.

4) Electric boats can be recharged from the propeller spinning (regeneration).

5) Electric boats can be recharged from shore power.

6) Electric boats can be recharged with a portable gasoline generator.

7) Electric boats can be recharged with a diesel generator.

8) Electric boats have redundancy in their energy supply. You may have to wait for solar to recharge your batteries, but you never completely run out of energy.
ELECTRIC BOATS ARE COMPONENT BASED AND CAN BE UPGRADED

1) Electric boats can be outfitted for less money than a diesel.
2) Range can be extended with the addition of larger battery banks at a later time.
3) Range can be further extended with the addition of solar panels, wind generator or a diesel or gas generator.
4) Individual components can be replaced without replacing the entire propulsion package.
5) Improvements in battery technology are increasing range. Lithium Iron Phosphate Batteries can provide enough range for the majority of sailing.
6) Diesel generators can be added in the future when they can be afforded.

LOW WEIGHT SYSTEMS FOR RACERS

1) Electric boats can be outfitted for inshore races with less weight than a diesel.
2) Batteries can be placed on a boat for optimum weight distribution.

ELECTRIC BOAT DESIGN ALLOWS FOR MORE FLEXIBILITY

1) Electric drives are smaller than diesel engines and can be fit into smaller spaces, allowing for larger living spaces or storage compartments.
2) Electric drives do not need as much access space because there is less maintenance requirements.
3) Fly by Wire Electronic throttles can be mounted anywhere without the need for cables.
DIESEL ELECTRIC HYBRIDS BOATS OFFER THE BEST OF BOTH WORLDS

1) Serial hybrid boats can mount the generator outside the living spaces of the boat to eliminate the smell of diesel fuel in the boat.

2) Serial Hybrid boats can mount the diesel generator anywhere in the boat - this helps with maximizing interior space or weight distribution.

3) Diesel Electric boats have longer range than diesel boats in normal multi-speed and low speed operation.

4) Hybrid boats can run the diesel at opportune times to avoid backwinding of the exhaust into the cockpit.

5) Two electric motors can be employed with a single diesel generator for increased handling and redundancy.

6) Diesel Generators run the diesel at the rpm where the diesel is most efficient, resulting in less fuel consumed, less engine run time, and longer engine life.

7) Hybrids minimize the smell of diesel or exhaust on your boat. Hybrid boats don’t have to run the diesel in harbor areas and rarely run their diesel at all.

8) The diesel generator on a hybrid boat supplies house and propulsion loads at many times the efficiency or a diesel driven alternator, resulting in far less engine run time on anchor.

9) By consolidating energy storage into one high voltage battery bank, greater efficiencies are obtained which results in less charging time.
APPENDIX 2: ELECTROPROP INSTALLATION MANUAL

Electroprop
6 Harbor Way # 226,
Santa Barbara, CA
93109

5.5 KW ELECTROPROP INSTALLATION MANUAL

Thank you for the purchase of your Propulsion Marine 5.5 KW electric drive.

Please read the entire contents of this manual before starting the installation of your Electroprop. Following these directions will give you years of safe, reliable and efficient operation of your Electroprop.

HAULING OUT

Although it is possible to install an electric drive in the water, we recommend hauling out. The reason for this is to determine if your propeller shaft is centered in your shaft log, and how close the propeller is to your hull. Installing a new dripless packing gland is highly recommended and only possible if you haul out. Hauling out gives you peace of mind that comes with knowing that your boat can’t leak while you are working on the driveline.

In my boat Kapowai, I was surprised to find the propeller shaft at the side of the shaft log – not even close to center. The shaft log is aligned with the cutlass bearing. If it is not centered it causes increased friction and wear on the cutlass bearing. If you have a dripless shaft seal, it can cause leakage.

If you can’t haul out, try the best you can to center the propeller shaft in the shaft log, and examine it at your next haul out. You can do this by moving the propeller from side to side and up and down then marking on the boat where the outer points are with a template, then keeping to the center of these points.

IF YOU DO HAULOUT, DON’T RUN YOUR ENGINE WITH THE CUTLASS BEARING DRY! After you install your new electric motor it is tempting to show it off…but you will damage the cutlass bearing if it is not in the water!
HULL DESIGN

Ultra-efficient electric drives cannot escape the effects of a rough bottom. It is highly recommended that the bottom is smooth with as few through hulls and underwater protrusions as possible. With Kapowai, I faired the keel from previous grinding, removed the large depth transducer in favor of an in hull transducer, and deleted 3 other through hulls made unnecessary by a sea chest.

To get advice on your bottom, just ask a local racer. The racers have all the tricks that electric boats should employ to maximize efficiency which increases speed and range.

REMOVING THE OLD ENGINE

For many of us, getting rid of the old stinky diesel or gas engine is one of the best moments of boat ownership. We tend to rush into it with giddy excitement. It’s a good idea to take some photos of the engine installation for future reference.

We have taken out diesel engines in many different ways. Perhaps the hardest was on a Serendipity 43 on anchorage at San Luis Obispo, California. The Serendipity was an IOR racer with a large and heavy 40 horsepower diesel. We slid it forward out of its engine bay, then hoisted it out with a block and tackle off the boom. The boom allowed us to swing it over the side and drop it into a dinghy.

Some of the engines we lifted out with a couple of strong guys. Some we took to the Navy pier and used the hoist.

If the engine has been sold in running condition, then try to keep it together for the new owner. Be careful with the shifters and the wiring harness and extra careful that it doesn’t swing into something causing damage.

If the engine is being scrapped, then strip down the block as much as possible. It will make the job a whole lot easier by decreasing the weight that you have to wrestle with. You may have difficulty with the coupling - the bolts tend to get rusty and are in an awkward place to get to. The engine mounts are usually held in place with lag bolts which come out easily or you can part the mounts at the engine block instead. All the cables and wiring harness can be cut and the engine can usually be removed within a couple of hours. There hasn’t been a fossil fuel engine that we couldn’t remove, but some have challenged us.
CLEANING THE ENGINE COMPARTMENT

A scraper blade can be helpful to remove the grime and grundge that accompanies a fossil fuel engine. Once that is mostly removed, take a rag with solvent to get rid of the rest. Bilge paint is a quick and easy one step solution to painting the bilge, however it is not a hard surface and can stain easily. There really is no substitute for a good epoxy primer and two part linear polyurethane paint. Be careful to use a good mask and gloves when you are working with LP paint or solvents. Solvents can be especially dangerous as they can penetrate your skin and get into your bloodstream. I will often put 5 or 6 gloves on each hand and remove them one at a time when they get slippery.

It takes some time, but when you are complete, you will have sealed the engine bay and removed the associated diesel, oil and grease smell from your boat. You will notice your boat starting to smell better right away and will keep smelling better over time as the oil smell comes out of the cushions and any other porous boat surfaces.

EXISTING COUPLING LOCATION

It is important to mark the fore to aft location of the coupling. Moving the coupling affects the propeller clearance. Forward and the prop clearance decreases, aft and the prop clearance increases. You do not want to move the propeller forward because the decreased tip clearance will result in cavitation, most noticeably in reverse. You can move the propeller backward, and in most cases moving the prop backwards will result in higher efficiency. However if the propeller hub is more than 1/4 of the propeller diameter away from the cutlass bearing, shaft whip may happen which can wear out the cutlass bearing and potentially bend the shaft. Many prop guys like the propeller an inch away from the cutlass bearing, but I’ve had luck with it further out than that. Larger propellers and small shaft diameters are most prone to propeller shaft whip.

If the propeller is in an aperture, you should not move the propeller at all because it may cause the propeller to hit the aperture. If the propeller is too close to the aperture, it will decrease performance and may cause cavitation.

Most of our conversions have included a new high efficiency propeller. These props are deeper and may have a clearance problem with the rudder. Some of our customers have increased the size of the aperture to fit the new propeller. If that is not an option, then the new propeller should be as centered as possible in the aperture.

Propellers should have at least a 15% tip clearance and a minimum of 2 inches is desirable. With propellers in an aperture, this clearance should be from any point of the aperture.
REMOVING THE COUPLING FROM THE EXISTING PROPELLER SHAFT

The shaft coupling has to be removed from the propeller shaft in order to install the dripless shaft seal. Use a heavy duty puller to remove the coupling from the propeller shaft.

Some propeller couplings have been press fit onto the propeller shaft, heated prior to installation, or corrosion has seized the coupling onto the propeller shaft making removal difficult. In such cases the propeller shaft has to be removed from the boat.

The only way to remove the propeller shaft with coupling is to slide the shaft out from the inside of the boat. Some manufacturers haven’t made allowances for this and have placed furniture or bulkheads in the way. You will need to remove any obstructions to get the shaft out of the boat if you are unable to remove the coupling from the shaft while in the boat. On one boat we drilled a 4 inch hole through a fiberglass panel so that we could remove the shaft and coupling from the inside of the boat.

If it is completely impossible to remove the propeller shaft with coupling attached, then the shaft will have to be cut, the coupling removed, the rudder turned out of the way or removed, and the propeller shaft removed by sliding rearward out of the boat. The new propeller shaft can be installed by reversing this procedure. In such a case, the coupling will have to be machined for a slip fit so that it can be installed from inside the boat.

INSTALLING THE DRIPLESS SHAFT SEAL

The boat must be removed from the water prior to installing the dripless shaft seal.

A dripless shaft seal is recommended to increase efficiency. Dripless shaft seals ride on a film of water between a carbon disc and a stainless disc. They are almost 100 percent efficient. By contrast, a packing gland puts friction on the propeller shaft as it is tightened to seal the water out.

Once the old coupling is removed from the propeller shaft make sure there are no burrs on the propeller shaft that can damage the rubber o rings inside the dripless shaft seal collar.
Be careful not to damage the carbon on the bellows or the stainless of the collar that ride against each other to make the final seal.

Install the bellows on the shaft log. Make sure the bellows are centered on the shaft before tightening the clamps.

Lubricate the shaft with dishwasher detergent. Do not use grease or oil as a lubricant as it can damage the rubber o-rings. Slide the collar up the propeller shaft far enough that the clamps are clamping down on the shaft log but not so far that the shaft log can damage the inside of the bellows. Compress the bellows with the collar by the recommended amount and tighten the set screws on the collar. Install a second set screw on top of the first set screw as a lock on the first set screw.

Add two hose clamps or additional solid stainless clamp onto the propeller shaft to prevent the collar from sliding up the shaft.

Install the vent hose and run to a place midships as far above the waterline as possible. If using an older shaft seal, burp the shaft seal after the boat is put back into the water to make sure there is no air trapped inside the shaft seal. Water lubricates the shaft seal and if air is trapped the seal can overheat and be damaged by the friction.

PACKING GLANDS

If you have to continue using your packing gland then it is vitally important that the gland is tightened to the right amount and checked after the engine is run and periodically after that.

Hold the base of the packing gland and loosen off the thin lock nut. Tighten the thicker nut located around where the propeller shaft exits the gland. Turn the lock nut up against the exit nut and turn the two nuts against each other until they lock.

Typically we recommend that the packing gland leaks one drop of water every 20 to 30 seconds. This provides lubrication for the flax packing.

PROPELLER

We recommend installing a new propeller with the installation of an electric drive. We recommend propellers that are CNC machined using computer models resulting in substantially higher efficiency.
Changing my propeller from a 12 X 6 to a 12.5 x 14, slowed the propeller down from 2500 rpm to 700 rpm, decreased noise, increased efficiency and consequently range. A new propeller is a great idea!

Propellers have to be matched to the gear ratio. If you can’t change the propeller at the time of your installation, you can later, but the gear ratio has to match the final choice of propeller.

**INSTALLING THE ELECTROPROP WITH DROP PAN MOUNT**

Alignment matters! When a shaft is not aligned it binds on every revolution costing precious energy and consequently range.

Install the four motor mounts onto the drop pan mount in the center of the large adjustment holes. Place the Electroprop into position on the stringers and align the gearbox coupling as close as possible to the coupling on the propeller shaft. Mark the holes in the motor mounts on the stringers. Remove the Electroprop. Drill the holes in the stringers. Lag the motor mounts to the stringers. Place the Electroprop back onto the motor mounts.

**ALIGNING THE ELECTROPROP WITH DROP PAN MOUNT**

Install the flexible coupling insert between the two coupling halves and tighten the 8 bolts on the two couplings. Notice that one of the bolts on the flexible coupling has a red head. Place a feeler guage between the raised portion of the red headed bolt and the coupling flange. Move the coupling and measure with the feeler gages at 0, 90, 180 and 270 degrees and make sure the alignment is within 1/1000 of an inch in all positions. Adjust the nuts on the motor mounts and the position of the drop pan mount to achieve proper alignment. If the alignment is too far off, then the coupling can fail prematurely.

Whatever misalignment that is still in the system will be taken care of by the flexible coupling. The flexible coupling protects the bearing in the back of the gearbox from the affects of misalignment. This adds to the life of the gearbox bearings.

Remember the flexible coupling is the weakest point of the drivetrain and is designed to shear if the propeller is caught up on a rock or ropes. It is a good idea to have an extra flexible insert on the boat when cruising to distant places.
Make sure that the coupling on the propeller shaft has the two set screws tightened into recesses in the shaft, then wired together with binding wire to prevent them from coming loose.

**INSTALLING THE ELECTROPROP ON A FIBERGLASS BASE**

Full keel boats that are stiff between the cutlass bearing and the motor can have the gearbox lagged directly into a fiberglass / wood pad glassed onto the hull. Some fin keel boats or boats with a skeg are stiff enough for this installation. I would not recommend a racing hull to be installed in this fashion. Boats that are lightly laid up require additional alignment of the drivetrain after the boat is put back into the water.

This is the preferred way for an OEM to build an electric boat. The OEM can guarantee the structure between the Motor base, shaft log and cutlass bearing by adding additional fiberglass in this area.

Without the engine rails and drop pan mount there is additional room for batteries, wiring, and electrical components. On Admiral Oliver’s Shannon 38 there was enough room for a 22 KWH Lithium Iron Phosphate battery pack in the engine area. This made the Electric Conversion possible as there was no other place to mount the batteries on his boat.

Mounting directly to a fiberglass base is possible because there is no vibration in an electric drive.

Electric drives mounted in this manner are quieter than utilizing other mounting methods. Any noise or vibration is dampened by the mass of the sailboat.

I recommend hiring a skilled fiberglass installer to make the mount. The mount becomes the alignment and needs to be within one thousandths of an inch to be done correctly. The final layup is what determines the final alignment and there is no adjustment available from motor mounts.

It is not impossible to do - just requires patience and skill.

Start by hooking the entire driveline together and suspending the drivetrain from the cabin roof.

If you are planning on using lag bolts then the mounting pad should be comprised of 4 sheets of 3/4 ply glued together. If you are planning on through bolting, then only 2 sheets of 3/4 ply are necessary.

Cut the plywood to a shape that matches the hull in alignment 1/4 to 1/2 inch below the base of the suspended gearbox. Prime the plywood with resin. Mix up a batch of
resin and fillers to peanut butter consistency so it is not runny. Glass a minimum of one sheet of fiberglass matt on each side of each piece of fitted plywood. Add the resin with fillers. The resin / fillers mix gives you the ability to set the base in alignment under the gearbox. You can squish out excessive mixture and move the base around to make this alignment. Let the plywood / resin mixture harden about 1/4 to 1/2 an inch below the gearbox and as close to parallel to the base of the gearbox as possible.

Final alignment is done by building up to the final position of the gearbox. You can use another sheet of plywood or multiple layers of fiberglass cloth. Its a good idea to use additional cloth to tie the mount into the hull. The mount should be tabbed in with glass in all directions so it becomes part of the hull. When complete, this mount will be the strongest part of the hull and will add to the integrity of the hull. After each layer is installed and the fiberglass has set off, install the gearbox and check for alignment. If one corner is lower, then add some fill, until you get perfect alignment of your drivetrain.

On the Shannon 38 I installed a bulkhead to hold the front of the shaft log in place. I remade the shaft log to be longer and supported the inside end. Many boats leak around the shaft log so it is important that it is firmly held in place so it can’t move. Once the support bulkhead was in place, I installed the shaft log with copious amounts of Lifecalk for the final seal.

It sounds like a lot of work but for an OEM, once a pattern is made, it is a very simple process to complete and can be done in less than 8 hours spread out over a couple of days for drying times. A sophisticated OEM installation can be achieved by making a liner mold and installing the entire drivetrain with shaft log at one time. The cutlass bearing can be installed in alignment afterwards.

Once complete, seal the entire area with an epoxy primecoat and two part linear polyurethane paint.
After the drivetrain was installed, we installed the shelves for the Lithium Iron Phosphate batteries to sit on. In an OEM situation these could be incorporated into one mold with the drivetrain mount.

The final product represents the highest power density of any electrical installation. All of the components are neatly organized within the engine compartment. Everything is easily serviceable due to adequate room for all components. Laying out an installation like this takes time, but the efforts pay off with an exceptional final product.

The Lithium Iron Phosphate cells come in many different sizes and can be mounted in a number of different configurations to fit in the available engine area. The entire system can be pre-manufactured including batteries and wiring on one mold that would then be installed in the boat.

**INSTALLING THE FAN**

Place the fan to circulate new air into the engine compartment and / or to exhaust air out of the engine compartment. It does not take much air circulation to prevent the ambient temperature of the engine compartment to rise. Be sure to allow for the ingress or egress of air as necessary from the engine compartment.

The auxiliary contacts are wired to a 24 volt relay that turns on the 12 volt fan from a 12 volt source. The relay is rated at 15 amps so several fans can be used. Aim the fan at the motor or use the fan to circulate air into or out of the engine compartment.

**INSTALLING THE CONTROLLER**

The Controller you have purchased is capable of operating at 110 amps continuous. The amount of power is determined by the system voltage. Peak power at 48 volts equates to 5.3 KW. If a generator is present and charging at 58 volts the controller maximum output is 6.3 KW. If you have very small batteries that droop, or discharged
batteries, the controller maximum output at 44 volts is 4.8 KW.

*The heat generated by the controller is proportional to the current. If you plan to use your electric drive at sustained high outputs, then increase the size of your controller’s heat sink if controller temperatures are continually above 75 C. Most often the controller is operating below 50 C or even lower. The Sevcon controller is a very efficient controller and runs cool.*

The temperature of the controller is displayed on the Clearview Screen. If the controller reaches a preset temperature it will cut back until that temperature stabilizes. Heat sinking keeps the controller running cooler. A cooler running controller is more efficient. Higher output heat sinks have fans and fins to promote cooling.

Use 1 inch spacers to keep the heat sink away from the wall and provide air flow behind the heat sink. The controller should be mounted vertically. Hot air rises and provides flow behind a vertically mounted controller.
INSTALL THE THROTTLE

The Electroprop throttle is fly by wire technology. Make every effort to protect the throttle wires from chafe or stress that can affect their continuity.

The throttle is rated IP 65 and can be mounted outside. The electronics need to be completely protected in an outdoor rated enclosure or mounted through the deck.

Two microswitches independently switch on to engage forward and reverse. These can be switched if you need to change the orientation of the throttle. Install the throttle the way you want it, check to make sure that the orientation is correct, then switch the wires as necessary.

Make sure that the faston connections are not loose and are hard to push on and can take some force before they are dislodged.

*When not in use, cover the throttle with a white Sunbrella fabric. This cuts down on temperature variations and protects the throttle from the weather.*

INSTALLING THE CLEARVIEW DISPLAY

Mount the Clearview display high and dry in the cabin at the electronics table or just inside the companionway. We have made the Battery Voltage and Current Letters larger so they can be read at a distance.

The Clearview display wire has an optional CAN connection for updating or troubleshooting the software of the controller.

The Clearview display wire has an alarm annunciator wire.
Some controller settings can be modified using the Clearview Display.

The temperature of the motor is displayed on the Clearview Display. If the motor gets too hot, the controller will cut back 10% of maximum torque for every degree over 120 degrees Celsius winding temperature. We recommend not exceeding 100 C Motor Temperature.

**INSTALL THE MOTOR POWER WIRES**

M1 goes to U stamped on the motor, also marked 1
M2 goes to V stamped on the motor, also marked 2
M3 goes to W stamped on the motor, also marked 3

Split loom each cable from the controller to the motor. Put a red cable end on each end of the cable. Keep the cables in a bundle zip tied together and attached to the furniture. **Keep the Motor Power Wires wires away from the speed encoder and temperature wires.**

The Motor Power Wires are running AC current. AC creates Electromagnetic Interference (EMI). So careful management of your AC motor wires, away from depth transducers and other sensitive electronics, is important. Bundling the wires in the same conduit reduces EMI. Never have wires powering the same circuit in a loop because this will accentuate EMI.

Do not put the motor control wires in the same bundle as the motor power wires. If they are to cross, make sure to cross at a 90 degree angle to minimize EMI.

**DC WIRING**

Use 2/0 tinned, multi-stranded battery cable for all battery connections, between the batteries, from the batteries to the contactor (red) and from the batteries to the controller (black). Make sure all the connections are tight and with adequate surface area. If you try and push 200 amps through a loose or small connection, that connection will heat up and possibly cause the insulation to melt or burn. **Every connection matters so be vigilant in making a low resistance circuit!**
Keep Positive and Negative DC in the same conduit. Never run the DC in a large loop because you will create a large magnet which can interfere with compasses and electronics. If you have batteries on both sides of the boat, the wiring should be completed down only one side of the boat to prevent a large loop.

The positive wire from the battery bank goes through the battery switch, through the contactor and gets connected to the B+ terminal on the controller.

The small red wire with the fuse attached gets connected to the battery side of the contactor or a 2 to 5 amp circuit breaker if you purchased the optional circuit breaker box.

The negative wire from the battery bank goes through the optional battery monitor shunt and gets hooked up to the – terminal on the controller, with the #8 gage negative wire coming from the 35 pin plug. Make sure all loads get hooked to the load side of the Battery Monitor Shunt.

It is not necessary to use the fuse on the controller if the entire system is fused at a value equivalent to or less than the controllers fuse. Sometimes the installation of the wires to the controller can have a more organized layout when going to the + terminal and deleting the controller fuse. If unsure about deleting the fuse, contact the factory for advice.

**INSTALLING THE CONTACTOR WIRE**

Locate the contactor as close to the controller as space permits. Connect to the orange and brown wire fastons.

When you first turn on your system, measure the control wire voltage at your contactor. The contactor engages at 24 volts then floats at 18 volts to keep the contacts closed. **Verify the floating voltage is 18 volts.**
The small fused power wire is hooked onto the battery lug at the top of the contactor on the battery side. This wire energizes the key switch, which energizes pin one on the controller.

The other side of the contactor is connected directly to the plus (+) terminal on the controller. Use 2/0 wires for all battery connections.

INSTALL THE CONTROL WIRING

Plug the 35 pin connector into the controller. After you position the wiring harness then heat shrink the tubing attached to the plug. Make sure you are happy with the layout of the wiring harness because after you shrink the tubing, the position of the wiring harness will be set in place.

*Make sure that you don’t heat up the insulation too much on the 18 gage wires. Be careful, the insulation can be compromised on the little wires with too much direct heat and the harness will need to be replaced.*

Run the motor information wires in their own dedicated conduit or wire run. If you have to cross the AC motor wires, then do so at a 90 degree angle.

Do not cut or splice any wire in the wiring harness. If you need a longer wiring harness please specify and we will make a custom wire harness for you.

RISK OF ELECTRIC SHOCK

Every person has their own tolerance to electric shock. People with a weak heart condition will have less tolerance.

There are varying opinions as to how much voltage can electrocute someone. ABYC considers 50 volts DC to be the safety threshold.

Electricians working on high voltage DC often work with only one hand as the risk of cardiac failure increases if the current path crosses the heart.

Water increases skin conductivity so if you are wet or sweaty be extra careful. Turn off all electricity before working on any circuit. Not only does this protect you, it also protects the component from a brown out condition.
RISK OF FIRE

High amperage circuits can experience thermals if the connections, or the wires, are of too high a resistance. It is important to be very conservative when choosing conductors and terminals. Make sure the conductors are of adequate ampacity and the connections have high enough surface area. Be conservative and choose larger wires for high currents.

RISK OF EXPLOSION

Flooded Lead Acid batteries emit explosive hydrogen gas when overcharged, at the end of their useable life, or when the batteries are working. The gases can be ignited by a terminal that is overheating due to high resistance from a bad connection.

Batteries in a series circuit can become unbalanced causing one battery to be running at a higher voltage than all of the other batteries in the string. These batteries run the risk of explosion or thermal runaway.

All batteries should be monitored for voltage and temperature.

FULLY FUSED ELECTRICAL SYSTEM

It is very important that every circuit in the system is fused or self-limiting. (All controller outputs are self limiting so do not require fuses.)

The batteries are arranged in series. The interconnects each have different potentials from 48 volt negative which is referred to as 0 volts. The potentials of the mid taps are 12, 24 and 36 volts. Top positive has a potential of 48 volts.

If 0 volts comes into close proximity of an interconnect wire, or an aluminum hull, then the interconnects and the 0 volt wire must be fused too.

An aluminum pontoon boat, with 2 batteries in each hull requires 3 fuses at or within 6 inches of the battery posts.
Each AGM battery is capable of starting and sustaining arcs. Put 4 of them together and you have a powerful arc welder on your hands.

Limiting of the arc potential (fusing), extinguishes a short circuit before an arc can get started. *Fusing is very important.*

Arcing is the sustainable ionization of air. Arcing is more sustainable on a DC system than on an AC system so more care must be taken to fuse wires at their source of power.

The potential of an arc increases with the voltage. In other words, the higher the voltage, the longer the arc, so more separation and insulation is required as voltage increases.

**FULLY INSULATED ELECTRICAL SYSTEM**

All circuits requires insulation, and double insulation is preferable.

*Use split loom and red terminal covers! There should be no place where you can touch the bare metal of any battery post or any motor or controller connection.*

**FLOATING ELECTRICAL SYSTEM**

Neither the positive or negative of the propulsion battery is hooked to ground.

**GROUNDING**

The non current carrying components of the drive train should be grounded to a dynaplate. All exposed conductive metal surfaces are held at the same potential to prevent electric shock caused by touching two conductive surfaces with different potentials at the same time. Install a 10 gage green grounding wire between all the cases of all the electrical equipment.

Metal through hulls are not recommended. In the event of stray current corrosion you run the risk of corroding the through hull and sinking the boat. Underwater metals should be avoided wherever possible. Two electrically connected, dissimilar metals immersed in an electrolyte creates a battery. Salt water is a perfect electrolyte and no
two metals are identically the same so whenever you put two metal through hulls in, you create a battery. The more dissimilar the metals are, the more the battery will work. When the battery works the anode (less noble of the metals) sheds electrons into the electrolyte and corrodes.

We recommend keeping the electric motor and gearbox isolated from the propeller shaft with the flexible coupling and grounding to a dynaplate on the hull. If you choose to use the propeller and shaft for your boat ground then you will need to install a wire between a nut on the propeller shaft coupling and a nut on the gearbox coupling. PYI sells a flexible insert that can be installed to provide continuity across the flexible coupling. If there is no wire or insert, then the propeller shaft will be isolated from the rest of the grounding system of the boat.

The use of two different ground points is recommended if you experience any noise problems. All electronics are grounded to one dynaplate designated as the clean ground. The remaining items requiring ground potential go to the second dynaplate including the electric drive case ground and AC grounds. These two grounds are then interconnected with a filter. This becomes increasingly important with higher voltage systems that can experience more noise than lower voltage systems.

**COMMISSIONING:**

Converting a boat to Electric drive is a big change for a boat. By this time you have done a lot of work, some for the first time. It's been interesting. There has been a learning curve. Prior to launching your boat, double check everything. Try to wiggle connections to make sure all the bolts have been tightened. Pull on wires to make sure the crimps are strong. Push on the Electroprop to make sure it doesn’t move and has been firmly bolted down in position.

Put some water on the faces of the dripless packing gland, then get a friend to aim a hose at the cutlass bearing and turn the propeller a couple of times to verify that the throttle is engaging in forward when pushed forward. A right hand propeller turns clockwise when viewed from the aft of the boat to drive the boat forward. Close all your seacocks and launch your boat.

Climb aboard your boat and open the seacocks one at a time, looking for any leaks. Burp the dripless packing gland and make sure it seals in place when you let go.

Check the alignment. Some boats with lighter construction twist and change shape when the boat is put into the water.

Engage the throttle in forward and reverse and check the prop wash to make sure the boat is in forward and reverse.
Run the boat up to full throttle in forward and reverse while still attached to the dock. Make sure there are fenders between the boat and the dock. Check for any vibration in the driveline. The 5 KW Electroprop will draw up to 10 KW while the boat is stationary.

Check that the Clearview display is reading the correct voltage and current from the battery. If a Battery Monitor has been installed, compare the values of the two displays.

Cast off the docklines, engage the throttle and power away from the dock. Make sure you have adequate room away from docks and other vessels for the initial sea trials as you get to know your boat.

Accelerate to full boat speed. Slowly engage reverse to put the brakes on. Check for vibration in the drivetrain and cavitation in reverse. Get used to how much braking power the vessel has. Propellers with cupping tend to have less braking power than propellers without cupping and you need to understand the braking power of the vessel to avoid potential obstacles.

Adjust the reverse rpm to achieve the maximum amount of braking power from full boat speed without cavitation on the propeller. Adjustment is made with the Clearview display and only if necessary.

Take your boat out on its maiden voyage as an electric boat!

**OPERATION:**

Before going for a sail, I will run up the electric motor to 500 rpm as a pre-launch test. Then I motor her out of her slip. This prevents me from casting off without turning the motor on!

I can shift from reverse, through neutral and into forward as fast as I want to. Acceleration ramps are built into the controller that prevent sudden acceleration, deceleration or pass through neutral. The acceleration ramps protect the flexible coupling which is designed as an intentional shear point in the drive system.

A joystick allows for accurate positioning of the solar array for either maximum solar power or horizontal for minimal windage.

I check the battery voltages once a month in bulk, absorption and float charging cycles.

I check to make sure the fans are on during the day and the lights are on at night.
When sailing, I always run with the motor on. Most of the time it is set at less than 5 amps – around 250 watts - for predictable sailing performance in any wind condition.

I usually increase the power of the motor when tacking or gibing to make sure that I don’t lose control of the boat as she passes through the wind.

If there is a very deep discharge on the battery banks – less than 50% of the amp hours consumed – then I use the Outback Inverter Charger to charge up the battery packs.

I check the oil in the gearbox once a year.

Kapowai is a very simple boat to operate with these few checks of her systems.

ELECTRIC MOTORING

Let’s consider an electric boat’s natural boat speed to be the square root of the waterline length. For our Catalina 30, this equals 5 knots for electric motoring. Exceeding this speed, range decreases dramatically.

At 4 knots we have all the directional stability we need, the boat handles well and our battery only range is 55 miles in calm conditions!

At 3 knots we still have directional stability and we are still covering ground. Over a 24 hour period we make 72 nautical miles which is still pretty respectable. At 3 knots, electric motoring range is 8 times the range of the boat at 6 knots. 3 knots is comfortable for the evening cocktail cruise or just out for a relaxing time on your boat.
Electric motoring is like sailing. Electric motoring is quiet with no noise, vibration or fumes. Many electric sailors go out electric motoring when there is no wind and yet they still want a quiet, relaxing time on the water. *Being able to use your boat in any wind condition opens up the amount of time the boat is available for use.* You no longer have to wait for the wind. You can go out in the early morning or late in the afternoon when the wind has dropped off, and enjoy your boat, the surroundings and the experience.

**ELECTRIC SAILING**

Electric Sailing is definitely the sweet spot for operating an electric boat.

We all know that adding a folding propeller to a sailboat increases boat speed by 1 knot. What we don’t know is that an electric boat increases boat speed by 2 or 3 knots using very little energy.

When a boat’s propeller is not turning it acts like a bucket of a similar diameter, being pulled behind the boat. Yet it is very easy for the propeller to be turning at the speed of the water column, it’s just a matter of overcoming the friction of the drive system. It takes between 50 and 100 watts to overcome this friction. Once the propeller is turning the speed of the water column, the boat speeds up about 1 knot.

The addition of another 100 watts of power is enough for the propeller’s wash to start filling in the low pressure area behind the boat. This low pressure area is shifted from behind the boat to in front of the propeller and the boat is being pulled forward rather than pulled backward.

It takes 2 kilowatts to speed up our Catalina 30 from 3 knots to 5 knots under power alone. Under sail it takes only 200 watts.

The addition of some forward thrust results in apparent wind for the sailplan which fills out the sails. The electric motor is so effective that the throttle can be used to trim the sails!

Thank you for choosing Electroprop for your propulsion needs.

James Lambden
Electroprop
APPENDIX 3 - KAPOWAI

I moved to Santa Barbara in the summer of 1999. After working at the boat yard for three months I started Above the Waterline, Ltd., providing shipwright services for the boats in the Santa Barbara Harbor.

In 2001 I helped Matt Sanda jumpstart his car in the parking lot. He mentioned he had a boat that he wanted to sell before moving to New York City. We came to an agreement quickly and I bought Kapowai.

I learned to sail on small dinghies with my brothers as a teenager. Kapowai was the first boat I purchased and the largest boat I had ever owned. I remember how big it seemed to be at the time. She had an atomic 4 with the dubious distinction of being very moody and quitting at the most inopportune times. I didn't like having a gasoline inboard because of the explosive potentials. I really didn't like the intermittent nature of the motor so one day, after being frustrated by it for the last time, I removed it. It came out surprisingly quickly.

After several months I moved aboard. Kapowai had no running water, no toilet, a very challenged electrical system and was not all that comfortable to live on so I started the process of fixing her up. To get into and out of the marina, I bolted a 12 volt trolling motor onto a bracket on the stern, put in a couple of batteries, and off I went! She made about 2 knots - just enough to get me around - if there was no wind. That was ok for the time being because if there was wind, I just sailed. Not many people sail into and out of their slips, but it is possible, though not all that wise. It becomes a very choreographed event and if anything was in the way, dodging a collision became, well, dodgy.

It wasn't long before I couldn't live with the limitation of the 1/2 h.p. motor, so I started looking around. I was completely convinced that she could be propelled with an electric motor. I contacted Vetus and purchased the 2.2 KW Electric Hybrid Inboard. I figured that the hybrid version would regenerate. After much experimentation I gave up on that idea. The hybrid needed at least 1,000 rpm before it would start generating. I measured the phase to phase voltage at 6 volts ....not nearly enough to charge a 24 volt battery. That experiment failed. But I was not going to give up easily.

Without regeneration, I figured I needed a lot of battery power. I installed six 8D batteries plus four 4D batteries in a series parallel array. With lots of battery power aboard I set out for Santa Cruz Island, 22 miles away. I always motor-sailed because it was predictable and easy to do. And I always came back with over half a charge left on my batteries. It was a fairly successful conversion, doing what I needed, although a bit slow at only 4 knots.

One day while motoring around in the marina with friends, the propeller picked up some kelp, the motor over-heated from too much amperage, and we were left drifting. One of
us launched a kayak and towed Kapowai back to her slip. I thought it was an isolated event that I could live with until it happened again a few months later. Another intermittent motor? This was not good. Back to the drawing board! And I started again.

At the time in 2004, there was not much around. I searched the competition. A few European motors existed with controversial reviews. I knew I needed more power. I bought a single stator, 8 KW, permanent magnet AC motor off the internet. At over 4 times larger, I figured it would be plenty of power. I deleted two of the batteries, keeping two strings of 48 volts which I kept in parallel to increase the size of the battery bank.

The motor came as a package with a controller. I mounted the motor on a gearbox and hooked the whole system up to the existing propeller. With giddy excitement I headed away from the dock.

Inventing things from scratch is the hard way of doing things. You just can't anticipate what will go wrong, what the weak spot is. You think that you have done all of the hard work, all of the research, but inevitably something is going to need improvement. The 8 KW motor that I had purchased I had thought was a continuous rating. Fat chance on that! Running at 8 KW, the motor overheated in less than a minute. I thought that the motor was bad so ordered another one with the same result. By now I was getting totally frustrated. How could this be? It turns out that there is no convention on how motors are rated. So to just purchase a motor and believe the nameplate or the advertisement is wrong. What matters is what the conditions were that the rating was taking place at. We were running the motor at 2,000 rpm - the motor had a maximum rpm of 5,000 rpm. Since horsepower is determined by rpm, off the top we have to take 60% off the advertised power. That brings us down to 3.2 KW. I mounted the motor onto a gearbox. The motor was rated without a gearbox. The gearbox inhibits the transfer of heat from the back side of the motor. There goes another KW. The rating may have been done in an air conditioned room - we were working at an ambient
temperature of 75 degrees - perhaps we lost some of the rating there. After doing exhaustive testing we revealed that the 8 KW motor was really less than 2 KW continuous at 2,000 rpm, and even then it was running hotter than we would like it to.

The controller didn’t fair much better. We assumed it to be a very efficient controller. Turns out the old controller consumed 750 watts just to turn it on and had an overhead of 750 watts in any situation, so even at our 2 KW, we were burning 750 watts.

But one thing I have learned as an inventor over the years is the value of a failed experiment. A failed experiment highlights the issues and the areas that need improvement. With this knowledge in hand, I set out from scratch to make a drive that accomplished the power, efficiency and reliability that was needed. I knew who and what to ask. From that point forward all I needed was patience and persistence.

Over the course of the next two years I befriended the folks at Mars Electric Motors and Sevcon and started working on our own solution.

The amount of heat that a motor creates is proportional to the square of the current, known as the i squared losses. So if you halve the amount of current in a winding, you create 1/4 the amount of heat.

By redesigning the motor with two stators instead of one, for the same amount of power each stator is working with half the current and 1/4 the heat. So for the same amount of power, the double stator motor gives off 1/2 the amount of heat.

A single stator motor pulls the rotor around but at the same time pulls the rotor towards the stator and puts an axial load on the bearings. With a double stator motor, the axial forces pulling on the stator cancel each other out, and the rotor levitates between the stators and puts no axial load on the bearings.

These are the two main reasons why high power permanent magnet motors employ double stators.

Motors require two magnetic fields to operate. Induction motors create the second magnetic field by inducing a current in the rotor winding and making a second electromagnet. Permanent magnet motors employ rare earth neodymium magnets to create the second magnetic field. A permanent magnet motor has higher efficiency because it does not require power to create the second magnetic field.

Permanent Magnet Motor controllers need to be programmed for the specific motor. Either a hall sensor or a sine/cosine encoder inside the motor transmits the rotors location to the controller so the controller can alter the speed at which it generates its next magnetic pulse which turns the rotor. All this happens very quickly. The controllers have to respond to the demands put on the motor by the propeller.
As a boat goes over a wave, or gets hit by a gust of wind, the torque on the propeller changes. The controller senses this torque requirement and responds to it. The motors can be controlled only by speed or only by torque or by both. We use the speed/torque setting on the controller. The speed torque setting of the Sevcon controller limits both speed and torque. When you put your throttle half way down you are asking for half of the torque capability of the system. However if the system does not have any load placed on it, half of the torque might be more than the maximum rpm of the motor. By limiting speed as well, the half throttle setting provides half the torque without exceeding half of the speed. This is the setting that works best on boats.

Each motor reacts differently so the controller corrects in real time by employing data correction loops. The program employs three of these loops, one past, one present and one future anticipating what’s going to happen next.

There are about 50 different settings that need to be programmed into the controller, including induction, resistance, timing, maximum winding temperature to name a few. The motor is placed on a dynamometer to find out its characteristics and the whole process is call characterizing the motor.

Once the controller has been programmed for the motor, the user settings must be input. These include top motor rpm in forward and reverse and all of the acceleration ramps to mention a few. This is what gives the electric drive its personality.

When building an electric drive we must assume that the operator can and will do anything to break the drive. So after we have done the programming, we take the boat out and try and break the drive. Sounds a little odd, but this is what makes for a reliable drive. In our driveline we employ a flexible coupling which provides for an alignment indicator, has some give in it for remaining misalignment and is the intentional weak spot in the drivetrain. What we don’t want happening is the electric drive braking the flexible coupling by exerting too much torque on it. We are able to limit the torque, speed of acceleration, deceleration and speed through a direction change. Correct settings protect the flexible coupling.

Kapowai was the first boat to use the Sevcon Controller / Mars motor combination as a drive motor. This combination is now widely available within the industry and will probably remain the number one drive combination for re-powering small boats. It is cost effective and very reliable.

Our next job was to program the display for the application. We settled on a green background to protect night vision. Battery data is in large letters so the display can be mounted downstairs yet viewed from 10 feet away in the cockpit. In small type is the motor operating data including motor voltage, current, and temperature. Additional screens allow for programming of some of the personality settings including forward and reverse speeds, and fault management.
After Kapowai’s drive motor was perfected, we started selling them as the 5.5 KW Electroprop. It has been an amazing electric drive with 100 percent reliability and good sales.

Kapowai has been used to prototype our larger 7 KW drive by adding a cooling coil to the 5.5 KW and using the boat as a test bed for the larger drive. We sell all of our drives with continuous duty ratings which other manufacturers are hesitant to do. All the continuous duty ratings have been observed on Kapowai.

When I completed the conversion I made the website www.electricboatdesign.com which remains mostly unchanged from the day of conversion. It won’t remain a static site for much longer though. Soon you will see the next round of updates including the solar installation.

After designing, building and installing the new 5.5 KW Electroprop we removed the propeller from the boat and pulled her through the marina so we could understand the forces involved and confirm the gearbox was capable of handling the thrust. We graphed the data, then continued on to record the power at speed and graphed that.

After graphing Power to Speed I graphed Thrust per Kilowatt at boat speed and noticed something I wasn’t expecting. As boat speed increased, thrust per kilowatt decreased. At 2 knots the boat was getting 76 lbs of thrust per kilowatt which dropped to 30 lbs of thrust per kilowatt at 6 knots. This represents the true efficiency rating of the entire boat system. It takes into account the design and condition of the bottom, the amount of heat that is dissipating through the motor, gearbox, controller, contactor and all the cabling. The propeller is responsible for the majority of these efficiency losses at speed.

As power levels increase, efficiency decreases. Picking the happy medium while motoring our boats around, or better yet, motor-sailing our boats around is what electric sailing is all about.

If we are going a long distance, we pull back on the throttle and let the sails do the work. If we are going a short distance, we have the luxury of approaching hull speed. In general we are operating in the 4 to 5 knot range and the 1 - 2 knot decrease from top speed does not add up to much time over the ownership of your boat. Being on the water is all about relaxing and enjoying your time anyway.
Kapowai has the ultimate DC conversion system. I was just plain lucky when I figured this out. I purchased three equalizers which I placed between the batteries. They work like a waterfall with three pools. The 48 volt battery overflows into the 36 and on down the line to the 12 volt battery. By pulling my 12 volt house loads out of the bottom battery the equalizing action is activated which keeps the batteries in balance. The really cool part about this setup is I can install a brand new battery with the 7 year old batteries and don’t have to replace the entire string at once when the batteries start dying. It works like a charm producing up to 80 amps continuous and over 250 amps intermittent making this setup the most powerful available. It also allows me to tap into 24 volts or 36 volts all the while keeping everything in balance. This can be handy for running high power 24 volt gear.

At $2,500 it is the most expensive DC conversion you will get. But the additional battery management system makes it pay off over time.

**Batteries in Parallel**

The batteries on Kapowai are Absorbed Glass Matt. There are two strings of batteries held in parallel (4 x 4D and 4 x 8D) I installed 3 Vanner Equalizers on each battery bank which keeps the batteries at the same voltage plus provide 12 volts DC at 80 amps continuous and as much as 250 amps intermittent. This DC conversion is very efficient. I have had 3 battery failures over the last 8 years and installed new batteries at the top of the same string as the old batteries. This is possible only because of this unique battery management system in place.

Whenever I go out of town, I uncombine the two strings of batteries. I keep a close eye on these batteries and regularly check the voltage of each individual battery. For the last three years, the boat has been completely charged by solar power.

For electric boats looking for a large capacity sealed battery bank like this, I now recommend Lifeline 400 amp hour 6 volt batteries in series for safety reasons. Batteries in parallel can be problematic, especially when they get out of balance at the end of their life.
My next project is to install a diode block on the two batteries so they can be isolated - each drive the load and each be charged independently. Then I can leave them paralleled indefinitely.

For three years Kapowai has been completely energy independent barring two occasions - a heater for an overnight girlfriend and an equalization of the battery bank. The slip’s meter reads just 22 KWH’s which I plan to erase in the future with a grid tie inverter. I keep her unplugged from the dock so have no worries about being part of the grid. I’ve sailed her over to Santa Cruz Island 22 miles away, lived on her extensively, and have never run out of power. Kapowai is almost completely maintenance free so once she was completed my bills went down to almost nothing. The longer I own her the more I save. Converting Kapowai to electric has been the best thing I have ever done. Buying her was a great day in my life, and every other day that I owner her keeps getting better. By sharing her story I hope to influence others to have the enjoyment that I have been fortunate to have for these past 11 years.

THE FUTURE

As leading manufacturers start to endorse electric boats, designs will evolve making electric boats more practical, and further enhance the layout of your boat.

Boat manufacturers are reluctant to build electric boats because of the additional costs involved. But demand for user-friendly technology will drive down component cost and at the same time demand for electric boats will increase. Rising fuel costs also give incentive to more efficient technologies. European boat manufacturers are already building electric boats. Hunter is now building an electric boat in the US.

Efficiency and capacity determine how much products can develop in the future.

Motors are currently up to 96% efficient, though the majority of commercially successful motors are running around around 90%. Higher capacity motors at reasonable prices
are in development. The maximum increase in efficiency will be 6 to 7 percent in commercially available products and 2 to 3 percent in experimental models.

Controllers are currently at 95% efficiency and may improve by a couple of percent. The Gen 4 controller was developed by Sevcon over the last 10 years. The next generation of controller will probably take just as long to develop.

Gear reduction, currently at 96 percent efficiency, can be increased by up to 100 percent efficiency - but you will have to come back to the second edition of this book to find out how we accomplish that!

Motors, Controllers, and Gearboxes at most will increase in efficiency by 10 percent combined over the next ten years.

The biggest advancements will be in battery capacity. Battery capacity has not increased significantly in 100 years – the lost century of development - largely due to our dependence on fossil fuels.

Lithium batteries represent a huge development in battery capacity, but they are priced too high for commercial acceptance on boats. Different chemistries of Lithium Batteries will most likely be developed. Other chemistries not based on Lithium may be developed but the likelihood is low.

The majority of research, development and funding is now currently based on Lithium technology. A huge advancement will be made if the price per watt-hour for Lithium batteries comes down to a commercially viable level. If we are lucky, we will also see a large increase in capacity.

THE ELECTRIC BOAT COMMUNITY

Over the years I’ve noticed that my electric conversion customers are a very relaxed group of people who are not in a big hurry. If a shipment was delayed for lack of a part, or by customs, it was never a big problem. Every one of our electric customers has been patient, trusting and otherwise great to deal with. People who choose electric are just this way and it makes the entire business pleasurable.

When people come together in a spirit of co-operation with our planet only good can come of it. Over time this group will bond together in a cohesive unit and expand. Over time people will come over to this new way of sailing, and at life in general.
In particular I’m looking forward to solar sailboat races where both wind and sun power our boats. The tacticians job will get more challenging as our boats get faster from the two energy sources. What fun that will be.

Electric Boats provide an environmentally friendly solution while enhancing our life aboard. They are lower maintenance, quieter and fresh like the breeze that catches your sails. More work goes into building them, but the dividends pay off in years of quiet enjoyment.

Life is good onboard The Electric Boat!

Kapowai at Dawn, Santa Cruz Island

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