ELECTRIC OUTBOARD DRIVE

for

SMALL BOATS

A Do-It-Yourself Handbook

July 15, 2010

by

Todd Wells

PREFACE

We feel blessed to live on one of the few navigable waterways in Central Oregon, the Upper Deschutes River, just south of Bend, Oregon. Every summer weekend, a parade of small recreational boats motors upriver past our backyard. They come in all descriptions—humble jon boats, fancy drift boats, proud pontoon boats and dozens of everyday aluminum utility boats. Most are set up for fishing, though some are just for sightseeing. But they all have three things in common: they are all between 12’ and 20’ in length, they are all trailerable, and every one of them is powered by a gas outboard motor. These craft are the focus of this handbook.

Years ago, we first became involved in electric propulsion when we tired of paddling our canoe upriver against the current and installed a small electric trolling motor with one 12-volt storage battery to power it. This has led over the years to somewhat larger craft with more capable electric outboards and to 48-volt battery banks with more sophisticated electrical systems. Even these larger installations, though, are well within the abilities of the average do-it-yourselfer.

As we’ve gained hands-on experience in setting up and operating these small electric boats, we’ve sometimes wondered why this simple and long-established technology hasn’t found a wider following among recreational boaters. Why aren’t more of the boats passing by our backyard on a summer weekend utilizing electric outboards?

Our conclusion is that it’s mainly inertia. No local boat dealer sells electric outboards and do-it-yourself boat owners have to go out of their way to find good information on setting up and installing an electric outboard. This handbook is a small effort toward overcoming that inertia.

NOTICES

Disclaimer: The author is a self-taught electric boat enthusiast who has successfully converted several small craft to electric outboard drive. This handbook was also reviewed by Todd Sims, an ABYC marine electrician who specializes in electric boats. Though every effort has been made to ensure the accuracy of the information herein, neither the author nor Mr. Sims warrant the correctness of this handbook. In the true spirit of do-it-yourself endeavors, the reader assumes complete responsibility for any use of this information.

Representations: Though specific products, services and web sites are cited in this handbook, these result from the author's personal experience and opinions only, and he does not represent, endorse or guarantee any product, service or web site.

Acknowledgments: The author would first like to thank Todd Sims, the ABYC marine electrician who generously reviewed this handbook and made several important suggestions for its improvement. Also, thanks go to three other authors who have indirectly inspired and informed the preparation of this handbook:

> Douglas Little, whose *Electric Boats: The Handbook of Clean, Quiet Boating*, published in 1994, encouraged a generation of recreational boaters to consider electric drive;
>
> Naval architect Dave Gerr, whose *The Nature of Boats* and many magazine articles revealed to the layman the mysteries of why boats behave the way they do; and
>
> Nigel Calder, whose *Boatowner's Mechanical and Electrical Manual* is a must-have reference for anyone seeking more in-depth technical guidance on electricity and boats.

Finally, the author would like to thank his life partner and boating mate, Nancy Burgon, for her love, support and many other contributions to this project.

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1. INTRODUCTION

Many recreational boaters and fishermen who ply inland lakes and waterways could easily be enjoying the benefits of electric outboard propulsion, but often lack the most basic information about this well-established technology.

This handbook is designed, first, to help recreational boat owners decide whether electric propulsion is suitable for their needs and, second, to give those with a do-it-yourself bent the information needed to set up their boat for electric outboard drive. Anyone who is reasonably handy and willing to learn the basics of marine wiring can perform a successful installation.

Electric outboards are not for everyone. They definitely have their limitations. But with the recent commercial availability of high quality and affordable electric outboards in the United States, many more recreational boaters could be utilizing and benefiting from this technology—if only they are willing to look beyond the habit of gas outboards to consider a cleaner, quieter approach.

What are the advantages of electric outboards for the recreational boater?

Simplicity. Many boaters, especially fishermen, run both a gas outboard (to get them quickly to their destination) and an electric trolling motor (for fine speed control and maneuverability once there). This requires installing and maintaining two systems: the gas motor, tank and lines, plus the battery, wiring and charger for the trolling motor. Modern electric outboards can fulfill both of these roles in one simple and reliable installation.

Quiet Running. Electric outboards are not completely silent—at high rpm, they sound about like a loud sewing machine—but they are many times quieter than any gas outboard motor available.

Zero Emissions. While four-stroke gas outboards create less water and air pollution than their two-stroke predecessors (and get twice the mileage), they still burn fossil fuel—and everything that entails, including the noxious fumes. Electric outboards create no polluting emissions at all while running and are as green as your electric utility is green while recharging.

Low Maintenance. Once properly installed, an electric outboard is extremely low maintenance. Occasionally, electrical connections can become corroded, especially in salt water environments, but these are easily cleaned and restored to service. There's no fuel filter to check, no carburetors to adjust, no spark plugs to clean, and no worries about ethanol in your fuel tank.

Low Operating Cost. Once the boat owner makes the initial investment in an electric outboard and the related batteries, charger and wiring, the subsequent cost of recharging the battery bank is normally less than a dollar or two per recharge (for example, 120 volts x 12 amps = 1440 watts x 6 hours = 8.64 kilowatt hours @ $0.12 per kilowatt hour = $1.04) .

Highly Reliable. One hallmark of electric outboards is their push-button reliability. If you've taken proper care of your batteries and kept them charged, you just flip the switch and go. There is none of the stress and anxiety of starting a balky gas outboard miles from your launch site.

Fine Speed Control. All electric outboards have extremely fine throttle control, especially at very low speeds. This allows every electric outboard, even the most powerful models, to serve as both a trolling motor and a primary propulsion motor, all in one unit.

Access to Restricted Waters. Increasingly, more lakes and waterways around the world are being restricted to electric motors only. Perhaps you've seen this happen to a local water body near you. Electric outboards allow you unlimited access to all of these lakes and waterways.

Any there any disadvantages to electric outboard drive?

Less Range. Even with an efficient boat hull and high capacity batteries. the maximum range of travel for a small electric boat running on still waters (without strong currents or tides) is likely to be 40 miles or less between recharges. This range depends on the size of your battery bank and how deeply you are willing to discharge it each time. While most battery manufacturers recommend a 50% depth of discharge for maximum battery life, many electric boat owners believe a 70%-80% discharge is just fine, as long as the batteries are recharged immediately after use. However, all agree that the less deeply you regularly discharge your battery bank (and therefore the less your boat's range), the longer the service life of your batteries.

Less Speed. Since nearly all electric boats function as displacement hulls, and not planing hulls, the maximum speed of the boat will depend on the boat's length at the waterline and not the horsepower of the motor (the longer the boat, the faster it goes). Some additional speed can be gained by pouring on more power, but not very much—and at a great cost to your battery reserve. As an example, the maximum theoretical hull speed for an 18-foot electric boat is 6.5 mph, and it may actually top out near 8 mph under full electric power—but its most efficient and practical speed is 4-5 mph.

> **Calculating Speed of a Displacement Hull Boat**
>
> **Speed, in mph = 1.54 x square root of Waterline Length, in feet.**

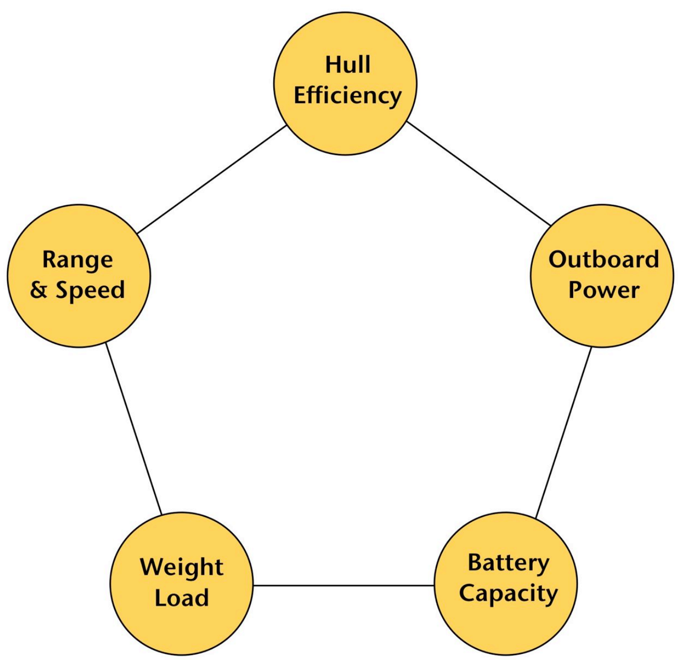
Added Battery Weight. Given that deep-cycle, lead-acid batteries are the most reliable and affordable storage batteries currently available (though this may change with recent advances in lithium-ion battery technology), the added weight of these batteries is just an accepted fact of life for today's electric boaters. Depending on the voltage of the electric outboard (24-, 36-, 48- or 60-volt) and the capacity of the battery bank required, a small electric boat can't avoid carrying from 100 to 400 lbs. in added battery weight. This obviously reduces the boat's carrying capacity for passengers and other loads. As a consolation, if the battery weight is distributed properly, it can improve the stability of many boats, due to the lowered center of gravity.

Higher Initial Investment. There's no doubt that setting up a small boat for electric outboard drive requires a higher initial investment than for a comparable gas outboard—even though the boat owner can expect to recoup this difference (and more) in lower operating costs over time. For example, a 48-volt electric outboard (comparable to an 8 HP gas motor) could cost from $2,200 for a serviceable Chinese model to $3,750 for a top-of-the-line German model. The battery pack could cost from $900 for a minimal, 75 amp-hour pack to over $1,500 for a 150 amp-hour, extended range pack. Added to this are the costs of wiring, circuit breakers, chargers and accessories. In total, a small boat owner can expect to initially invest from $4,000 to $6,000 (at 2010 prices) to set up an electric outboard drive, depending upon his/her needs.

So the first decision facing a recreational boater is whether the advantages of electric drive outweigh the drawbacks for his or her particular use. Certainly, if your boat trips are long, multi-day outings carrying heavy loads into remote areas without access to overnight shore power (say moose hunting trips in Alaska), then your only real option is a good four-stroke, gas outboard with plenty of extra fuel aboard. However, if you normally take day trips of 40 miles or less, are able to plug your boat into shore power at night, and are willing to live within certain speed and weight limitations on your boat trips (say for a day of fishing, birding or exploring on your local waters), then there's no reason you can't enjoy the benefits of electric propulsion.

Many recreational boaters, especially fishermen, could find the benefits of electric outboards so compelling (e.g., simplicity, reliability, fine speed control and access to restricted waters) that they are willing to modify their established boating habits just a bit—say by accepting less speed and range on their boats, or perhaps inviting one fewer buddy along. At least, it's an option that deserves wider and more careful consideration.

As you'll see, setting up a boat for an electric outboard is all about balancing trade-offs. The chart below shows the five principal factors that must be balanced for a successful installation. All five are interrelated and every do-it-yourself electric boat owner needs a basic understanding of each. In the next few sections, we'll discuss these factors in detail. The goal of this handbook is to provide you with sufficient information about these trade-offs and their consequences, then let you decide what's best for you and your boat.



2.   HULL EFFICIENCY

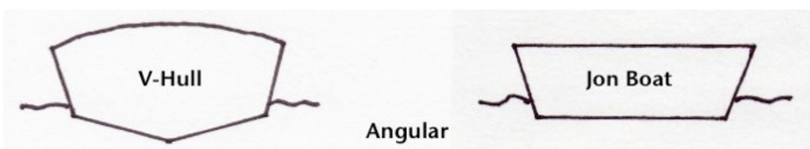
Any small boat can be fitted with an electric outboard. However, things aren't quite that simple. The less drag your boat hull creates as it travels through the water (i.e., its efficiency), the smaller the motor and battery bank you'll need for a given range of miles—or, conversely, the more miles you'll be able to travel on a given motor and battery pack. Hull efficiency is important.

What are the factors that determine a small boat's hull efficiency?

Displacement Hulls vs. Planing Hulls. All boats at rest (or moving slowly) function as displacement hulls, in that they displace a volume of water equal in weight to their own weight. In other words, each boat sinks into the water until the weight of the boat just equals the weight of the water it displaces. It's only when boat hulls pick up speed that differences are apparent.

Displacement hulls are designed to efficiently push aside the water they displace as they move forward at speed. However, the faster they go, the horsepower required to push aside this water increases geometrically—which means there is a practical limit to the speed they can attain. At low speeds, though, these hulls are very energy efficient, and they can carry heavy loads (e.g., lead-acid batteries and passengers) with little drop off in performance. They normally have moderate rocker, rounded cross-sections and a transom narrower than their beam. Displacement hull boats include dories and other rowing boats, freighter canoes and drift boats.

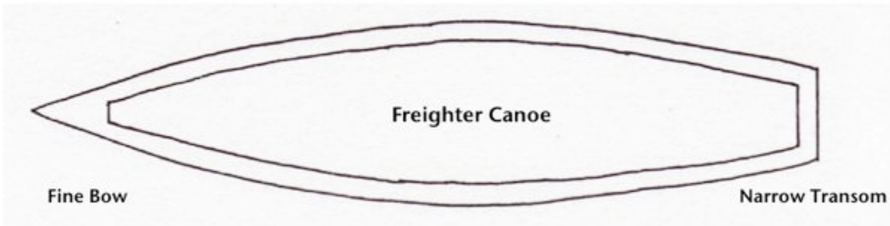
Planing hulls, on the other hand, don't worry about efficiently pushing aside the water they displace. As their speed increases, they're designed to derive more and more lift from the water beneath their hull until they are mostly riding on top of it (i.e., being on plane)—at which point they use most of their power to move forward instead of pushing water aside. Most have straight bottoms (no rocker), angular cross-sections and wide, square sterns—all great for planing, but not as efficient when running at slower speeds in displacement mode. Small planing hull boats include nearly all v-hull utility and fishing boats, jon boats and many skiffs.



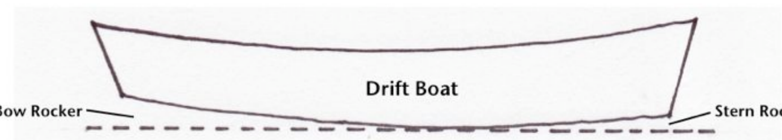
For all practical purposes, the electric outboards available today just do not have the horsepower required to push a boat up onto plane, regardless of its hull design. As a result, almost every electric boat on the water today is either a displacement hull or is a planing hull that is being run at slower speed in displacement mode.

Hull Shape. The quickest way to assess any hull's efficiency is simply to compare the length of the hull with its width at the beam. As we've discussed, the longer the hull, the faster it will go at displacement speeds. And the narrower the hull, the less frontal area it has, so the less water it needs to push aside at speed. Longer and narrower is better! In fact, the best hulls for small electric boats are at least 16' to 20' in length and have length-to-beam ratios of around 4:1.

The "fineness" of the hull at the bow and stern is also important. Obviously, we want a bow that is at least pointed and knifes through the water rather than plowing into it. But equally valuable is a narrow transom (at least narrower than the beam) that lets the water return behind the boat with a minimum of turbulence. Any turbulence causes drag, which consumes battery power.



Other small refinements to hull shape can dramatically increase efficiency. Some are subtle, like an upward sweeping stern (rake), a curved boat bottom (rocker) and rounded hull cross-sections, all of which reduce eddying and drag. Others are less subtle, such as avoiding large sun awnings that can significantly increase wind resistance.



What if I already own a small boat with an inefficient planing hull?

This won't preclude you from installing an electric outboard drive, but you'll need to make some compromises. If you want to match the performance of a more efficient hull, you'll need to oversize your electric outboard and battery bank, perhaps by 40%. This will increase your initial investment, reduce the load carrying capacity of your boat (due to the increased battery weight), but your speed and range should then be comparable to the more efficient hull.

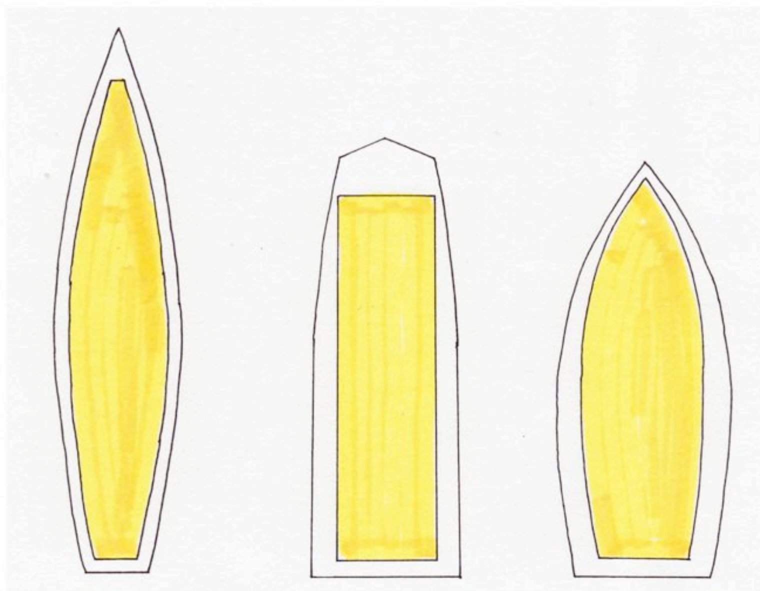
It may make more sense, though, to just accept limited performance. There's no crime in setting up an inefficient electric boat, as long as the setup is *efficient enough* to meet your needs. For example, if you only fish with one companion on restricted lakes that are less than 5 miles long, then all you need is enough horsepower and battery capacity to get you around the lake and back (with a reserve) at adequate speed. Beyond this, what does it matter if your hull is inefficient?

How do small boat types compare in their hull efficiency?

For comparison, let's look at three common small boat types—the freighter canoe, the jon boat and the drift boat. These are chosen not because they're all ideal for electric propulsion, but because they have different enough hull characteristics that their efficiencies can be analyzed—and all three types are widely owned, at least here in the Pacific Northwest.

Qualitative Comparison. Let's start by looking at the data in Figure 1. Every prospective electric boater should be able to glance at the specifications of these three boats and quickly spot the most efficient hull. The freighter canoe, with its high length-to-beam ratio, its fine bow and transom, its moderate rocker and its rounded hull cross-sections, is by far the most efficient hull. However, this efficiency comes at the price of somewhat less floor area and payload capacity.

Figure 1. Comparison of Hull Shapes and Characteristics



	Freighter Canoe	Jon Boat	Drift Boat
Construction	Fiberglass	Aluminum	Wood
Floor Area (in yellow)	32 sq. ft.	36 sq. ft.	38 sq. ft.
Hull Length	18'-4"	14'-0"	13'-6"
Beam Width	50"	58"	68"
Length-to-Beam Ratio	4.4	2.9	2.4
Transom Width	26"	58"	46"
Waterline Beam	40"	40"	48"
Side Height, at center	18"	19"	24"
Bottom Rocker	2"	None	4"
Hull Cross-section	Rounded	Angular	Angular
Hull Weight	185 lbs.	205 lbs.	260 lbs.
Payload Capacity	700 lbs.	780 lbs.	900 lbs.

How does the efficiency of the jon boat and the drift boat compare? This is a harder call. The jon boat has a longer, narrower shape, so might appear at first to be the more efficient hull—but its flat, straight bottom and its wide, square transom will create tremendous eddying behind the boat at displacement speeds, which will greatly increase its drag. So, even with its wider, shorter shape, the drift boat should be the more efficient hull, due to its finer bow, its bottom rocker and a transom narrower than its beam—which returns water behind the boat with less turbulence and drag. One caveat: In consistently windy locales, the greater wind resistance created by the higher sides and freeboard of the drift boat may well negate the advantages of its better hull.

Quantitative Comparison. We can see that the freighter canoe is a more efficient hull than the other two boats at displacement speeds—but how much more efficient? The only quantitative data I've seen comes from Ray Electric Outboards in Florida who field tested one of their efficient boat hulls, the Explorer, against a jon boat of equal displacement, both using the same 48-volt electric outboards (complete report at http://www.rayeo.com/inside-art_3.php):

	at 25 amp draw	at 75 amp draw (max.)
Jon Boat	4.3 mph	6.0 mph
Explorer	6.2 mph	7.0 mph
Speed Advantage	*44%*	*17%*

With both boats drawing 25 amps at the cruising speeds above, the better designed hull will be able to travel 44% more miles than the jon boat, on the same amount of battery energy. The jon boat would thus need to carry a much larger battery bank (and more weight) to match the performance of the better hull—or else be content with a 30% shorter range of travel on the same battery bank. That's a striking difference, all due to a less efficient hull shape.

3. ELECTRIC OUTBOARDS

In this section, we'll discuss a few of the basics of electric outboard drive and how the manufacturers establish power ratings for their motors. Then we'll introduce the various makes and models of electric outboards that are currently on the market.

How are horsepower ratings of electric outboards determined?

When comparison shopping for an electric outboard, the most essential fact to determine is how much power a particular outboard will actually deliver for moving your boat. This is the outboard's *propulsion horsepower* and is defined as the thrust acting on the craft times speed. Unfortunately, few manufacturers publish this information in their specifications. What they usually provide are these two horsepower ratings:

Calculating Motor Power

Power, in Watts = Volts x Amps

1 Horsepower = 746 watts

Input Horsepower: This is helpful to know, as an indicator of the maximum energy a motor will consume. But it doesn't tell us anything about how much of the energy consumed is actually supplied to the boat, after subtracting losses for the motor, the drive mechanism and the propellor. These losses, in total, can vary from 80% for trolling motors, to 65% for conventional electric outboards, and to 50% for the more efficient, modern electrics.

Shaft Horsepower: This is the headline horsepower rating usually given by electric and gas outboard manufacturers ("it's a 5 HP motor") and is measured at the propellor shaft. However, it does not account for propellor losses, which can vary from 30% to 70% for different models. So, while informative, it still doesn't tell us the expected propulsion power of a particular outboard.

(We are indebted to Torqeedo, Inc. at http://www.torqeedo.com/us/hn/home.html for these points on horsepower ratings and power losses.)

Given this, a buyer should be extremely cautious about using manufacturers' horsepower ratings to compare the propulsion power of electric outboards under consideration. Horsepower ratings just do not give a complete picture. But all is not lost.

Can static thrust ratings be used to compare electric outboards?

Most manufacturers (and some third parties) test the thrust of their motors pulling against a stationary object, where there is no movement of the outboard or the water (other than the water passing the propellor). The test results are reported as static thrust, in pounds.

Static thrust still isn't the ideal measure of propulsion power, since the tests do not include speed over the water—but it's probably the most useful data available for comparing various makes and models of electrics across different manufacturers. Keep in mind, though, that static thrust determined in a stationary test will not be the same as actual boat thrust measured under speed. Here we're using it only as a *relative indicator* of motor power.

Are static thrust and horsepower related?

Not directly. Since static thrust is a measure of force exerted on a stationary object—and horsepower, as we saw above, is a measure of work performed (force times speed)—there is no magic formula to convert from one to the other. However, by static testing the performance of outboards in the field (in this case, one variable voltage electric outboard running from 24 to 72 volts), and measuring the static thrust at various input horsepowers, we can create a chart that roughly correlates these two power ratings for modern electric outboards:

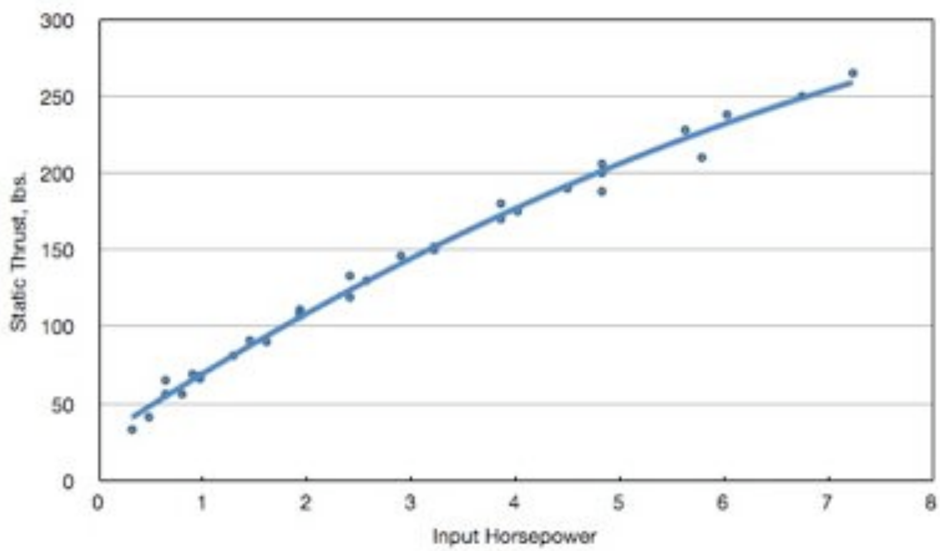


Figure 2. Relationship of Static Thrust and Input Horsepower in a Modern Electric Outboard (test data from EPIC Corporation spec sheet at http://oemc.biz/motors/whisper-xt.html)

Please note that Figure 2 only applies to electric outboards that utilize a large propellor, generally greater than 10” diameter. These include most major manufacturers (Ray Electric, Torqeedo and Minn Kota) who incorporate the “large prop, turning slowly” principle in their outboard design. Figure 2 will not work for smaller prop outboards (such as the Parsun), which use the “small prop, turning fast” design. These smaller prop outboards produce less thrust per unit of horsepower (due to higher propellor losses, see Figure 3) and are comparatively less efficient—though differing methods of measuring static thrust between manufacturers may also be at play.

Who are the major manufacturers of electric outboards today?

Ray Electric Outboard. Based in Florida, this company has been producing heavy duty electric outboards since 1974. They make three models—one at 60 volts (250 lbs. thrust), one at 48 volts (195 lbs. thrust) and one at 36 volts (135 lbs. thrust). Using brushed motor technology, each features a vertically aligned, above water motor that is air cooled, with a 2.6:1 gear reduction turning a 12.5” aluminum propellor. Each model is available in short or long shaft, with tiller or remote control. These are heavyweight electric outboards that are designed for reliability and continuous commercial use—and they’re the most expensive motors on the market.

Figure 3. Commercially Available Electric Outboards, 2 HP and Greater
(All data from manufacturers' published specifications)

	Company	Model	Static Thrust, lbs	Volts	Max Amps	Input HP	Shaft HP	Thrust, per HP	Weight	Price **
HIGH POWER	Ray Electric	500	250	60	84	6.8	5.0	50 lbs	100 lbs	$4,820
	Torqeedo	4.0 R	214	48	83	5.3	4.0	54 lbs	40 lbs	$3,749
MID POWER	Ray Electric	300	195	48	80	5.1	4.0	49 lbs	72 lbs	$4,690
	Torqeedo	2.0 R	110	24	83	2.7	2.0	55 lbs	38 lbs	$2,699
	Parsun	5 HP	130/160*	48	100/140*	6.4	5.0	26 lbs	75 lbs	$2,999
LOW POWER	Ray Electric	200	135	36	65	3.1	2.5	54 lbs	72 lbs	$4,690
	Minn Kota	E-Drive	130 (est)	48	40	2.6	2.0	65 lbs	90 lbs	$2,699
	Parsun	4 HP	130	48	80	5.1	4.0	33 lbs	70 lbs	$2,180

* 160 lbs. thrust and 140 amp draw for 10 seconds, then drops to 130 lbs. thrust and 100 amp draw .
Thrust measured using Bollard Pull Test method.

** Manufacterers' suggested retail prices in mid-2010.

Torqeedo. Manufactured in Germany since 2005, these electric outboards are on the leading edge of technological innovation. Their most powerful outboards are their Cruise models. One runs at 48 volts (214 lbs. thrust) and is remote control only, and the other runs at 24 volts (110 lbs. thrust), with both tiller and remote versions. Both feature submersed, water cooled, permanent magnet motors that drive a 12", highly engineered, hard plastic propellor. These are by far the lightest weight and most ultra-efficient electric outboards available today, with the most sophisticated electronics (including a built-in GPS for determining speed and range). They're mid-priced within the overall market.

Parsun Electric Outboard. Manufactured in China, there are two models to choose from, both running at 48 volts. The larger is rated at 5 HP with remote control only, long shaft and an electric tilt feature. The smaller is rated at 4 HP and comes in short or long shaft, with tiller or remote control. Both are rated at 130 lbs. thrust, though the 5 HP will produce 160 lbs. thrust for 10 seconds. These outboards feature a brushless, vertically-aligned, above water, water cooled motor, with gear reduction to a 7" aluminum propellor.. These are the least expensive of all electric outboards on the market today, though they are also the least efficient (the least thrust per horsepower, see Figure 3).

Minn Kota. Based in Wisconsin, Minn Kota has been a leading manufacturer of trolling motors since 1934. They offer one electric outboard designed mainly for pontoon boats. It runs at 48-volts (130 lbs. thrust estimated) and comes in two models: a remote control version that bolts onto the transom, and a tiller version. The outboard features a submersed, brushed motor on a 20" shaft, driving a 10" stainless steel prop. For its relatively low thrust, this outboard is heavy at 90 lbs. and requires at least four 12-volt batteries—which is fine for pontoon boats, but makes it a less attractive option for powering small boats with less weight capacity. It is mid-priced in the low power category.

A table summarizing all of these electric outboard models, including their specifications and their manufacturers' suggested retail prices (as of mid-2010) can be found in Figure 3.

Which models are best for the recreational boater?

If your needs dictate the most durable, heavy duty electric outboards available, the Ray Electric models are probably the best choice, as these are designed for continuous, commercial duty.

For the average recreational boater, though, with an efficient 12' to 20' hull carrying moderate loads, the Torqeedo outboards are hard to beat. They are extremely light weight, well engineered, have excellent electronics and are moderately priced. The only quibble is with their plastic propellors. The Parsun outboards are a low cost alternative, but their internal water cooling system makes them more appropriate for freshwater rather than saltwater use.

For the pontoon boat owner, the Minn Kota outboard is a reasonable choice, but only if you travel on still waters (with no strong currents or tides). For regular river and estuary use, you will likely need an outboard with greater thrust, such as the Torqeedo 4.0 or the Ray 300.

4. STORAGE BATTERIES

We are presently on the verge of a major revolution in storage battery technology, driven by the demand for lighter, more efficient batteries to power electric vehicles. Many new battery technologies are now under development, with lithium-ion currently the most promising. However, at mid-2010, none are commercially available at prices affordable to the recreational boater. When these lighter batteries do become available, they will greatly increase the range and performance of electric boats. In the meanwhile, we have to work with the best storage technology we have now, which is the deep cycle, lead-acid battery.

Which type of lead-acid battery is best for use on small boats?

The most widely used storage batteries on small electric boats are sealed, absorbed glass mat (called AGMs). It is easy to see why. Since all of their electrolyte is contained in the glass mats, there is no water to add and they cannot leak or spill acid, even if broken. The plates in AGMs are tightly packed and rigidly mounted, so they withstand shock and vibration better than any standard battery. Finally, they can be installed in any orientation (on their side, on their end, at an angle, anything except up-side down), which allows them to be fitted into many more locations on a small boat.

Other advantages: They have very low self-discharge (from 1%-3% per month) and they are almost immune from freeze damage. Since their internal resistance is very low, they can be recharged very quickly—and there is almost no heating of the battery under heavy charge and discharge currents. Also, their charging voltages are similar to flooded lead-acid batteries, so no special chargers are needed.

Drawbacks to AGMs: Their chief drawback is price. Though affordable, they are two to three times as expensive as comparable flooded lead-acids. Another shortcoming is their sensitivity to chronic undercharging—if an AGM battery (flooded battery too) remains in a discharged state for any length of time, sulfate quickly crystallizes on the plates, permanently diminishing the battery's capacity. So it's important to fully recharge AGM batteries after each day of boating and not let them sit around in a discharged state.

NOTE: AGM batteries are not the same as gel-cells. Gel cell batteries are not as vibration resistant, they cannot be fast charged like AGMs, and they require a special charger (or a lower voltage setting on a standard charger).

What size and capacity of AGM batteries are commonly available?

AGM batteries can be found in a bewildering variety of sizes and energy capacities—however, all are classified into "group" sizes that are based on the *physical size* of the battery and their terminal placement. Group size is not a measure of a battery's *capacity*, as this can vary between manufacturers within the same group size. Here's a listing of the group sizes most commonly used in small boat installations:.

Battery Group	Length, inches	Width, inches	Height , inches	Weight, lbs.	Capacity, amp-hours
Group 24	10.9	6.6	9.9	53 lbs	70-85
Group 27	12.6	6.6	10.0	63 lbs	85-105
Group 31	13.0	6.7	10.3	68 lbs	95-125
Group 30H	13.5	6.8	12.0	95 lbs	150
Group 4D	20.7	8.7	10.3	130 lbs	180-215

Figure 4. Common AGM Battery Sizes, 12-volt, less than 150 lbs.

AGM batteries are also available in other obscure group sizes of almost any dimension. Of particular interest are the larger capacity batteries (greater than 150 amp-hour) that are designed for specialized applications (e.g., aircraft or communications), but can easily be utilized on electric boats. When planning an installation, it's good to check beyond the standard sizes to see if there are alternatives that can better fit your use.

How are AGM batteries normally configured for electric outboard drive?

Using the 12-volt battery as the building block, battery banks are easily constructed to match the voltage of your electric outboard, whether 24-, 36-, 48-, or 60-volt. In small boat installations, batteries are normally connected in series, like this:

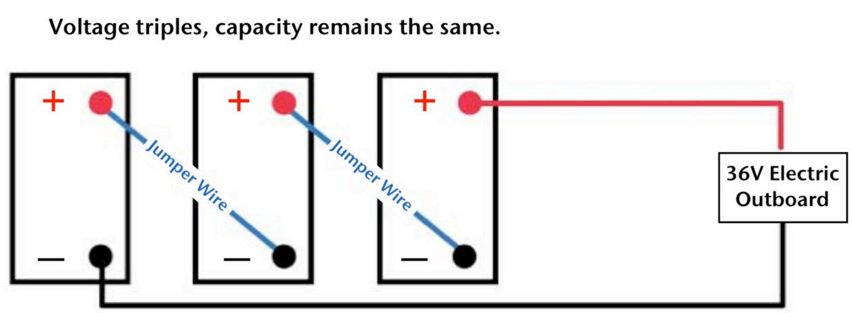


Figure 5. Three 12-volt Batteries Wired in Series for a 36-volt Electric Outboard

Notice that, though the voltage increases to 36 volts, the amp-hour capacity of the battery bank is unchanged. In other words, if you want to increase the capacity of your battery bank to give your boat a greater range of travel, often the only practical option is to install batteries with a higher rated capacity, e.g., 150 amp-hours instead of 100 amp-hours. Given the weight and space limitations on small boats (pontoon boats excepted), the option of adding a second battery bank, wired in parallel, to increase capacity is usually not practical. Choosing the right capacity batteries for your installation is thus critical and will be discussed in Section 5.

How long will my batteries last on a typical boat trip?

Once you've chosen an outboard powerful enough for your boat and installed a battery bank with enough reserve for the range of miles you normally travel, the rate at which your batteries deplete on a given trip depends mainly on your speed of travel. The faster you push your boat, the higher the amperage draw your outboard pulls from your battery bank (chart at left)—and the less total run time your boat will have (chart at right):

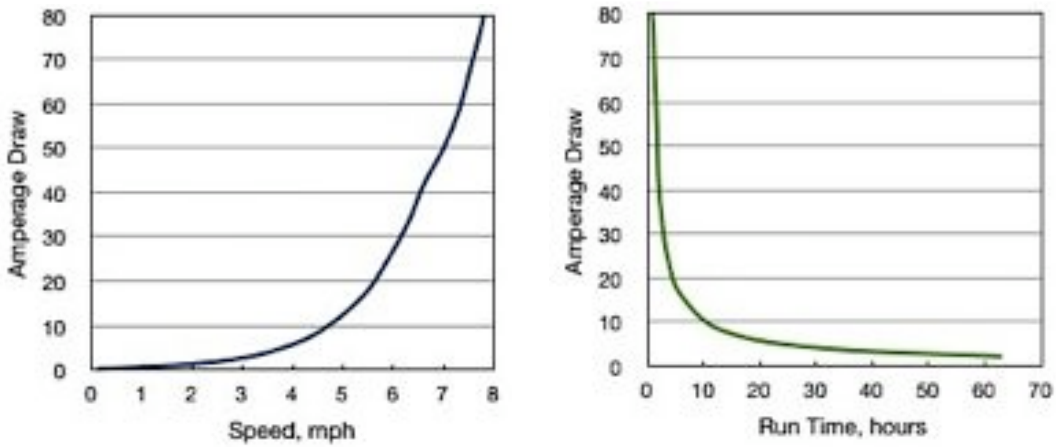


Figure 6. Relationship of Speed, Amperage Draw and Run Time
(18' Freighter Canoe, 48-volt Torqeedo 4.0 Outboard, 150 amp-hr Battery Bank, depleted by 70%)

Notice on these charts how, at 5 miles per hour, the outboard is drawing a reasonable 10 amps, which gives a run time of 10 hours (and a range of 50 miles). But if the boat is pushed up to 7 mph, the amp draw jumps to 50 amps, and the run time plummets to 1.7 hours (and a range of only 12 miles). Not to say you can't run your boat occasionally at 7 mph if you need to, but the takeaway point from these charts is that slower speeds can dramatically extend the duration and range of your electric boat trips.

As a general rule: The most energy efficient speed of a small boat is about 75% of its hull speed.

Keep in mind that these charts reflect a long, efficient, displacement hull boat, with a properly sized outboard and an ample battery bank drawn down by 70%. If your hull is shorter or less efficient, your outboard is underpowered or your battery bank is smaller, your mileage will vary!

Are some brands of batteries are better than others?

In the world of AGM batteries, you essentially get what you are willing to pay for. They are an industrial commodity in a very competitive marketplace, so prices tend to reflect the quality of the battery you're buying. The more expensive brands can have extra-thick or more pure lead plates, more rugged construction and are designed for a longer service life. But if your budget is limited, you can certainly find good quality, serviceable batteries at budget prices, so it pays to do some research. In mid-2010, the lowest web pricing is about $2.10 per amp-hour. However, there are a few battery brands that deserve special mention:

Lifeline AGM Batteries. This company has been a leader in the development of AGM batteries and produces them for the U.S Navy and Air Force, as well as for consumer marine and recreational applications. They have a strong reputation for making high quality AGM batteries, and they offer them in most common group sizes. Web pricing for Lifeline AGMs in mid-2010 is about $2.60 per amp-hour.

Odyssey AGM Batteries. Odyssey has distinguished itself in the consumer marketplace by supplying unique, military-grade, pure lead AGM batteries that can be used as both deep cycle storage batteries and as cranking batteries. The quality most attractive to electric boat applications is their outstanding ability to recover from deep discharges (70-80%) and to retain their rated capacity after many deep discharge cycles. Web pricing in mid-2010 is about $4.00 per amp-hour.

Valence Lithium-ion Batteries. Though these batteries are not yet in wide distribution, this company bears watching for the future. Under the brand name U-Charge, they produce batteries in group sizes 24 and 27 (unique for lithium-ions), which are 40% higher in capacity than AGMs but weigh 33% less! If they ever become widely available (and affordable), they can just be dropped into existing battery boxes on electric boats as replacement for AGMs. No battery management system is required, as each battery has one built-in.

What type of battery charger is best for AGM battery banks?

Though any modern, multi-stage “smart charger” can be used for AGM batteries, when multiple AGMs are connected in series, like on an electric boat, it’s recommended to use a multiple output charger (i.e., a bank charger) that connects individually to each battery. These chargers have separate positive and negative connectors for each battery, and a separate microprocessor as well. The advantage of charging each battery individually (instead of the whole bank together) is that any imbalances that develop between the individual batteries get corrected with every charge cycle.

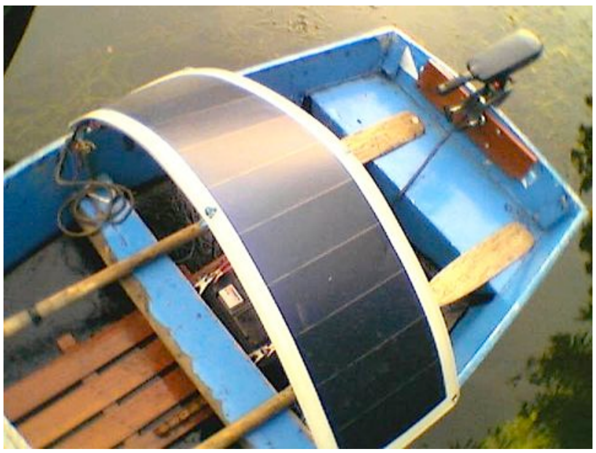
Bank chargers are available in models that charge one to four batteries, and can be combined to handle banks with more than 4 batteries (e.g., a three bank plus a two bank for a 5 battery pack). These chargers are self-contained and simply plug into a heavy-duty extension cord connected to a standard 120 volt, 15 amp outlet. They either shut off or go into “float mode” after recharging. The units are quite light and compact, allowing them to fit easily into onboard battery boxes—though they can generate quite a bit of heat while recharging, so it’s a good idea to open the lids and fully ventilate any enclosed cabinets containing them during the recharge cycle.

Since AGMs can handle very high charge currents, it makes sense to get the highest output bank charger you can find and afford, as it will reduce your recharge times. Several different brands are available to choose from at most marine supply outlets.

While on the go, can I recharge my batteries using solar or wind power or a gas generator?

For overnight trips or extended travel without access to shore power, many electric boat owners have contemplated using alternative methods of recharging their storage batteries. While many methods are technically possible, few of them are practical and affordable on small boats.

Hard glass solar panels, the least expensive and most efficient photovoltaics available, are unfortunately not suitable for use on small boats. There are flexible solar panels on the market, however, that can be used either while underway or when pulled up on shore. But these flexible panels come at a steep price (about $15 per watt, compared to $2 per watt for glass panels)—and most do not equal the energy efficiency of their glass counterparts.



While it would be cost prohibitive to purchase a large enough solar array to completely recharge a boat's battery bank, a smaller array of flexible panels can be used to "boost" or supplement the energy supply of an electric boat. These panels are generally wired in series if used for recharging a battery bank (to provide a high enough voltage), or they can be wired in parallel (to provide more current at their rated voltage). It is always recommended to install a solar charge controller to prevent both overcharging of the batteries and the back feeding of power into the panels at night. If using multiple panels, it is a good idea not to mix different panel sizes and manufacturers.

A wind turbine large enough to recharge even a modest battery bank is just not physically practical to install on a small boat.

A small, portable gas generator, however, can be a viable option for completely recharging a battery bank on an extended trip—but not without giving up many of the benefits that make electric boating worthwhile in the first place (simplicity, quiet running, zero emissions and low operating cost). Common sense suggests that using a gas generator to recharge batteries for an electric outboard will not be the most energy efficient method of propulsion, but it can be a practical means to temporarily extend the range of your electric boat on a longer trip.

The bottom line: While alternative methods are available to boost the energy supply of your battery bank (e.g., flexible solar panels) or to recharge it completely (e.g., a portable gas generator), neither method is a substitute for a properly-sized battery bank to begin with. If you plan to regularly take extended trips with your electric boat, it makes the best sense to install a larger capacity battery bank that will accommodate your extended run times.

5. SIZING THE SYSTEM

The two most important decisions a prospective electric boat owner will make are the size (power) of the electric outboard to purchase and the capacity (amp-hours) of the battery bank to install. Not only are these both large capital investments, but they both require a bit of planning before being installed in the boat—so you want to get these two decisions right the first time.

What factors determine the size of electric outboard to install on my boat?

Displacement Weight. The first factor is the total weight your boat displaces in the water. To determine this, first add up the weight of the people and their gear, then add a rough estimate of battery and outboard weight just to get started (see Figures 3 and 4). This gives the "payload" weight you'll be adding to your boat hull. Finally, add the weight of your boat hull itself:

People (2 @ 165 lbs.)…….……..	330		
Gear………………………………	50		
Outboard………………………….	70		
Battery Bank……………………...	300	750	(Payload Weight)
Weight of Hull……………….…...………		250	
BOAT DISPLACEMENT……………….….		1,000 lbs.	

NOTE: Before going further, it's a good idea to check the U.S. Coast Guard capacity plate on your boat hull. There you'll find two ratings: the maximum number and weight of people your boat is rated for, and the maximum rated weight capacity of your boat (including people). Be sure that your estimates above of people and "payload" weight conform to these USCG ratings.

Design Speed. For any given displacement weight, the faster you want to propel your boat, the more horsepower you're going to need. So it's helpful to decide on a design speed for your boat that you're comfortable with. For planning purposes, *a good design speed is the hull speed of your boat*. Applying even twice the horsepower won't propel a boat much faster than its hull speed. As we learned earlier, the formula for calculating a boat's hull speed is: Speed, in mph = 1.54 x square root of Length at Waterline, in feet. Since this handbook focuses on small boats from 12' to 20' in length, our hull speeds are going to range between 5.3 and 6.9 mph.

Note that hull speed is not the same as the most energy efficient speed for your boat. As we saw earlier in Figure 6, the most energy efficient cruising speed will be about 75% of hull speed.

Water Current. What if you regularly boat on waters with strong currents or tides, such as rivers and estuaries? One might think that by installing a more powerful electric outboard, you'd be able to maintain your hull speed against the current—the approach usually taken with gas outboards.

Figure 7 below shows a field test of the same electric boat running on a lake and then running upstream on a river against a 2.5 mph current. The takeaway point from this chart is that, if you regularly run against strong currents, it's impractical to expect hull speed in an electric boat. Even if you installed the highest horsepower outboard available, you might achieve hull speed, but

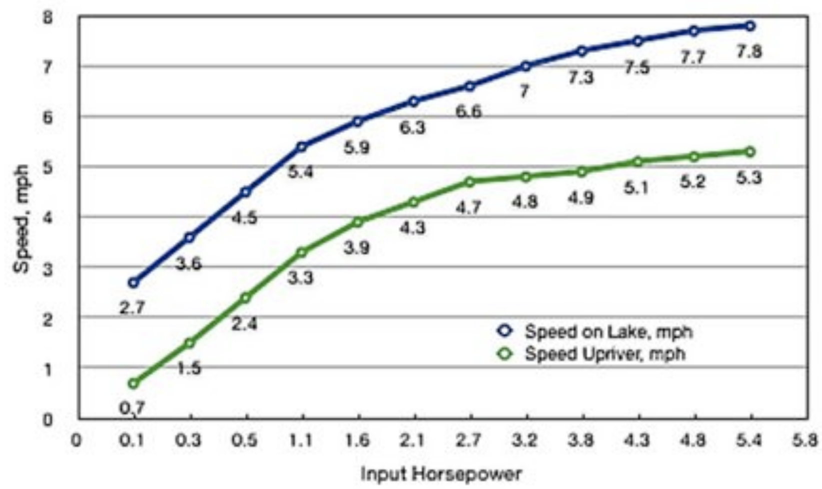


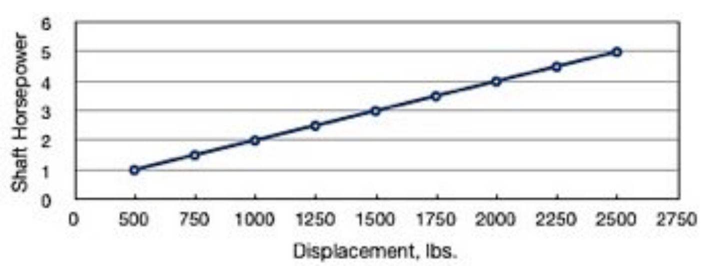
Figure 7. Effect of Current on Speed and Input Horsepower
(18' Freighter Canoe, 48-volt Torqeedo 4.0 Outboard, 6.5 mph hull speed, 2.5 mph river current)

you'd quickly deplete your battery bank. The better alternative is just to accept slower speeds against a current. If you subtract the current speed from your hull speed (in this case, 6.5 - 2.5 = 4.0 mph), you'll have a reasonable expected maximum speed for your boat against the current. Then if you multiply this by 75% (4.0 x 75% = 3.0 mph), you'll have the efficient boat speed.

Knowing displacement weight and hull speed, how do I determine horsepower required?

If you're content with the hull speed of your boat as your design speed, then the shaft horsepower required to propel the displacement weight of your boat at this hull speed is easy to calculate. The formula is *1 HP for every 500 lbs. of displacement*.

500 lbs.	=	1.0 HP
750 lbs.	=	1.5 HP
1,000 lbs.	=	2.0 HP
1,250 lbs.	=	2.5 HP
1,500 lbs.	=	3.0 HP
1,750 lbs.	=	3.5 HP
2,000 lbs.	=	4.0 HP
2,250 lbs.	=	4.5 HP
2,500 lbs.	=	5.0 HP



Please note that these shaft horsepower requirements are for true displacement hull boats only. If the outboard is being installed in a planing hull boat that you know is going to be less efficient (have more drag), it's reasonable to choose the next higher horsepower motor—say a 4 HP instead of a 2 HP. Conversely, if the installation is in a multi-hull boat such as a pontoon boat or catamaran with more efficiency than a mono-hull displacement boat, you could choose the next lower horsepower motor, at least for use in still waters (no currents). If you are in between motor sizes for a displacement hull boat, choose the next higher horsepower motor.

How do I determine the capacity of the battery bank needed?

Once you've chosen an outboard that properly fits the weight and efficiency of your loaded boat, the next task is to size the battery bank that will store the energy to drive it. The size of the battery bank will depend on the amp draw you plan to regularly place upon it and the range of miles you desire to travel—and will be limited by the payload capacity of your boat to carry the batteries.

Amp Draw of Outboard. In designing a battery bank, it's helpful to first estimate the expected amp draw of your outboard at the cruising speed you normally expect to travel. Above, we determined that hull speed would be the design speed of the boat—and we saw that the most energy efficient speed would be about 75% of hull speed. But how many amps will this draw?

The answer depends upon the voltage of the outboard you've chosen. Figure 8 shows the input horsepower (consumption) of motors running at 36-, 48- and 60-volts. If your outboard is sized correctly, it will almost never be running at full horsepower—your normal power usage will be some fraction of this. A good estimate for design purposes is *one-quarter of full input horsepower*, which will produce a speed about half way between hull speed and most efficient speed in most boats. The amp draw at one-quarter input horsepower will vary for each motor voltage, but is calculated as follows (for the 48-volt motor):

5.2 HP x 25% = 1.3 HP
1.3 HP x 746 watts = 970 watts
970 watts/48 volts = 20.2 amps

If we make these calculations for all three outboards in Figure 8, we arrive at these design amperage draws:

36-volt Outboard = 15 amps

48-volt Outboard = 20 amps

60-volt Outboard = 22 amps

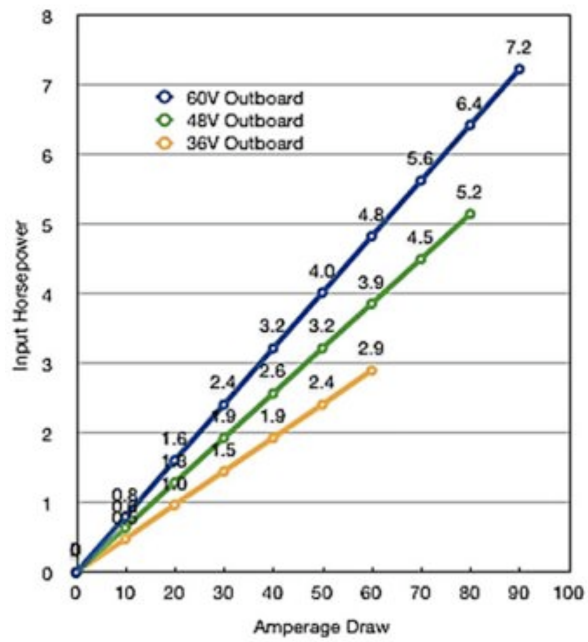
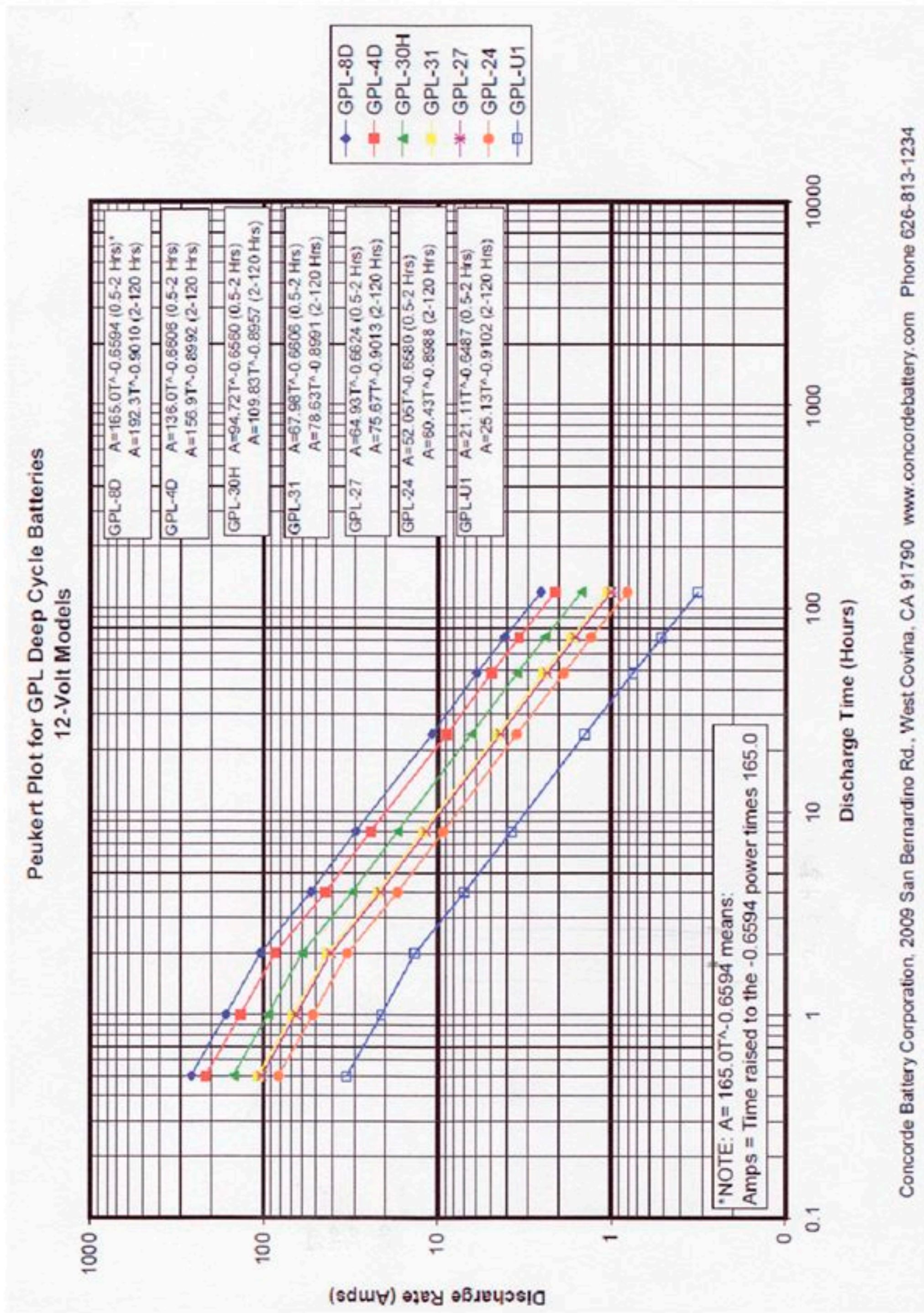


Figure 8. Input Horsepower and Amp Draw

With these design amperage draws (based on one-quarter full input horsepower) and a properly sized battery bank, a boat should enjoy comfortable cruising capacity as well as plenty of reserve power for the unexpected—such as running against a wind or tide for an extended period, changes in trip plans or an emergency.

Discharge Rate of Batteries. If lead-acid batteries yielded their energy uniformly at all amp draws, our job would now be easy. We could simply divide the amp-hour rating of prospective batteries by our design amp draw and we'd know the number of hours of travel we'd have (allowing for a reserve)—for example, a 100 amp-hour battery drawing 20 amps will last 5 hours (or 3.5 hours, if we limit our depth of discharge to 70%). But batteries don't behave this way.

Figure 9. Discharge Curves for Common AGM Battery Group Sizes



The lower the amp draw on a lead-acid battery, the more easily it yields up its energy. As the amp draw increases, it yields up its energy more reluctantly. Figure 9 shows the discharge curves for most common group sizes of batteries (i.e., Group 24, 27, 31, 30H and 4D—see Figure 4). If you locate your design amp draw on the left of this chart, you can read across and determine the hours of travel time for each battery size. Remember to multiply by 70%, the depth of discharge limit.

From here, sizing your battery bank is just an iterative process, where you compare discharge (run) times with battery weights, and then compare these weights with the payload capacity of your boat—and back again, until you've reached an acceptable balance between boat run time, battery weight and the payload capacity of your boat.

Capacity Guidelines. Over the years, based on the experience of electric boaters and the recommendations of engineers, a few guidelines have developed for the proper capacity of battery banks. Once you've worked out the capacity of battery bank that fits your boat and your intended needs, it's a good idea to check your number against these guidelines.

Rule # 1: Average amp draw should not exceed 20% of bank capacity.

Using the design amp draws for the three motors in Figure 8 (based on one-quarter of full input horsepower), we can determine the *minimum* battery bank capacity for each of these motors:

36-volt Outboard:	15 amps/20%	=	75 amp hours
48-volt Outboard:	20 amps/20%	=	100 amp hours
60-volt Outboard:	22 amps/20%	=	110 amp hours

Rule # 2: Peak (short duration) demand should not exceed 40% of bank capacity.

If we assume a peak, short duration demand of *one-half* of full input horsepower for the three motors in Figure 8 (which will be pushing most boats beyond their hull speed), we arrive at exactly the same numbers—which confirms these minimum bank capacities:

36-volt Outboard:	30 amps/40%	=	75 amp hours
48-volt Outboard:	40 amps/40%	=	100 amp hours
60-volt Outboard:	44 amps/40%	=	110 amp hours

Rule # 3: The depth of discharge should not exceed 70% of bank capacity.

As discussed, battery manufacturers recommend a 50% depth-of-discharge limit for maximum battery service life. However, if you recharge your battery bank immediately after use each time, most electric boaters are satisfied with the service life provided by a 70% deep discharge limit—and are happy for the extra miles they can travel on their battery banks.

6. DESIGNING THE LAYOUT

Once you've chosen an electric outboard for your boat and determined the number and capacity of storage batteries you need, before going ahead with the installation, it's wise to spend some time planning the physical layout of this equipment. This will insure that your boat rides level in the water and that you've got enough flotation aboard to keep her afloat if swamped. We'll discuss the wiring layout in the next section.

To maintain level boat trim, how do I position the batteries?

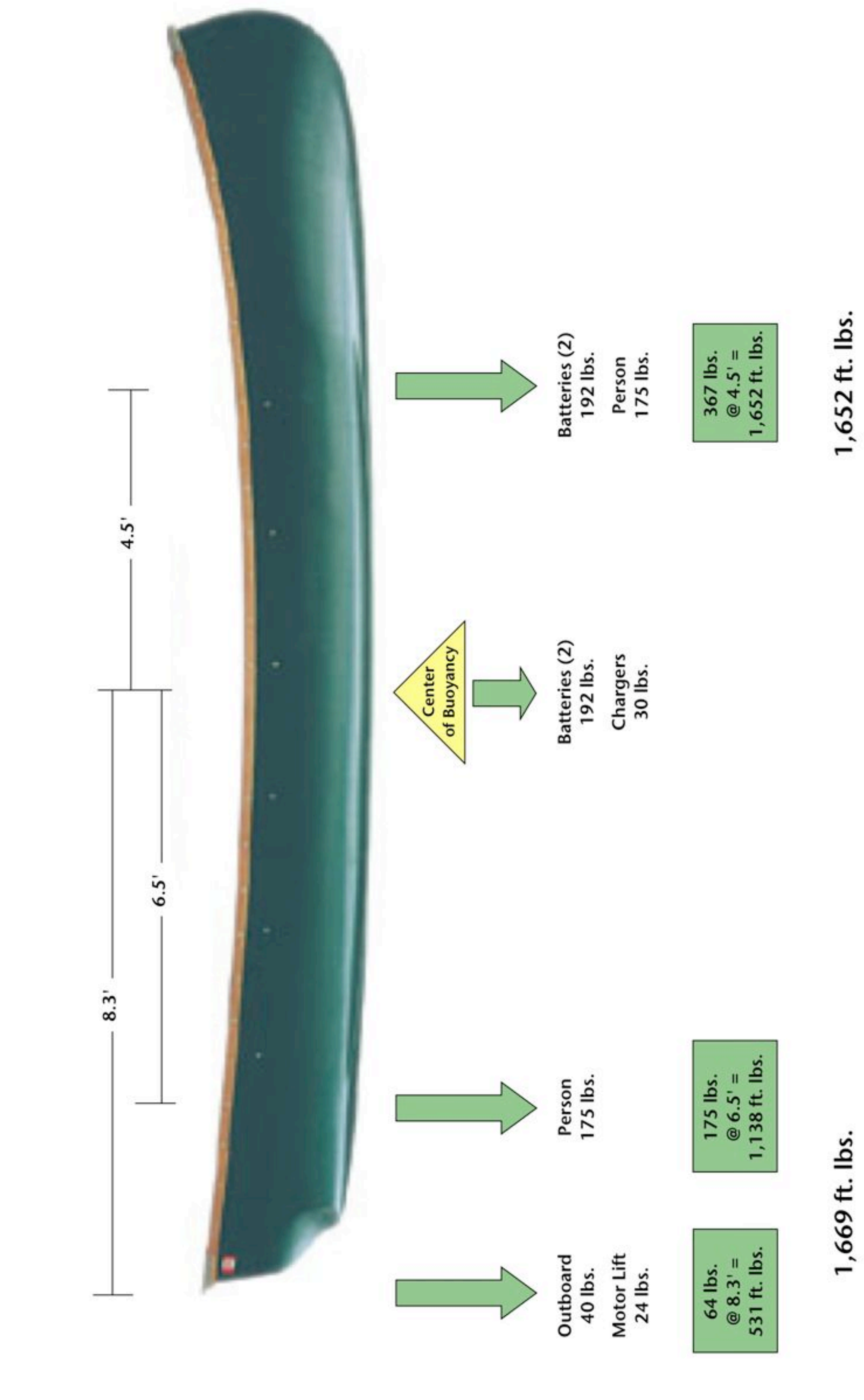
Positioning the batteries properly requires some forethought. Having your boat run at level trim adds to its efficiency as it travels through the water. Also, adding batteries presents an opportunity to correct any trim imbalances that might already exist in your boat. With a few simple calculations, you can ensure that your entire installation will be level and trim neutral. (We are indebted to David Gerr and his book, *The Nature of Boats*, Chapter 16, for this insight).

The first step is to locate the center of buoyancy in your boat. With smaller hulls, this can be done by physically placing the boat on a fulcrum point (e.g., a 2x4 flat on a concrete floor) and finding the balance point. With larger hulls and access to a boat hoist, the same thing can be accomplished by placing nylon straps under the hull and making a few test suspensions until the exact balance point is found. If neither of these methods is practical, the center of buoyancy can be estimated, according to Mr. Gerr. For displacement hull powerboats, it is approximately 55% of the waterline aft of the bow. For planing hulls, it can be as much as 65% aft of the bow—with 60% being a good average for most powerboats.

The further we place any load (batteries, outboard, passengers and gear) from the boat's center of buoyancy, the more it will raise or lower the bow and stern. Any load placed right at the center of buoyancy will of course have no effect on trim. The trick is to balance all the added loads on each side of the center of buoyancy, like balancing a see-saw, so the net effect on boat trim is zero. Figure 10 shows a sample set of calculations for balancing a boat's trim.

As you can see, it's first a matter of establishing the weight of each load (in lbs.) and the distance (in ft.) of each load from the center of buoyancy. When we multiply pounds times feet for each load, we get foot pounds—which is what we're aiming to balance, fore and aft of the balance point. By adjusting each weight and its distance from the balance point, you can work out the best positions for your batteries, passengers and equipment in just a few minutes with a calculator and a scratch pad.

Figure 10. Sample Calculation for Neutral Boat Trim



Do I need to install extra flotation to offset the added battery weight?

The U.S. Coast Guard requires manufacturers and builders of mono-hull boats less than 20' in length and rated for more than 2 HP (except canoes, kayaks, etc.) to install sufficient flotation so the boat will float level near the surface when swamped with water (the Level Flotation Standard). The idea is for passengers to be able to remain inside the hull and possibly be able to bail out the boat and proceed to shore. If your boat was built after August 1978, it will already have sufficient flotation to meet this standard.

Though the regulations don't address *modifications* to boats, it just makes sense that, if you're going to add 300 lbs. of batteries to your craft, you should also add enough flotation to offset this weight. The USCG has a helpful handbook entitled Safety Standards for Backyard Boat Builders (available here: files.dnr.state.mn.us/education_safety/safety/boatwater/backyardboatbuilders.pdf), which outlines how to calculate the volume of flotation needed, the types of flotation available and where to place it in the boat. We'll briefly summarize a few highlights here.

Volume of Flotation Needed. The calculation for volume entails listing the weight of all the materials you're adding to the boat, multiplying these weights by a specific gravity factor for each material (some, like wood, will have a positive buoyancy), then summing the total:

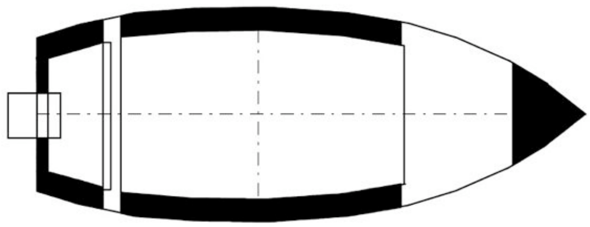
	Weight	Factor	
Batteries……………..	272 lbs.	0.91	248
Chargers and Wiring....	30 lbs.	0.70	21
Wood Seat Boxes…….	70 lbs	-0.81	-57
Total……………………………………….			212 lbs.
Divided by Buoyancy of Foam, per cu. ft……			60.4
Flotation Needed to Support Weight, cu. ft ….			3.5, rounded up to 4 cu. ft.

The USCG Handbook provides specific gravity factors for all the most common materials. To determine the buoyancy value of any flotation material, subtract its weight per cubic foot from 62.4, the weight of a cubic foot of water. For example, 2-pound density foam will provide 60.4 lbs. of buoyancy per cubic foot (62.4 - 2.0 = 60.4).

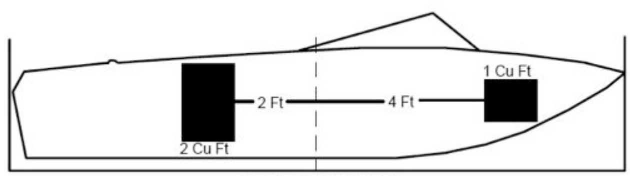
Flotation Material. By far the easiest material to work with for the do-it-yourselfer is blocks of foam, which come in a variety of densities, sizes and colors. Another option is two-part, pour-in-place, liquid urethane foam that expands into cavities, though this is much trickier to install. Air bags or air chambers can also be used, but these are subject to puncture and are hard to secure.

If you decide on foam blocks, you want to choose a foam that doesn't absorb water, doesn't break down easily in sunlight and is resistant to solvents (e.g., gasoline). This leaves out polystyrene (styrofoam and rigid foam board). Polyurethane foam is an option as it resists gasoline, but it quickly degrades in sunlight, so can only be installed in fully protected compartments. The best (and most expensive) foam is polyethylene, a closed-cell foam that is gasoline, sunlight and abrasion resistant and doesn't absorb water. It can even be left exposed to the elements, without protective covering.

Location of Flotation. Since we're adding flotation to a hull that the manufacturer has already built to meet the Level Flotation Standard, we want to avoid imbalancing this existing flotation. The easiest way is to place the new flotation in the same location as the new batteries (assuming you've already positioned these for neutral trim). In other words, if you're installing battery boxes or battery seat boxes, just oversize them sufficiently that they hold enough foam to offset the weight added in each box. If this isn't practical, another option is to distribute the new foam uniformly around the hull, which will preserve level flotation if the trim is already balanced.



The final alternative is positioning the foam wherever you can in the boat, but taking care to balance its volume and distance fore and aft of the boat's center of buoyancy—using a similar calculation method as used above for boat trim.

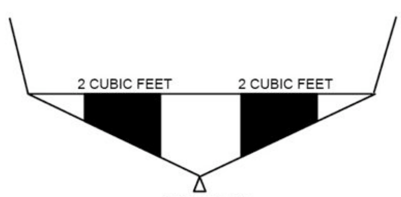


UNEQUAL QUANTITIES
TWICE THE QUANTITY - HALF THE DISTANCE
FROM MIDPOINT

Any more tips for designing the boat layout?

- Position the batteries as low as you possibly can in the boat, even laying them on their sides if practical. This will lower the center of gravity and improve stability in most small boats.

- Be mindful also of side-to-side balance when positioning the batteries and the added flotation. You want to maintain side-to-side trim and level flotation over the centerline of the boat, just as you do fore-and-aft. Uneven side-to-side loads can be positioned and balanced using the same calculation method as for the fore-and-aft loads above.



(We are indebted to the USCG Handbook, *Safety Standard for Backyard Boat Builders*, published in 1993, for the floatation information and drawings above).

7.   PLANNING THE WIRING

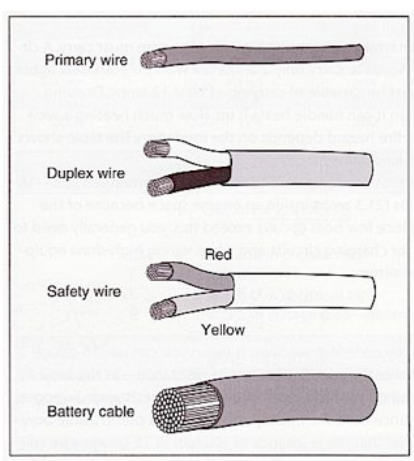
Once you are comfortable with the location of the loads and flotation in your boat, including the batteries, the chargers and the passengers, it's time to plan the layout of the wiring. This need not be elaborate, just a simple wiring diagram such as Figure 11, which locates the various wire runs, the breakers and the master switch. Don't be tempted to skip this step—it's better to make your revisions at the planning stage than to rip out wiring you've installed in haste. The wiring diagram can also help you develop a shopping list for electrical components and connectors.

What type and size of wire and terminal connectors should I install?

Every wire you install in your boat needs to be the correct type to withstand flexing and vibration, the right size to match the current it is carrying, and properly insulated to resist moisture, solvents and sunlight. Wiring your electric boat is not a project you want to re-do or take chances with, so it makes sense to use only the best materials and to install these to the highest standards.

Type of Wire. All boat wiring must be copper, but not all copper wire is the same. Solid-core copper wire should never be used in a boat, as the vibrations of the motor and waves will eventually fracture it. Stranded cable is more flexible and is therefore standard for marine applications. Type 3 stranded cable has the most strands, is the most flexible (very useful in the tight quarters of small boats) and is the best for all the wiring on your boat.

All copper wire eventually corrodes with marine use, reducing its conductivity, especially at terminals and connections. Plating each strand with a thin coat of tin significantly improves corrosion resistance. Tinned cable is more expensive than regular cable, but the long term benefits are well worth the cost. How often do you want to re-wire your boat?



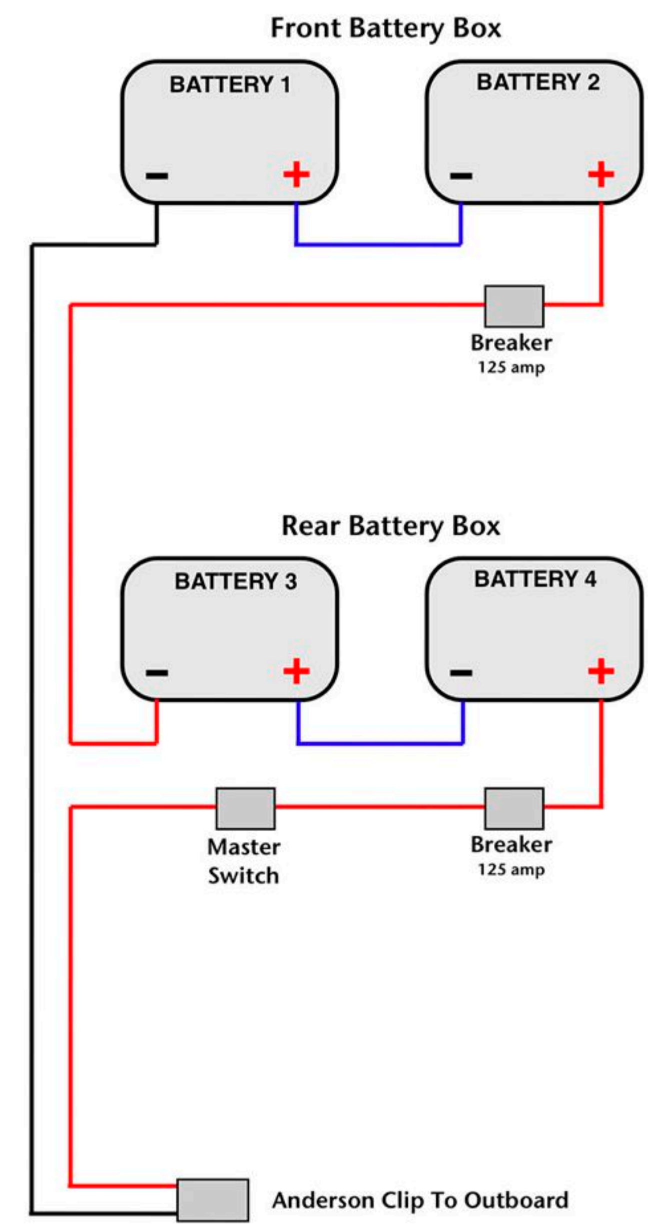
Source: Don Casey, *Sailboat Electrics Simplified*, 1999.

Stamped on the insulation of all wire are codes for the type of wire, voltage, wire size and heat and moisture ratings. To avoid entering this thicket of ratings, you cannot go wrong if you only buy wire for your boat that is rated "BC5W2, Oil Resistant"—and is called boat cable.

To summarize, the best wire for electric boats is *tinned boat cable with Type 3 stranded copper conductors in an oil resistant jacket*. If you don't have a reputable marine supply house near you, this wire is available from: http://shop.genuinedealz.com/ , and is sold by the foot or in 25', 50' and 100' rolls.

Boat cable comes in a variety of colors, but it's best to stick with the standard ones—red for DC positive leads and either black or yellow for DC negative leads. To be super correct, you could choose yellow for the negative leads, as this has officially replaced the former black for all DC circuits (to distinguish them from AC marine circuits, in which black still = 'hot'; white = 'ungrounded', or sometimes known as neutral).

Figure 11. Sample Wiring Diagram for 48-volt Outboard



Sizing of Wire Cables. All electrical cables have a certain internal resistance, so anytime a current passes through them, some heat is generated. At a certain level of current flow, any cable will become hot enough to start a fire. To be safe, cables have to be sized large enough to handle the maximum expected current on the circuit without overheating.

The first step in wire sizing then is to determine the maximum current that will flow through the wire. For an electric outboard, this is its maximum amperage draw, and will vary between 40 and 100 amps, depending on the size of the motor. Refer to your motor specifications.

The second step is to measure the actual distance from the farthest battery to the equipment *and back again*. Just doubling the straight line distance is not enough. You must determine the actual length of the wire by measuring carefully along its path—up, over and around. Each wire should be a single, continuous run between terminals. It's wise to install a foot or two of extra wire in each run (i.e., a service loop) in case you need to adjust battery positions or replace connectors.

Thirdly, you need to account for voltage drop in the circuit. You'll find many 10% voltage drop tables designed for conventional DC circuits, but for electric outboard circuits and most marine wiring you shouldn't accept more than a 3% voltage drop. Also, most tables are designed for 12-volt circuits, which aren't any help in sizing a 36-, 48-, or 60-volt circuit for an electric outboard. Fortunately, there is a wire size formula that can be adapted to any circuit voltage :

$$CM = \frac{I \times L \times 10.75}{E}$$

where, CM = Wire Size, in circular mills
I = Maximum Current, in amps
L = Length of Wire (round trip), in feet
E = Allowable Voltage Drop at 3%, in volts
(E = 0.36V for a 12-volt circuit
0.72V for a 24-volt circuit
1.08V for a 36-volt circuit
1.44V for a 48-volt circuit
1.80V for a 60-volt circuit)

(Source: Nigel Calder, *Boatowner's Mechanical & Electrical Manual*, Third Edition, 2005)

Once you've calculated the size of wire needed in circular mills, you can refer to Figure 12, which will tell you the corresponding AWG wire size. Choose the AWG wire size that exceeds your calculated value of circular mills, as bigger is always better in sizing electrical wires.

Terminal Connectors. Most all wiring problems occur at the terminal connections, so it's good to take extra care when installing these. Terminals used on a boat must always be copper (never aluminum or steel) and they should be tin-coated to resist corrosion.

Crimp-on ring terminals are the best choice for most connections. Selecting the right size requires that you properly match both the wire gauge and size of the terminal screw. Household wire nuts are never allowed in marine applications, so if you need to join wires, get the proper crimp-on, tinned copper butt connectors that match your wire size.

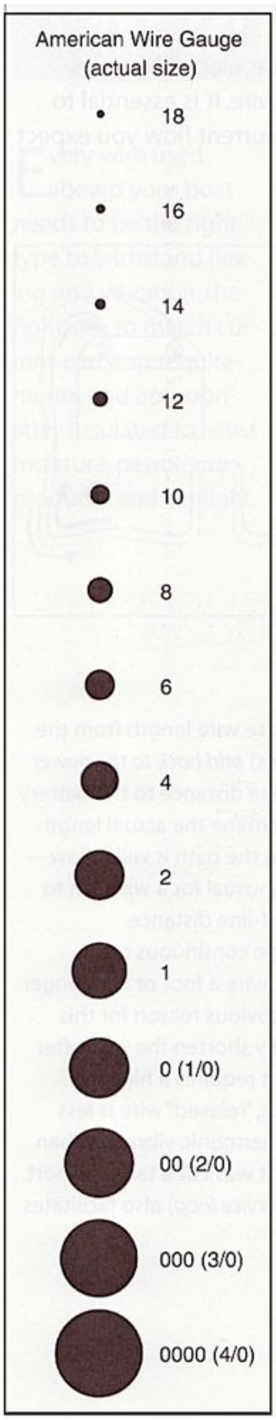


Figure 12. American Wire Gauge (AWG) Sizes

WIRE RESISTANCE		
Circular Mils (CM)	**Wire Gauge (AWG)**	**Ohms per 100 Feet (@ 77°F)**
1,620	18	.654
2,580	16	.409
4,110	14	.258
6,530	12	.162
10,380	10	.102
16,510	8	.064
26,240	6	.040
41,740	4	.025
66,360	2	.016
83,690	1	.013
105,600	0	.010
133,100	00	.008
167,800	000	.006
211,600	0000	.005

Note: Circular mils are calculated by squaring the wire diameter in mils (thousandths of an inch)

Source: Don Casey, *Sailboat Electrics Simplified*, 1999.

In order to make quality crimp connections, you'll need the proper tools. Because SAE wire is smaller, most hardware store wire strippers will cut into AWG wire. You can use a larger wire hole in a standard stripper, but it's better to get a wire stripper designed for AWG wire. When installing heavy battery cable (greater than 6 gauge), such as for the electric outboard circuit, you'll need heavy wire cutters and a special crimping tool. These circuits will be carrying heavy loads, so it's especially important that these connections be done properly. There are several tools available for crimping large cable connectors, but one of the most inexpensive and effective is the hammer crimp tool. You simply place the wire in the connector, place the connector on the anvil, and strike it until the connector is tight. The only way to test for a proper crimp job is to pull hard on the crimped connection after you've finished—if you've done the job right, it won't come loose.

Finally, soldering the crimped connection is not necessary. Many do-it-yourselfers swear by it, but most experts agree that a properly-made mechanical crimp, done with right tools, is not only reliable but preferable. What is required, though, is heat shrink tubing to seal all terminal connections from moisture. The tube is slipped over the crimped connection, heated with a heat gun, and shrunk to form a tight fit around the terminal barrel and the wire. Electrical tape is never a substitute! Use only the best heat shrink tubing that is thick-walled with an adhesive lining.

What type of overcurrent protection should I install and where?

Overcurrent protection should be provided for each circuit *at the source of power*. For the electric outboard circuit, this is at the battery bank (see Figure 11). For secondary circuits, this could be at the battery bank or at a point of connection some distance from the bank (e.g., at a buss bar— see Section 8 on Accessories). The takeaway point is that EVERY positive (red) lead from your battery bank and other points of connection to a DC circuit needs overcurrent protection.

The general rule is to install the overcurrent protection *within 7 inches* of the source of power. Since we're using AGM batteries (which release only minute amounts of explosive gases during charging) in the open air or in well-ventilated battery boxes, it's possible to install the breakers and fuses close to the batteries—in fact, right in or just outside the battery boxes. However, only ignition-protected breakers should be used. It is also allowed to install the circuit breaker or fuse *as close as practical* to the battery—but no further than 72 inches away—if the positive lead is sheathed in a flexible plastic conduit. So there is some flexibility here.

Circuit breakers don't protect a circuit any better than a fuse, but since they can be manually reset (without the need for having the right replacement fuse onboard), they are preferable for the high amp circuit powering the electric outboard. Breakers can also do double duty as a switch to de-energize the circuit. In-line fuses are more appropriate for smaller, secondary circuits. They are cheap, foolproof, and inconvenient only when they blow—which will be almost never in a properly wired circuit. But you'll still need to keep a stash of extra fuses onboard.

What size of overcurrent protection should I install?

Overcurrent protection is installed *to protect the wire* and not the equipment to which the wire is running. Most equipment, such as an electric outboard, will have its own overcurrent protection built in. So first we need to determine the type of overload we're trying to protect the wire from.

If a wire feeds a predetermined load that does not change (e.g., a depth finder), the main concern is short-circuit protection. The circuit wire is already sized so that it safely carries its intended load. If there is a short, the high current only lasts a brief moment before the fuse blows, and therefore does not generally damage the wire. Precise sizing of short-circuit protection is thus not critical. A fuse or circuit breaker rated at an amperage equal to the wire rating, or even up to 150% of the wire rating, is sufficient because the over-current condition lasts only a brief time.

However, if the wire feeds a load that is variable (such as an electric outboard motor) and can increase into a *sustained* overload condition of 110%-150% of the wire rating, the wire and the protective device in the circuit will heat up. This makes selecting a fuse or breaker more complex than choosing one for simple short-circuit protection.

In general, wire should not continuously carry a current at more than 80% of its rating. The blow point or trip value of most circuit protectors is about 130% of their nominal rating. Thus, to provide sustained overload protection for a wire, choose a protection device that is rated at 80% of the wire's capacity. The amp capacities for AWG wire sizes are shown in the table at right.

Allowable amperage of conductors under 50 Volts with 105˚C insulation

AWG Wire Size	Metric (Sq mm)	AWG CM Area	SAE CM Area	Ohms /1000ft	Ampacity Engine Space Outside	Inside
18	0.8	1,600	1,537	6.385	20	17
16	1	2,600	2,336	4.016	25	21.3
14	2	4,100	3,702	2.525	35	29.8
12	3	6,500	5,833	1.588	45	38.3
10	5	10,500	9,343	0.9989	60	51
8	8	16,800	14,810	0.6282	80	68
6	13	26,600	24,538	0.3951	120	102
4	19	42,000	37,360	0.2485	160	136
2	32	66,500	62,450	0.1563	210	178.5
1	40	83,690	77,790	0.1239	245	208
0	50	105,600	98,980	0.09827	285	242.3
2/0	62	133,100	125,100	0.07793	330	280.5
3/0	81	167,800	158,600	0.06180	385	327.3
4/0	103	211,600	205,500	0.04901	445	378.3

Source: Blue Sea Systems

Example: Choosing a Fuse or Breaker for Short-Circuit Protection
According to the table, a 4 gauge AWG wire will safely carry 160 amps. Since fuses blow at 130% of their nominal rating, choose a fuse that is rated at 80% of 160 amps (80% x 160A = 128A). A 125A nominal rated fuse is a good choice—it has blow point of 162A (125A x 130%).

Sizing Circuit Protection to the Load
A fuse or breaker should not continuously carry more than 80% of its rating to avoid overheating the circuit protector itself. In the above example, we chose a 125A fuse to protect the 4 gauge AWG wire. The fuse should not carry more than 100 amps continuously (125A x 80%). If the maximum sustained load on this circuit is less, this fuse (or breaker) is fine. If the maximum sustained load is greater, choose a larger wire size and a larger circuit protector.

(We are indebted to Blue Sea Systems at http://bluesea.com for the table, examples and main points above.)

8. WIRING 12-VOLT ACCESSORIES

Installing a battery bank for propulsion on your boat creates a huge reservoir of electrical energy that begs to be tapped for myriad other uses beyond propulsion. Once you begin to think about it, many ideas for adding electrical accessories to your boat will cross your mind—a fish finder or a simple depth sounder, a bilge pump, an outboard lift, running lights—the possibilities are many. When you begin to add 12-volt accessories, though, you're immediately faced with the problem of getting 12-volts out of your 36-, 48- or 60-volt battery bank.

How do I get 12-volt power from my battery bank?

Stand-alone 12-volt Battery. One option is to leave your propulsion battery bank alone and add an extra 12-volt battery and circuit that are dedicated only to your 12-volt accessories. However, most small electric boats are already near their weight and space limits after installing the propulsion battery bank, and they just can't accommodate yet another battery. An exception would be pontoon boats, where weight and space are less limited. In this case, be sure to size your bank charger(s) to include the extra battery—for example, a four bank charger for a 36-volt propulsion bank plus the stand-alone accessory battery.

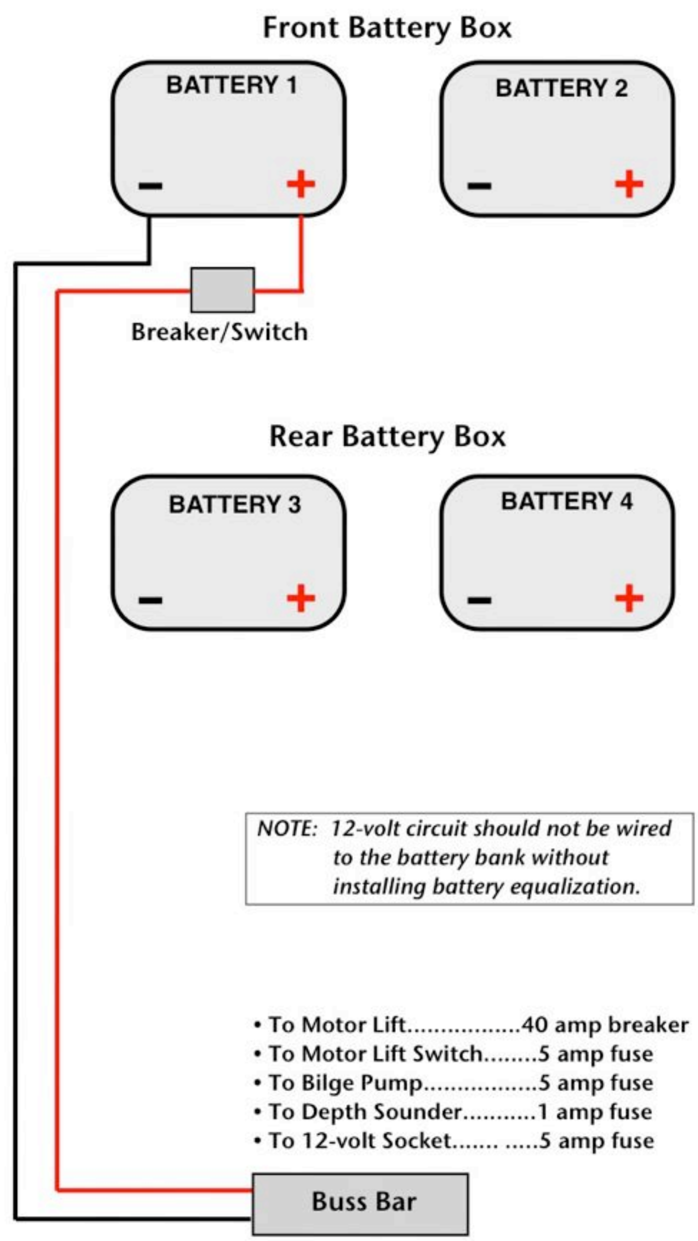
DC-to-DC Converter. If your 12-volt power needs are modest, say up to 15 amps, a converter that steps down the voltage of your propulsion battery bank (from 24, 36, 48, or 60 volts) to 12 volts can easily be installed. Converters are available up to 50 amps output, but these are bulky, expensive units that are probably beyond the scope of most small boats. One advantage of a DC converter is that it acts like a filter, taking out voltage transients and spikes from your battery bank, and producing a clean DC output with no electrical interference. This is a benefit if you plan to install sensitive 12-volt electronics such as a marine VHF radio, a GPS or a fish finder. Follow the wiring and installation instructions that come with your model of DC converter.

Battery Equalizers. If your 12-volt needs include heavy, variable loads (such as an outboard tilt/trim unit), the best option is to tap one of the 12-volt batteries in your propulsion battery bank. With your 12-volt equipment wired directly to a battery in your bank, it can supply its full output, including any surge loads. The downside is that the tapped battery will get drawn down more than the other batteries, creating an imbalance in the bank. The solution is battery equalizers, which sense the falling voltage in the tapped battery and draw energy off the other batteries in the bank to "recharge" the tapped battery. This keeps all the batteries in an equal state of charge/discharge.

There is a limit, however, to how much energy these equalizers can shuttle between batteries to keep them balanced. As a rule of thumb, it's best *to limit your 12-volt loads to 10% of your battery bank capacity*. For example, if your battery bank has a capacity of 150 amp-hours, it can handle a continuous 12-volt load of 3 amps for 5 hours, or 30 amps for 30 minutes.

Figure 13 shows a sample wiring diagram for a 12-volt accessory circuit connected to one battery in a 48-volt bank. It is generally recommended to tap the most negative battery in the bank, in this

Figure 13. Sample Wiring Diagram for 12-volt Accessory Circuit

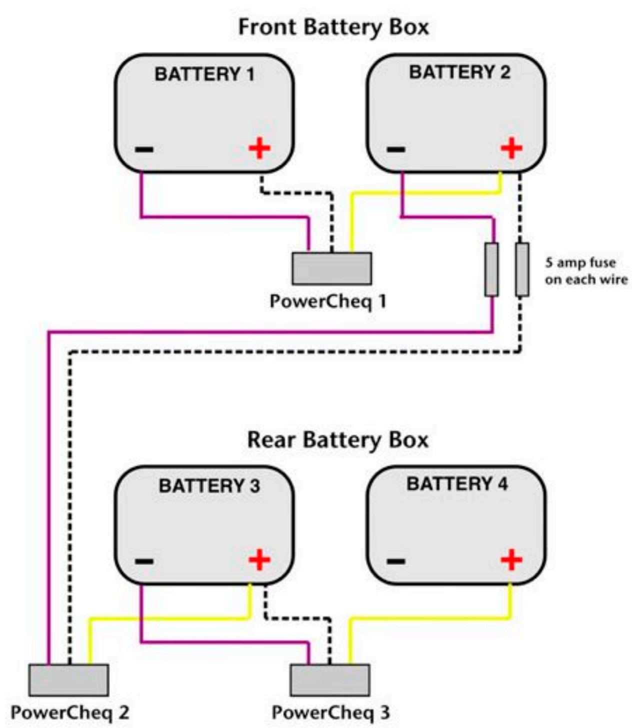


case Battery #1, to avoid the potential for ground loops. If you are powering multiple 12-volt accessories, rather than run each accessory circuit back to the tapped battery, it's often better to run one heavy cable to a conveniently located buss bar, from which smaller secondary circuits can service each accessory. This will reduce the clutter on your battery terminals and create a cleaner installation.

If I use a battery equalizer, what type is best?

You can sometimes find battery equalizers that are designed as central, stand-alone units, with leads going to each battery in the bank. However, the selection is quite limited for battery banks above 24 volts—and those that are available tend to be large, bulky boxes with fixed amperage outputs. For example, one 48-volt equalizer used in solar installations is a box 10"x12"x4" and is limited to 30 amps output. This is a bulky installation to fit in most small boats.

A better solution can be small, modular equalizers that connect between each battery in the bank. Because they are modular, they can be used in any size of bank with any number of batteries. You buy only as many modules as you need—usually one less module than the number of batteries in the bank. One brand of modular equalizer with a good track record is called PowerCheq, and is available on the web. These are small 2.4"x2.8"x0.9" units, fully fused, that equalize during charging, discharging and at idle. If the equalizers cannot keep up with a particular load you've placed on the tapped battery, they catch up after the load is turned off—in fact, they are running 24/7 (and always drawing a minute amount of energy from the bank). A wiring diagram for PowerCheq equalizers in a 48-volt bank:



Do I need a battery bank monitor?

All electric outboards have some type of battery meter built into them, either on the remote control console or on the motor cowling itself. Some are simple “fuel gauge” meters (such as the Ray Electric models), while others are more sophisticated state-of-charge meters that give both voltage and current, and even speed and remaining range via GPS (as in the Torqeedo models).

If you desire more detailed information about the status of your battery bank, such as the state-of-charge of individual batteries or the total amp hours used, there are third party battery monitors you can install. Popular models include the Xantrex Link 10, the Vitron BMV 600 and the Paktrakr 600. Each has different options, recording and displaying data somewhat differently, so it pays to do your research to find the one that best suits your needs.

Is it important to route electronic data wires separately from power cables?

Yes! Because of the potential for electro-magnetic interference, especially from the high amp cables serving the electric outboard, it pays to route all your power feed cables (including the 12 volt wires) on one side of the boat, and all your sensitive electronic data wires on the opposite side, if possible. It’s also good practice not to separate the positive and negative leads of any power circuit—these should be run as pairs in the same conduit on the same side of the boat.

Sensitive electronic wires include the transducer wire running to your fish finder or depth display, battery monitor wires running between the bank and the display, etc. These wires should never be bundled in the same conduit with power cables and should be separated from them as far as possible. This is one area where a little advance planning can save you headaches in the end.

In fact, before installing any sensitive equipment in your electric boat, it’s a good idea to connect it up with its intended cable runs, place it in its intended location and test it. The test should be conducted with your outboard running under power and with all other electrical systems turned on. Sometimes simply moving a piece of equipment a few inches, or running its cables via a different path, will solve interference problems. Better to test first than to be sorry later.

Any final tips on wiring an electric boat?

- If you have an aluminum hull boat, do not be tempted to use the hull as a ground wire! Every circuit in your boat needs to be two wires, including a return wire. The negative lead from every device should be a properly-sized, stranded copper wire that runs back to the boat’s negative buss bar or the negative terminal of a battery.

- Once you install any electric circuit, be sure to label each wire at both ends. Use a paper label encased in clear, waterproof tape or any other permanent system. This will save you (and those who follow) many headaches when later working on your boat’s wiring.

9. INSTALLING THE EQUIPMENT

Since adding electric outboard drive is a more permanent installation in your boat than just clamping a gas outboard onto the transom, it pays to give extra attention to the details of the installation, as you will likely be living with them for a long while. In this section, we'll discuss tips and suggestions for making your installation one you will be proud of.

What are the best construction practices for battery boxes?

- As the boxes are supporting considerable weight, it's essential they are securely fastened to the boat hull. This can be tricky in some hulls, but there's most always a way. In aluminum boats, box supports can be screwed or pop-riveted into the metal reinforcing members inside the hull. Even small fiberglass boats often have aluminum reinforcing glassed into the hull floor. Marine epoxy glues are also an option.

- Plywood is the material of choice for most do-it-yourself battery boxes. For a budget installation, exterior grade plywood will work, but it needs to be thoroughly sealed, as the voids will collect condensed moisture and rot from the inside out. A step up in quality is marine plywood, which is just exterior plywood with no voids. For the strongest, lightest and most beautiful boxes, okoume plywood is an option, but at a stiff price. It can be ordered in full sheets from several web suppliers and shipped by freight to your location.

- Any wood added to your boat needs to be completely sealed. For a budget installation, a good quality exterior paint will do, perhaps matching your existing boat color. For those wanting to finish their boxes "bright," with a natural wood finish, the new synthetic finishes are best, such as WoodPro Plus from West Marine. They go on smoothly, with no sanding between coats or when re-coating, and they dry quickly to a semi-gloss, amber finish. These have mostly replaced varnish in marine applications.

- All hardware used in your boxes (screws, hinges, latches, etc.) should be stainless steel. Even if you're not currently using your boat in a salt water environment, a future owner might, so it's best to install quality hardware in the beginning.

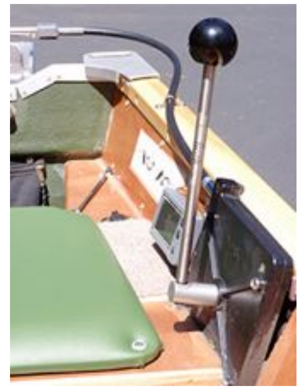
- Every battery box you construct needs to be adequately vented. As discussed, AGM batteries give off only a minute amount of gas during charging, but this gas can build up in a completely sealed box and create an explosion hazard. So cut vent holes into your boxes and cover them with vent plates designed to deflect rain and water spray.

- If your battery boxes are built the full width of the boat, it's wise to install a drain pipe through the bottom of the boxes, so water is not isolated in one section of the hull. If you take on a big wave, you want the water to spread evenly to all sections of the boat.

- Finally, the batteries need to be secured in the boxes, using either nylon straps or hold-down brackets. The idea is for your battery boxes to withstand a complete roll-over of your boat—so you won't have flying or shifting batteries to worry about at a critical time.

Any helpful tips for installing the electric outboard?

- Setting up the steering is often problematic in small boats, especially those with narrow sterns. Tiller steering can be cramped and uncomfortable. Remote steering is an option with most electric outboards, but what if your boat doesn't have a steering console? One elegant solution for small boats is stick steering—a lever that installs anywhere along the port side of your boat and controls a conventional steering cable back to the outboard. Pushing and pulling a lever to turn the boat, rather than turning a wheel, takes some getting used to, but it's easily learned. Ezy-Glide, Inc. in Florida makes several models and can provide custom length steering cables for any installation.



- If you choose to steer your electric outboard remotely, you reduce your ability to reach back and manually lift the motor when encountering obstacles or shallow water. Most electric outboards have a "pop-up" feature that allows the lower end to kick up when it hits an obstacle. But if you often run your boat in shallow rivers or lakes, you may want better control. A good option is an electric tilt/trim bracket that installs between your outboard and the transom, allowing you to raise or lower your motor with a touch of a switch. An excellent bracket designed for small boats is the CMC Model PT-35, which features an electrically-controlled, hydraulic actuator.

- Securing your electric outboard to your boat is essential—you don't want thieves walking off with your $3,000 motor. Security brackets are made for outboards (gas and electric), but the most effective method is also the simplest. Bolt the outboard to your transom or lift bracket, then replace one of the nuts with a security nut requiring a special key to remove. McGard USA supplies these security nuts in several sizes and thread patterns.

Any additional tips for installing the wiring?

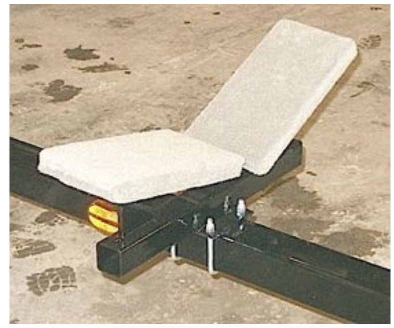
- All the wiring runs you install in your boat should be within some type of conduit. Not only does this help protect the wires, but it will allow you to pull out and replace any buried wiring at a later time. If your wire runs are within the side of the hull or floor of the boat and are covered, flexible black plastic PVC tubing will work fine. If your runs are exposed, such as under the gunwales or along the edge of the boat floor, it's best to use rigid, grey PVC conduit with glued joints—and make sure it is securely fastened at intervals to the hull.

- As discussed, it's best to separate all power cables from sensitive electronic wires, even running them down opposite sides of the boat, if possible. See Page 38.

Will my boat trailer require any modifications for an electric boat?

- As you'll be adding considerable weight to your boat, it's a good idea to check the load capacity of your boat trailer to make sure you'll still be within its design weight range.

- For any electric boat, but especially fiberglass hulls, it's important that the bunks and supports on your boat trailer match up well with the battery loads in your hull. If the supports do not fit tightly against the hull under the battery boxes, the added weight may deform the hull over time. If your bunk boards do not flex under load to the correct curve, one solution is to laminate 1"x6" boards together with glue and screws to make stiff, curved bunks that match the shape of your hull. Another option is to fabricate custom V-supports that bolt to your trailer frame and provide targeted support under the battery boxes.



- Since your boat will be heavier and a bit harder to slide, you may want to replace any carpet on your trailer bunks with plastic polymer glides. These are slick strips that screw onto the top of your bunks (even over the carpet if you prefer) and make it much easier to launch and retrieve any boat. A good online source for these glides is Surfix, Inc., which offers them in various widths and lengths at a reasonable price.

10. CONCLUSION

If you've reached this point in the handbook, you may be feeling that setting up your boat for electric outboard drive is a lot of work—and you'd be right. It takes planning, perhaps learning a few new skills and a considerable capital investment. It certainly involves more work and dedication than installing a comparable gas outboard.

However, I can say from personal experience, none of the do-it-yourself projects I've undertaken in my lifetime have given more lasting, simple satisfaction than setting up an electric drive boat. When you are finished, you have a clean, quiet craft that not only you, your family and friends can enjoy, but also generations to come. You have a boat that is not only environmentally responsible, but one that is a joy and pleasure to use every time you take it out for a spin.

Don't be dissuaded by the extra work involved—you'll be more than rewarded for your effort.