The Inland Waterways Association

Sustainable Boating Group

An Introduction to Electric Narrowboating

Revision 1

NB Ampère

NB Tenacity

NB Free Phase

NB Firefly

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Contents

Note:

The opinions expressed in this guide are those of the author, offered in good faith and based on his experience and that of other members of the IWA Sustainable Boating Group. Nothing in this guide is intended to recommend or promote equipment from any specific supplier.

1. Scope

The guidance offered in this document applies directly only to narrowboats as other boats on our canal system vary so much in size and design that any attempt to cover all in a single document would be very difficult. That said, the basic engineering principles are universal so much of the advice should be adaptable to other types of boat, such as broad-beams and cruisers, though that adaptation must be done by those with more relevant expertise.

It should also be pointed out that this document is based on currently available technologies, many of which are still evolving, meaning that some recommendations may quickly become outdated. This is the first revision, and it will be revised again as and when significant changes in technology are recognised by the Sustainable Boating Group but it is suggested that readers check the revision date and seek further advice if it seems appropriate before proceeding with a project.

2. Introduction

The prospect of near silent cruising is probably what attracts most people to electric boating in the first place though its reduced environmental impact is arguably of much greater importance. A boat with a well-designed electric drive system can use as little as a third as much fuel for propulsion, and thus produce only a third as much CO_2, as it would if fitted with a modern, 2 litre diesel engine. Perhaps surprisingly, older, slower-running diesel engines used less fuel than modern ones, though their emissions of other pollutants were much worse.

The first four new-builds of the current generation of electric-drive narrowboats known to the author, Free Phase, Ampère, Tenacity and Firecrest, all got close to this though many subsequent ones appear to have fallen short. This document has been put together by the owner of Ampère, with help from other members of the IWA's Sustainable Boating Group, to try to identify the features which result in an efficient boat, though it must be emphasised that there can be no such thing as a 'one size fits all' specification.

By 'electric-drive' is meant a boat in which the only means of propulsion is an electric motor powered from batteries charged by a generator, solar panels and/or a shoreline. Such a system is often referred to as a 'Serial Hybrid', though this isn't really correct as it lacks the either/or option which is a feature of hybrids. 'Parallel Hybrids', which are true hybrids, are less efficient than 'Electric Drives' because they completely miss out on factor C below and largely miss out on factor A. How much they benefit from factor B depends on how they are used.

A Typical Parallel Hybrid Configuration

There are three principal reasons for the higher efficiency of an electric-drive boat:

A) A small generator engine, working hard, is much more efficient than a large propulsion one running light. Estimated fuel saving: up to 50%.

B) An electric boat uses little or no power when stopped while a diesel is invariably left ticking-over. Estimated fuel saving: up to 30%.

C) The torque characteristics of electric motors permit the fitting of larger and more efficient propellers. Estimated fuel saving: up to 10%.

Losses, mechanical in the case of diesels, battery charging in the case of electric drives with lead-acid batteries, are likely more-or-less to balance out. Lithium batteries have lower charging losses so enjoy a further advantage.

Almost any electric-drive boat will benefit sufficiently from factors A & B to be more efficient than a comparable diesel. If all three can be optimised simultaneously, fuel savings can approach 70%. Not only will emissions be reduced but a saving in running costs of over £500 p.a. (including a licence reduction) is likely relative to a diesel-engined boat using the average 250 litres of fuel per annum. Boats with significant solar input and/or doing more cruising will see even greater savings.

Factor A is well documented, and B is easily recognisable but, although it is universally acknowledged that propeller efficiency falls with increasing speed, C is often ignored. The torque characteristics of electric motors are better suited to turning propellers than those of diesels and to maximise efficiency this must be used to drive larger propellers more slowly. A maximum shaft speed of 1,000 rpm is suggested, though even slower should be better. Estimates of the fuel savings associated with this range up to 30%, though the author has been advised that 10% is more realistic. That said, the Group has recently learned of one boat whose power use was almost halved by an increase in prop size.

A larger propeller may require a deeper drafted boat than the current norm of 21-22", though years of inadequate dredging mean that going deeper than 27" is likely to be counter-productive, resulting in slow, and energy-wasteful, cruising. If a boat's draft won't allow adequate tip clearance for a 3-bladed propeller large enough to transmit its motor's power, a 4-bladed one, which will be smaller for the same power transmission, should be used. A 'dropped skeg' can increase the size of propeller that can be fitted to a boat of any given draft.

A Typical Four Bladed Propeller

3. Capital Costs

This is the main barrier to the adoption of electric drive as, while running costs will be lower, the capital cost of an electric-drive system will be higher than that of a diesel one. Buying a complete system from a single supplier is likely to cost over £40K, though this can be reduced by mixing and matching products from different suppliers, something which is not difficult for anyone with reasonable electrical knowledge, usually involving little more than ensuring that voltages and power ratings match. *[Ampère's major components came from five suppliers.]*

Buying from industrial suppliers can give even bigger savings. For example, boats on inland waterways don't really need marinised generators and buying equivalent industrial units can save up to £10K. Second-hand ones, often former stand-by units with very few running hours, can be even cheaper. Both will need extra soundproofing but this will cost hundreds of pounds while saving thousands.

4. **System Design**

Before considering components individually it must be pointed out that a well-shaped hull (one with long swims and, ideally, compound curvature) needs less power to propel it. More radical hull profiles, with still lower power requirements, are under development. Also, tank trials suggest that for maximum fuel efficiency a narrowboat should be ballasted to be as level as possible in the water.

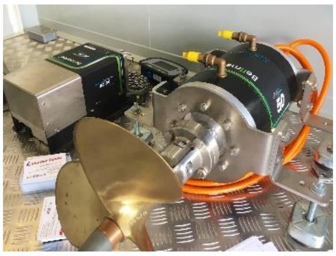
4.1 **Motors**

Suitably geared and propped electric motors need only about half the power of a modern diesel to achieve the widely accepted maximum design speed of 6 mph. 8-10kW is suggested for a boat up to 45', 12-15kW for one of 45-60', while 20kW might be best for a full-length boat. Ironically, these are almost exactly the powers of the diesel engines that were fitted to narrowboats 50 years ago when they ran slower but had higher torque.

Don't be swayed by claims that vastly more power is required to cope with adverse conditions. If a boat can reach 6 mph it should cope with any conditions in which it is safe for it to cruise.

A 48V system is to be preferred in most cases as motor currents are too high at lower voltages and components less available at higher ones. It is also under the 75V limit at which the more onerous installation standards of the Low Voltage Directive apply.

The greatest efficiency (~95%) is likely to be obtained from a permanent magnet, alternating current (PMAC) motor. These are available with maximum speeds of 1,000 rpm or less, low enough to make direct drive practicable. However, the majority on offer run at 1,400-1,600 rpm so have about a third less torque than 1,000 rpm motors of similar power and, unless geared down, must be fitted with smaller, less efficient propellers. Failure to recognise this has been the weakness of many electric-drive boats built since the four mentioned earlier.



A Typical PMAC Motor
With Control Gear

Brushed DC motors have a long and honourable history but used to be of low efficiency. However, modern ones are reported to exceed 90% so merit consideration. They come in a range of powers but are invariably too fast for direct drive so require gearing down, usually done using toothed belts. They are similar in cost to PMAC motors but their controllers are simpler and potentially more efficient.

A number of suppliers offer AC induction motors. These are considerably cheaper than PMAC ones but are larger and less efficient.

Also available are smaller and cheaper permanent magnet motors running at much higher speeds (typically 6,000 rpm) so needing gearing down a lot. These are basically designed for kit-cars, though at least one manufacturer advertises a marine version of his motor.

Most manufacturers supply pre-programmed controllers.

4.2 **Propellers**

The basics of this have already been discussed so the only thing to be said here is take care with prop-sizing websites. If fed with a motor's continuous power rating they almost invariably suggest propellers which are too small. Inputting its higher, instantaneous, rating gives more realistic recommendations, though often ones which will still give higher maximum speeds than required.

Evidence seems to be emerging that modest over-propping (sufficient to limit the motor to 80-90% of its maximum revs) can give better performance at normal cruising speeds while still permitting a 6 mph maximum, though this needs confirmation.

4.3 **Batteries**

The battery capacity needed depends on how fast and for how many hours per day a boat will cruise. 1.5 kWh per cruising hour will probably be slightly generous for typical, 1 lock/mile, canals, so a boat cruising for 6 hours/day is likely to use up to 9 kWh/day. Gentle use and/or shorter days will reduce this, though it is probably wise to provide for more demanding use than is actually envisaged. As the power required increases rapidly with speed (4 mph needs 2½ times as much power as 3 mph, for example), anyone wishing to cruise faster on a regular basis (on a river, for example) may want to install more capacity to avoid the need to charge more frequently, though space is likely to limit what can be installed .

A Lead-Acid Traction Cell Installation

2V Lead-acid traction cells are the cheapest option and, as they tolerate occasional deep (80%) discharge better than other standard lead-acid types, should probably be the first to be considered. However, they gas during charging so have to be ventilated and also need a top up system, meaning that AGM and Gel batteries, which don't, might be better for some installations.

Lead-Carbon batteries, although fairly new, have quickly become accepted. They can be discharged regularly to a greater depth of discharge (d-o-d) than other lead-acid batteries, meaning that the battery capacity can be reduced, which is just as well as they are more expensive. However, the details of their performance remain unclear as there are no universally accepted test standards. One manufacturer quotes 500 cycles to 100% d-o-d while others claim up to 2,000 cycles to 90%, though the general consensus seems to be that d-o-d should be restricted to 80%.

A weakness of all lead-acid batteries is what is termed ‘memory’, loss of capacity due to sulphation if not fully charged regularly. Lead-Carbon batteries are said to be less susceptible to sulphation so more tolerant of use in a partially discharged state but this has been queried and the few figures seen by the author are less than conclusive.

The final stages of charging a large battery bank using a generator can be very inefficient as it can take several hours, during which time the power taken for charging is minimal. On an all-electric boat this can be mitigated by arranging other loads but, in the absence of a sufficiently large solar installation, an occasional plug-in is preferable as the charger can then take only what it needs.

Lithium Iron Phosphate (LiFePO4) batteries are technically the best current option. Like Lead-Carbon ones they can be heavily discharged but, unlike the latter, are best not charged fully, meaning that there is no need for inefficient, full charging cycles. Most now have built-in Battery Management Systems which not only protect the batteries from abuse but can control compatible chargers. Batteries without these must be fitted with stand-alone ones, some of which are reported to be of dubious quality. If in doubt stick to the major brands even if they cost more.

When purchasing LiFePO4 batteries ensure that they are made from Grade A cells. Ones produced using B or C grade ones, are cheaper but may prove unsatisfactory.

Even allowing for the smaller battery banks needed, the cost of LiFePO4 batteries is likely to be at least double that of traction cells for comparable usable capacity.

> *Warning:*
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> *LiFePO4 batteries should not be confused with 'Lithium Ion' ones (a name used for several battery chemistries) which cannot be recommended despite their being widely used in products as diverse as mobile phones and electric vehicles. In the event of faults or damage they are prone to thermal runaway and the resultant fires cannot be extinguished with standard extinguishers. LiFePO4 batteries are similarly difficult to extinguish but are not subject to thermal runaway so are unlikely to ignite in the first place. This risk is particularly great if using repurposed ex-EV batteries as their original battery management systems must be replaced with lower voltage proprietary ones, some of which, as already mentioned, are of dubious quality.*
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> *Moreover, Lithium Ion batteries are environmentally undesirable as they include metals like Molybdenum and Cobalt, the mining of which is notoriously polluting and are also more difficult to recycle than LiFePO4 ones when life expired.*

The use of LiFePO4 batteries in parallel with Pb-acid ones has been proposed as a way of making the charging of the latter less inefficient. However, while this is undoubtedly possible, doing so safely requires considerable expertise so is best left to people with that expertise. At least one boat fire is reported to have been caused by a badly implemented installation of this kind.

20 kWh of usable power requires about 40 kWh (830 Ah @ 48V) of standard Lead-acid batteries or 30 kWh (625 Ah @ 48V) of Lead-Carbon or LiFePO4 batteries. For an all-electric boat these figures need to be increased by about 50% to cover domestic

use. A further 25% to compensate for loss of capacity with age is also suggested, certainly for Lead-acid systems.

Promised for some time, but yet to be commercialised, are Solid Electrolyte Batteries. These have much higher energy densities and should be game changers when they are, potentially providing enough energy storage for boats to manage a week between charges. This could make purely shore-based charging feasible and, by removing the need for generators, bring capital costs down to the point where they are within striking distance of diesel-engined craft.

4.4 Generators

A Typical Marinised Diesel Generator

If you are planning drive-only you only need your generator to charge your batteries and a DC unit will be best. If all-electric, an AC unit will allow you to share the domestic load between your generator and inverter, reducing the size of the latter.

For the sizes of battery bank mentioned above a generator with a continuous rating of 5-10 kVA is suggested. Read the small print carefully; most require downrating to 80%, or even 70%, of their nominal outputs for 'extended running', which can be as little as 20 minutes.

The final choice requires the balancing of opposing factors. A larger generator will charge more quickly so, being run for fewer hours, will disturb your peace less, require less maintenance and probably last longer. However, a smaller one running for longer will be more fuel efficient as it will permit more waste heat to be taken for domestic use and be less wasteful if used fully to charge Lead-acid batteries.

If buying an industrial unit the critical features are that it must be water cooled and have electric start and 230V AC output (some only offer 110V).

A Typical Generator Installation

If space restricts you to a smaller battery bank than suggested, you may want your generator to start automatically so that your cruising isn't curtailed. If so, it is best to opt for keel cooling and a dry exhaust as running a water-injected one while cruising increases the risk of blockages. Otherwise, water-injection has a lot to commend it it as not only is it cheaper but it permits the use of rubber hoses, thereby avoiding the embrittlement problems of metal exhausts.

There are two 'generator substitutes' waiting in the wings, technically developed but not yet commercially available in suitable forms. Briefly, these are:

- **Fuel Cells.** These produce electricity directly by the chemical reaction of fuels with Oxygen. The principal types are Proton Exchange Membrane (PEM), which can use only (extremely expensive) pure Hydrogen, and Solid Oxide (SO), which can also use Methane. At about 50%, both types are almost twice as efficient electrically as generators and the waste heat, being available almost continuously, should provide nearly all the water and space heating for a narrowboat, affording a further, very significant saving.

- **The Stirling (or external combustion) Engine**. These can run on a wide range of fuels, ranging from Hydrogen to solid fuels, but produce too much heat relative to their electrical output to make useful generators. However, using the Stirling Engine's 'waste' heat for boat heating during the colder months of the year while its electrical output tops-up the power from a solar installation could work well, particularly on larger boats which can accommodate more solar panels and are able to use more heat.

5. **Solar and Wind Power**

The usefulness of such power depends on the usage, battery capacity and other charging options. What amounts to a useful contribution to a three-battery domestic installation on a diesel-engined boat will barely be significant on an electric-drive one with a generator and up to 20 times the battery capacity.

Rigid Solar Panels on a Narrowboat

Solar panels are invariably worthwhile on boats where alternative power costs are high, particularly those whose only other means of battery charging is a propulsion engine's alternator, the marginal cost of power from which can easily exceed £3/kWh. On boats with generators, where the cost of power will be more like 40p/kWh, things are less clear.

Rigid panels can produce power more cheaply than a generator. 100W panels can be bought for not much more than £100 and will produce power worth over £30/annum (valued at 40 p/kWh) so will pay back in not much over 3 years, well within their expected lifetime. However, they can interfere with ropes, poles and the ability to walk on a boat's roof, potentially impacting safety.

Flexible panels, larger areas of which can be fitted as they can (within reason) be walked on, avoid this problem though, as they typically cost 2-3 times as much as rigids, their pay-back times are proportionately longer, meaning that justification must be on environmental grounds, particularly as there appear to be durability issues. Boat roofs get very hot and, while rigids usually suffer little permanent damage, there is increasing evidence that flexibles do, meaning that many may not last long enough to repay their capital cost. 5 year lives are widely reported on the Internet. *[Ampère's managed only 3.]*

Flexible Solar Panels

Finding space for boathooks, poles and ropes can also be a problem on a fully-filled roof.

It must also be made clear that, while solar power can make a significant contribution to the powering of an electric boat, relying completely on it is unlikely to be viable. The roof of a 60' boat completely filled with panels can theoretically generate about 10 kWh/day in mid-Summer, though 6-9 kWh is more likely because of shading by buildings and trees. This should be enough for domestic use and limited daily cruising for a few weeks, so may satisfy many boaters. However, as solar insolation falls by about 1/3rd (compound) for every month before or after mid-Summer's Day, even at the beginning of May or end of August less than half that power will be available, meaning eating or cruising but not both. With less than 1 kWh/day at Christmas there won't be enough to cook the turkey!

A Wind Turbine on a Narrowboat

Some boats carry wind turbines, but the apparently low cut-in speeds advertised by manufacturers are often higher than average wind speeds found on the inland waterways of the UK, meaning that they will run only occasionally unless in particularly exposed locations. Calculations for a typical 1.5 metre unit, the largest that can readily be carried on a narrowboat, suggest a pay-back time of well over 10 years so, while they might be financially justifiable for boats without generators, they are unlikely to be for ones with them. The obvious exception to this is when a larger one can be permanently installed ashore at a home mooring.

6. **Saving rather than generating power**

- The cooling water from the generator, as well as heating domestic hot water, can either be interfaced directly with a wet central heating system using a heat exchanger and thermostatic valve or fed to a second calorifier. In the first case the heat will be sufficient fully to operate the system while the generator is actually running; in the second, the stored heat can be used to run a low temperature heating system (underfloor or fan-assisted radiator), providing limited heating for some hours after it is stopped. *[Ampère has such an underfloor system.]*

- Unless they cruise every day, boats with large solar installations are likely to have surplus power at times during the sunnier months of the year. Arranging for this automatically to be used to heat domestic hot water, so-called Solar Dumps, can minimise wastage. If the calorifier is large enough and well enough insulated it can avoid the need to use power which might otherwise be wanted for cruising to heat water on subsequent days.

- Fitting a water source heat pump could save both money and energy. These upgrade heat from the canal using a reverse refrigeration process, providing 3 to 5 kW of heat for each 1 kW of power used to run them and discharging it into the boat *via* one of the low temperature systems mentioned earlier. As an electric-drive boat will have sufficient battery capacity comfortably to run a heat pump this is an extremely attractive option.

The Sustainable Boating Group has recently started work on domestic energy usage in boats and more detailed advice about these possibilities can be expected in due course.

Appendix 1 – Propulsion Layout of a Typical 'Electric Drive' Narrowboat