THE INLAND WATERWAYS ASSOCIATION

SUSTAINABLE BOATING GROUP

AN INTRODUCTION TO ELECTRIC – DRIVE NARROWBOATS

Issue 1

NB Ampère

NB Tenacity

NB Free Phase

NB Firefly

Author - Malcolm Bridge, Owner, NB Ampère

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available technologies, many of which are still evolving, meaning that some recommendations may quickly become outdated. It will be updated 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.

It is also recognised that there are many different types and ways of using narrowboats, ranging from residential boats which rarely move to extended cruisers who wish to cruise 10 or more hours per day on a three, or four season, basis, maybe on tidal rivers, and everything between. A specification for an electric boat that works for one may not work for another.

This guide is directed to a boat that has maximum flexibility to cover as much as possible of the above range. It is assumed that it can plug in to shore power when available and is equipped with a diesel generator. PV cells will probably be fitted and the proportion of power these can provide will depend on the extent, speed and location of cruising, the domestic electrical load, the time of year and the number of cells fitted.

The recommendations in this guide can be adapted to the type of cruising envisaged.

2. INTRODUCTION

The prospect of near silent cruising is 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, with a diesel

generator, 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 typical modern, 2 litre, diesel engine. The first four new-builds of the current generation of electric-drive narrowboats known to the author, Free Phase, Ampère, Tenacity and Firecrest, all get close to this though many subsequent ones have fallen short. This guide has been written by the owner of Ampère, with help from other members of the Inland Waterways Association's Sustainable Boating Group, to try to identify the features which result in an efficient boat, though 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. These can be charged by any combination of a built-in generator, a shorepower connection and PV cells . Such a generator-based system, is often referred to as a 'Serial Hybrid', though this isn't really correct as it lacks the either/or option which defines a hybrid. 'Parallel Hybrids', which are true hybrids, are less efficient than 'Electric Drives' because they miss out completely 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 an electric motor permit the fitting of a larger and more efficient propeller. Estimated fuel saving: up to 10%.

Losses, mechanical in the case of diesels, battery charging in the case of electric drives, are likely more-or-less to balance out.

Unless its design is extremely unusual any electric-drive boat will benefit sufficiently from factors A & B to be much 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 £400 p.a. (including a licence reduction) is likely relative to a typical diesel-engined boat using 250 litres of diesel per annum.

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. To maximise the benefit of electric drive it is necessary to use the higher torque available from an electric motor to drive a larger propeller more slowly. A maximum shaft speed of 1,000 rpm (about 2/3rds that of a typical diesel) 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 probably more realistic.

A larger propeller may require a deeper drafted boat than the current norm of about 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 (as on Tenacity and Firecrest), which will be smaller for the same power transmission, should be used.

A Typical Four Bladed Propellor

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 will cost over £40K, though this can be reduced by mixing and matching products from different suppliers. This is not difficult, if the necessary skills are available, usually involving little more than ensuring that voltages and power ratings match. (The major components of Ampère came from five suppliers.)

Buying from industrial suppliers can give even bigger savings. For example, boats on inland waterways don't really need fully 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 require extra soundproofing but that will cost hundreds of pounds against savings of thousands.

4. SYSTEM DESIGN

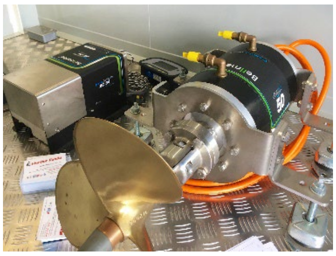
Before considering components individually it must be pointed out that a well-shaped hull (one with long swims and, ideally, compound curvature) needs less power to propel it. Also, for maximum fuel efficiency, tank trials suggest that a narrowboat should be ballasted to be level in the water with full tanks and no crew.

4.1 MOTORS

Their higher available and constant torque enables electric motors to turn larger, more efficient propellers than similarly rated modern diesels so they need only about half the latter's maximum power to achieve the widely accepted maximum design speed of 6 mph in open water. 8-10kW should suffice for a boat up to 45’, 12-15kW for one of 45-60’, while 20kW might be best for a full-length boat. These recommendations assume that the boat will occasionally be used in more challenging conditions such as tidal and non-tidal rivers when strong flows may be encountered.

Ironically, these are almost exactly the powers of the diesel engines that were fitted 50 years ago when they ran slower but had higher torque.

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



A Typical PMAC Motor
With Control Gear

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 (about 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 possible, though the majority on offer run at

1,400-1,600 rpm so, as torque is inversely related to rotational speed, have considerably less torque. Unless geared down, they must be fitted with smaller propellers. Failure to recognise this has been the weakness of many electric-drive boats built since the four examples mentioned here.

Brushed DC motors have a long history and can have efficiencies, exceeding 90%, so are worth considering. They come in a range of powers but are invariably too fast for direct drive so require gearing down. They are similar in cost to PMAC motors but their controllers are considerably less complicated and potentially more efficient.

Several suppliers offer induction motors. These are robust AC motors and are considerably cheaper than those mentioned above but are larger and less efficient. Also available are even smaller and cheaper motors running at much higher speeds (typically 6,000 rpm) so needing gearing down a lot. These are aimed primarily at the kit car market but at least two manufacturers offer marine versions. Most manufacturers supply pre-programmed controllers suitable for their motors. Since the jamming of propellers is an occupational hazard for canal boats, any system should protect the motor from burning out by cutting the power quickly. A reduction belt drive also offers a weak link in this situation and enables tailoring of the shaft speed to suit a larger, more efficient propeller.

4.2 PROPELLERS

The basics of this have already been discussed so the next thing to be said is take care with prop-sizing websites. If fed with a motor's continuous power rating, they invariably suggest propellers which are too small. Inputting its higher, instantaneous, power rating secures more realistic recommendations, though often ones which will 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) gives better performance at normal cruising speeds while still affording a 6 mph maximum, though this needs confirmation.

4.3 BATTERIES

A Lead-Acid Traction Cell Installation

Two days cruising between charges is probably a realistic target at the moment. An electric-drive boat cruising for 6 hours/day for two days is likely to use up to 20 kWh on typical, 1 lock/mile, canals. However, 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, possibly even while underway. 2V Lead-acid traction cells are the cheapest option and, as they tolerate occasional deep (80%) discharge better than most other 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 80% depth of discharge (d-o-d), meaning that the battery capacity can be reduced, which is just as well as they are more expensive.

A weakness of all Lead-acid batteries (though Lead-Carbons are claimed to be less vulnerable in this respect) is a 'memory' effect due to sulphation, meaning that, unless fully charged regularly their working capacity falls. 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 actually taken for charging is minimal. On an all-electric boat this can be mitigated by arranging domestic loads to use some of the surplus power, but an occasional plug-in or the use of PV cells (if adequate), is preferable.

Lithium Iron Phosphate (LiFePO4) batteries are technically the best current option. Like Lead-Carbon ones they can be discharged regularly to 80% d-o-d but, unlike the latter, are best not charged fully, meaning that there is no need for inefficient, full charging cycles. Most have built-in Battery Management Systems which not only protect the batteries but can control compatible chargers. Batteries without their own battery management systems must be fitted with stand-alone ones. Some of those available are reported to be of dubious functionality so research them carefully and 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; cheaper ones, using B or C grade ones, are likely to under-perform.

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:*
>
> *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 electric vehicles and mobile phones. 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, many of which, as already mentioned, are of dubious functionality.*
>
> *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 than LiFePO4 ones to recycle when life expired.*

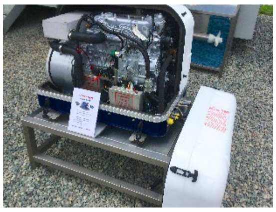
The use of LiFePO4 batteries in parallel with Pb-acid ones has been proposed as a way of making the charging of the latter less inefficient. However, while this is undoubtedly possible, doing so safely requires considerable expertise so is best left to people with that expertise. At least one boat fire 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 about 25 kWh (520 Ah @ 48V) of Lead-Carbon or LiFePO4 batteries. For an all-electric boat these figures need to be increased by about 50%. A 25% allowance to compensate for loss of capacity with age is also suggested.

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

4.4 GENERATORS

To establish what you need, consider these points:



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'.

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 inefficient when 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 at a certain level of discharge 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 as not only is it cheaper but the lower exhaust temperatures permit 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, which can use only very pure Hydrogen, and Solid Oxide (SO), which can also use other fuels, including gaseous hydrocarbons. At about 50%, both types are almost twice as efficient electrically as diesel generators and the waste heat, being available over a longer period, is likely to be enough to provide almost all the water and space heating in a narrowboat, affording a further, very significant saving. Were they available, SO cells fuelled by LPG would be a particularly good interim power source for boats.

- **The Stirling (or external combustion) Engine**. These can run on a wide range of fuels, ranging from solid fuels to Hydrogen, but produce too much heat relative to their electrical output to make useful generators. However, particularly if combined with a sizeable solar installation, one could be suitable for a non- (or minimally) cruising boat, essentially using the Stirling Engine as a central heating boiler and treating its electrical output as a bonus. This could work particularly well on larger boats which will have a greater roof area available for solar panels and be 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 not be significant on an electric-drive one with up to 20 times the battery capacity.

Rigid Solar Panels on a Narrowboat

Solar panels are clearly worthwhile on boats where alternative power costs are high, particularly those whose only other means of charging is a propulsion engine's alternator, the marginal cost of power from which is likely to exceed £3/kWh. On boats with diesel generators, where the cost of power will be more like 40p/kWh, things are less clear. It depends on the type of panel and use of the boat.

Rigid panels can often produce power more cheaply than a generator. 100W panels can be bought for not much more than £100 and will produce power worth about £35/annum (valued at 40 p/kWh) so will pay back within 3 years, well within their expected life. However, they can interfere with ropes, poles and the ability to walk on a boat's roof, potentially impacting safety.

Semi Flexible Solar Panels

Semi-flexible panels, larger areas of which can be fitted as they can (within reason) be walked on, avoid this problem though, as they are more expensive (2-3 times as much as rigids), their power is unlikely to be cost competitive with that from generators, meaning that justification must be on environmental grounds.

All solar panels suffer, in terms of output and working life, if they overheat. The roofs of narrowboats can get very hot and semi flexible panels bonded to the roof will suffer more from overheating than rigid panels, which are usually mounted with an air gap between them and the roof.

Suppliers and boat builders are seeking ways to mitigate this, and it is reported that one builder has provided insulation between the roof and the semi flexible panels. How effective this is not known.

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.

A Wind Turbine on a Narrowboat

6. FINAL THOUGHTS

- Not a propulsion issue, and saving rather than generating power, is the use of waste heat from the generator. Its cooling water, as well as heating domestic hot water, can either be interfaced directly with a wet central heating system (heat exchanger and thermostat required) 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 background heating for some hours after it is stopped. Ampère has one of the latter systems.

- Also not a propulsion issue but potentially saving both money and energy would be to fit a water source heat pump. 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 either as warm air or via one of the low temperature systems mentioned above. As an electric-drive boat will have sufficient battery capacity comfortably to run a heat pump this is an extremely attractive option.
- If surplus power is available from solar panels, this can also be used to heat domestic hot water. (a “Solar Dump”) This is likely to be particularly useful for boats with large solar installations which don't need to run their generators frequently.

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

APPENDIX 1 – PROPULSION LAYOUT OF A TYPICAL 'ELECTRIC DRIVE' NARROWBOAT