Consultation on Scotland’s Energy Efficiency Program:

Tidal Stream Energy from the Pentland Firth.

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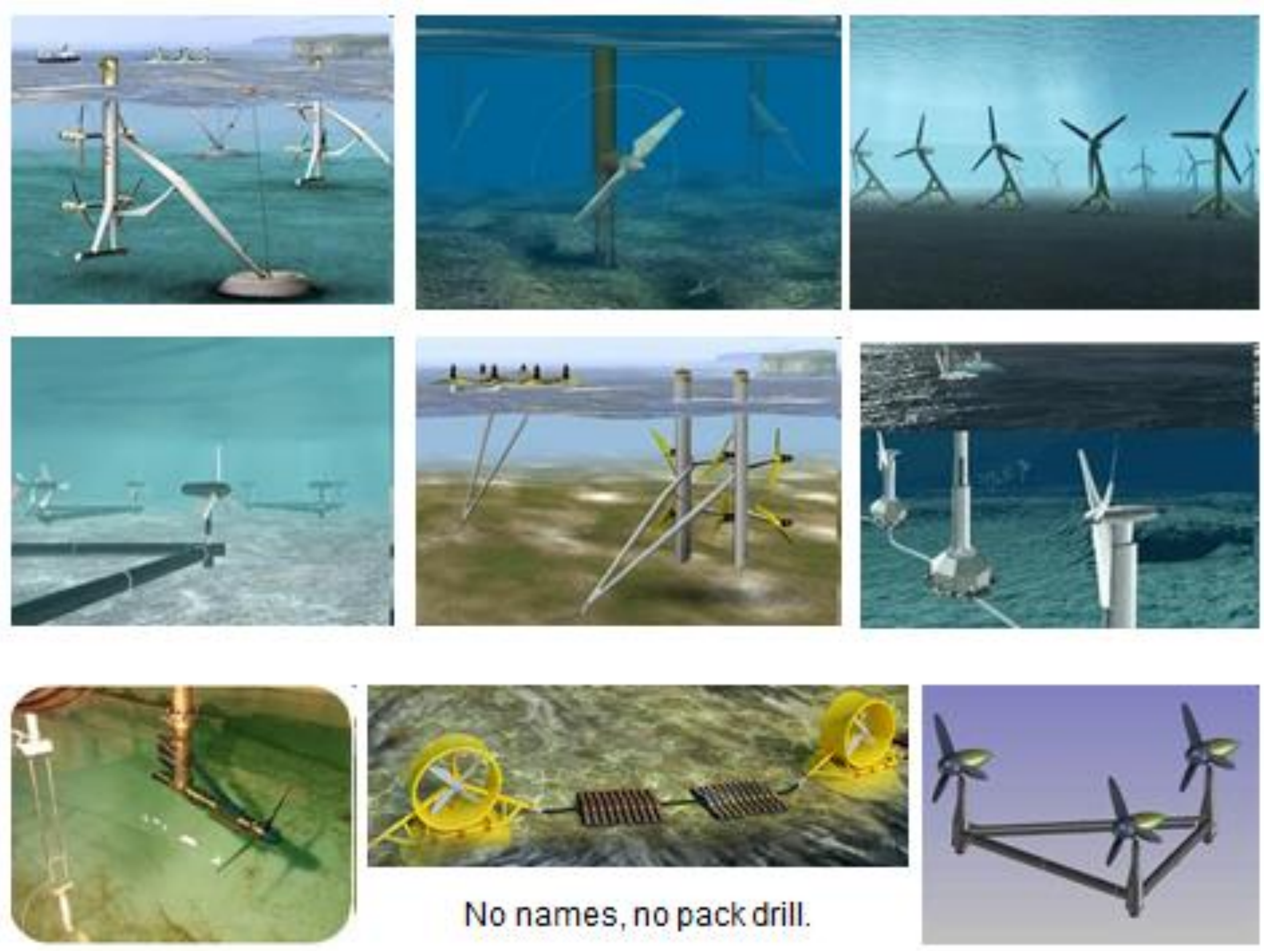

No names, no pack drill.

A recent paper in a respected peer-reviewed journal claimed that the tidal stream resource of the Pentland Firth could supply half the Scottish electricity demand.

This note argues that, while this estimate might be right for an open flow field, it is too ***low*** for flow in a duct where water cannot penetrate the walls or bed. It also suggests ways in which we could get a more accurate number.

“Like wind turbines under water”

Many tidal stream developers claim that their plant works ‘like wind turbines under water’. The figure on the front cover shows a selection of designs confirming this statement. A noticeable feature in all of them is the large gaps between rotors and the rather low ratio of the area swept by turbine blades to the projected area of the support structure. In many cases the ratio of swept area to the cross section of the flow channel, often called blockage, is about 5%. It could also be described as 95% leakage in a conventional hydro-electric scheme.

The key design equation for wind turbines in an open flow field (due originally to Lanchester but usually attributed to Betz) predicts that the maximum power would depend on the cube of the distant up-stream velocity and also that the wake velocity behind the optimum design of rotor should be one third of this. If a wind turbine designer is too greedy the air will flow around or above the rotor.

This argument and the resulting design equation would apply to the very first units installed in the Pentland Firth. But power depends on swept area. If we could design turbines which fill larger fractions of the area of the flow channel, the Betz equation becomes increasingly wrong. If we could *sweep* rather than block a high fraction of the flow passage, say 80%, we need to ask ‘where have the other two-thirds of the water gone’? Should power output be head times the first power of flow rate, not the cube?

What fraction can we sweep?

Tidal stream generators must exist in harmony with all other users of the sea.

The Scottish Government via Marine Scotland commissioned a report by Halcrow and Anatec on Shipping in the Pentland Firth and Orkney waters [1]. Data from the signals from the Automatic Identification System (AIS), that has to be carried by all commercial vessels over 300 tonnes, are given for seasons, vessel types, water line length, draught and displacement. Unfortunately data from vessels through the Pentland Firth have been combined with inter-island traffic and with traffic going north of North Ronaldsay. I am told that it will be expensive to reverse the combination. Until this can be done we are forced to used eyeball comparisons from figure 1 to suggest a fairly even split between the northern and southern traffic.

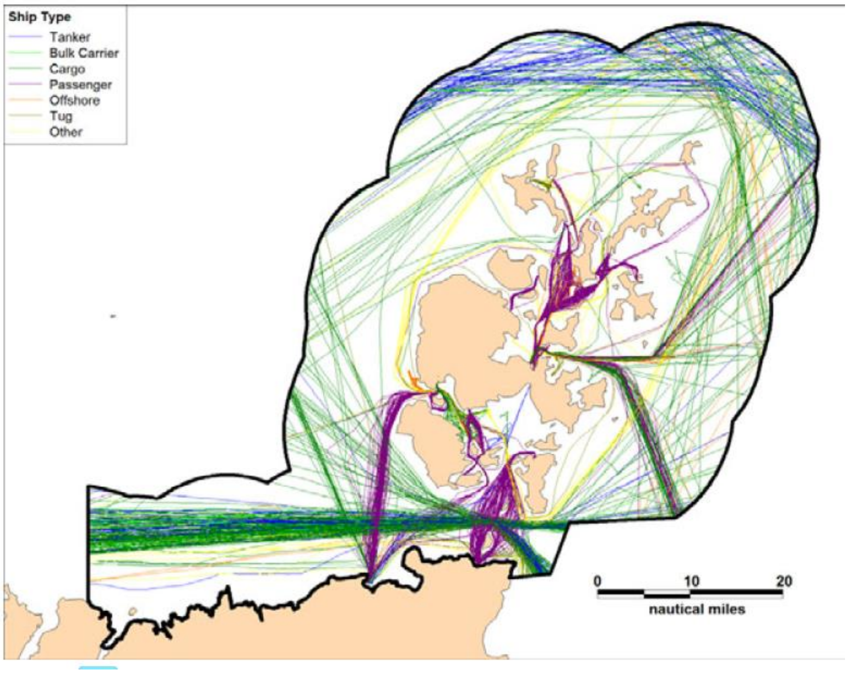

Figure 1. Winter 2012 track analysis by vessel type from [1].

From the vessel type analysis in figure 2 we can see that the average number of vessels per day through all routes is 179 with about half, say 90, going through the Pentland Firth.

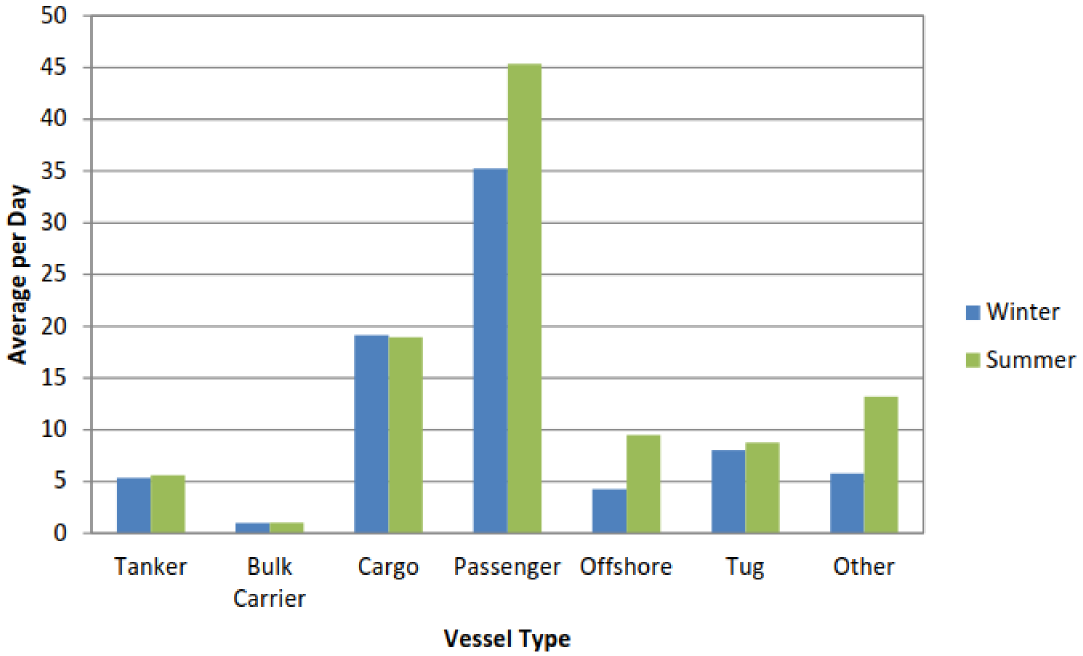

Figure 2. Seasonal traffic count for both the through and round passage by vessel type from [1].

Next from the analysis by vessel draught in figure 3 we see that only 5.5% of the traffic has a draught greater than 10 metres.

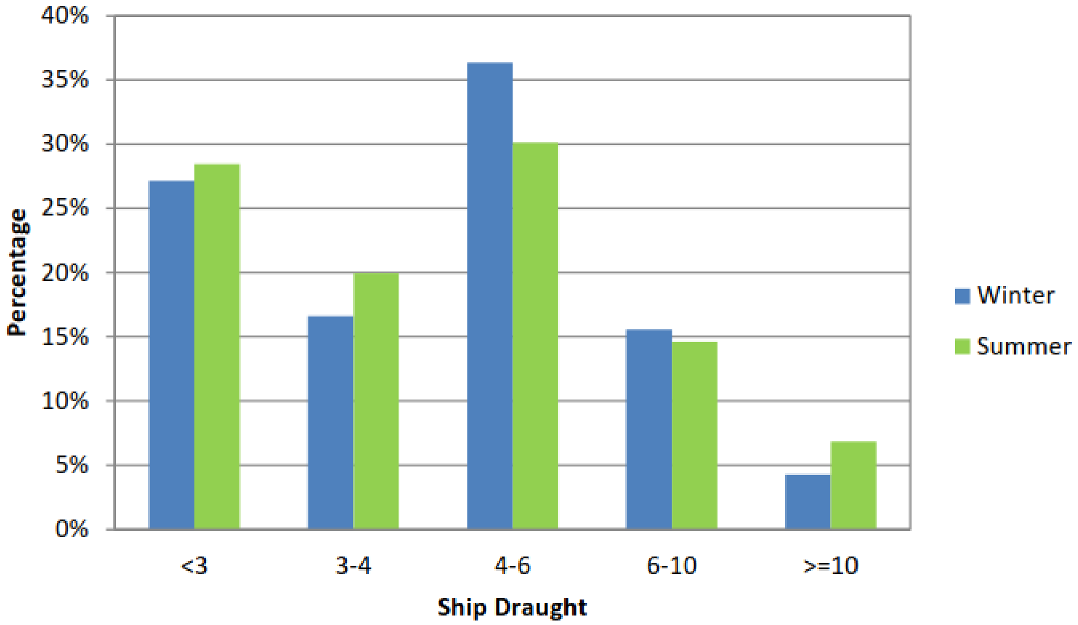

Figure 3. Traffic analysis by ship draught for all passages during summer and winter of 2012 from [1].

Tidal stream developers will not want to work in water depths as little at 10 metres and so small vessels can move either north or south of any line of turbines. Until we can get more information it is reasonable to assume that we need to allow for the passage of only 5 big ships a day through deeper water along the channel centre line compared with 'more than 500 a day' for the English channel [2]. High densities would justify traffic separation through two gaps but, for 5 ships a day, just one gap should be enough.

How big a gap do ships **really, really** need?

We can start by looking at the width of the entrances to large harbours. We can use the Google Earth to measure the gap between north and south jetties at Milford Haven, designed for very large oil-tankers, as 437 metres. The beam width of the 932,000 tonne Pioneering Spirit vessel (which can lift 48,000 tonne oil platform decks) is 127 metres. We need a gap in the 13 km width of the Pentland Firth s to allow Pioneering Spirit and her larger sister Amazing Grace (still building) to pass in opposite directions at the same time. The limiting size of the gap might be the requirement to move large tidal-stream rotors.

Turbulence in the Pentland Firth is serious for small vessels, particularly downstream of obstructing islands. It is certainly be much worse than the entrance to Milford Haven. However vertical-axis rotors with variable-pitch blades can easily and quickly alter flow directions so as to straighten flow and even wash vessels which have lost power towards safety.

Tidal stream plant will carry sensors to measure flow velocity and direction. This information can be made instantly available to the skippers and auto-pilots of large vessels so they will have much better look-ahead information than at present. Mariners have painfully got used to shallows, wrecks and submerged rocks and will tolerate them provided that they know exactly where they are. I argue that they prefer hazards which are very well marked with lights, bells, sirens, radar-reflectors, rocket flares and even patrol vessels. Some places are absolutely safe and some absolutely forbidden and skippers will know which are which.

Flow impedance

A necessary number for energy estimates from installations with a high sweepage fraction is the flow impedance. It can be used in equations analogous to Ohm's law in electrical engineering. It can be thought of as the 'determination' of the water to get through a passage. There are two kinds of impedance. One kind dissipates energy like an electrical resistance. The other does not dissipate energy but is analogous to combinations of inductance and capacitance in electrical circuits, with energy being transferred back and forth between kinetic and potential forms. Impedance can be mathematically defined as the increase of head multiplied by the density of water times the acceleration of gravity divided by the reduction of flow rate caused by the insertion of some obstruction. Although flow impedance should be as important to tidal stream developers as the density of sea water and strength of steel are to naval architects, nobody yet can give accurate values for the Pentland Firth. We need this information urgently.

Flow in the shallow water of the Pentland Firth will have both a reactive and a resistive component in series with reactive ones in the Atlantic and North Sea and in parallel with both kinds of impedance in the flow passages through and around the Orkney Archipelago. I am ashamed to say that I have not been able to do rigorous calculations from first principles of the reactive impedance of ocean systems but, given that two million tonnes a second has come all the way from Cape Cod through the North Sea to Skagerrak, I am sure that its determination will not be zero. The bypass channels are longer than the Pentland Firth and ones between islands are narrower. They have lots of sharp bends and will probably have similar bed roughness. They are already full of water which cannot be easily displaced. My shame is reduced by the fact that none of the tidal stream developers and the oceanographers whom I have asked, can give numbers either.

The highest power output from the Pentland Firth would be achieved if the resistive impedance of the turbines and the channel matches the sum of reactive source and parallel sinks either side. If the reactive impedances of the ocean are low then it would be best to make the resistance of the turbines equal to the present impedance of the flow channel. But if they are not low then the tidal stream resource would be higher. As more turbines are installed in a high impedance flow the upstream water level will increase and the downstream one will reduce head but there will be little reduction in the flow rate.

Impedance measurement

The very best way to measure the present flow impedance of the Pentland Firth itself (but not the open ocean) would be to measure the head difference of water across the ends of the channel, the flow rate through it and the phase between them. Satellites can easily measure the sea level changes across the Pacific to about one centimetre because they can measure millions of points and take an average. This is much harder for small areas. A better way would be to use pressure data from a string of instruments on the sea bed across the width of each end of the channel. Harbour water levels are not useful because there is no velocity. Pressure transducers are built in the acoustic Doppler current profilers which are giving good results for flow velocities. Sadly a proposal to the EPSRC to fund bed-pressure measurement was rejected because the Pentland Firth was thought to be ‘too regional’.

Until we can do proper pressure measurements we may be able to make a rough estimate from existing velocity data. If a flow system was linear and not too resonant we could assume that the astronomical forcing function would be directly related to the resulting flow velocities. Departures from a direct relationship should point to the magnitude of the non-linearity. We can make a computer record of any length of the forcing function but records of tidal streams are limited by instrument costs and battery life. Many are only just over a month in length. If we compare the forcing function with a real velocity signal we notice that the ratio of spring to neap velocities is lower in the real signal because square law drag hits higher velocities more than low ones. However this ratio gives only a few data points a month. Next we can use the slope of the velocity record at each zero crossing and compare it with the amplitudes of the preceding and subsequent crests and troughs. This gives us four numbers per day, still a bit low.

If we clip the crests and troughs of a pure sine wave we generate higher harmonics of the original signal. We can use a mathematical process called a Fourier transform to measure the size of the harmonics and so the amount of energy that has been lost. The upper trace in figure 4 shows a Fourier transform of the astronomical forcing function. The lower one, inverted, is the velocity signal from a site in the Pentland from an acoustic Doppler current profiler. The frequency scale has been normalised so that the dominant M2 lunar component is unity. Information from every data point is being used. The only snag is that the measuring instrument also has some inherent background noise, perhaps from the presence of air bubbles. It could be difficult to know how much of the high frequency content is due to clipping.

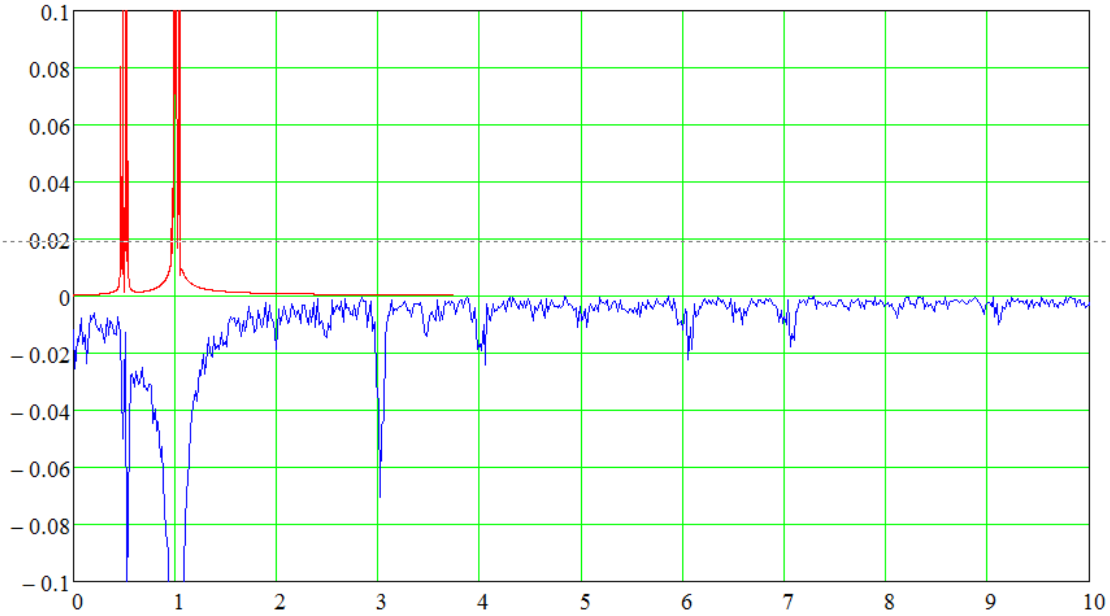

Figure 4. Fourier transforms might be used for loss measurement. Peak M2 values were 1.0 for the forcing function and -1.41 for the real measurement.

Another method for squeezing present loss estimates from single-point velocity data uses histograms of velocity signals. This gives information from every data point. But if we pass the astronomical forcing signal through algebraic square-law drag with increasing drag coefficients we get the histograms of figure 5. The outer skirts and the inner core have been munched. We can calculate the ratio of power densities (PDR) of the flow either side of the algebraic loss simulator. Figure 6 shows the histogram of a real velocity signal from a site in the Pentland Firth to compare with figure 5. I am trying to get a rigorous mathematical way to measure munching but for now we have to use eyeball comparison. Readers are invited to compare munch factors and corresponding energy reductions.

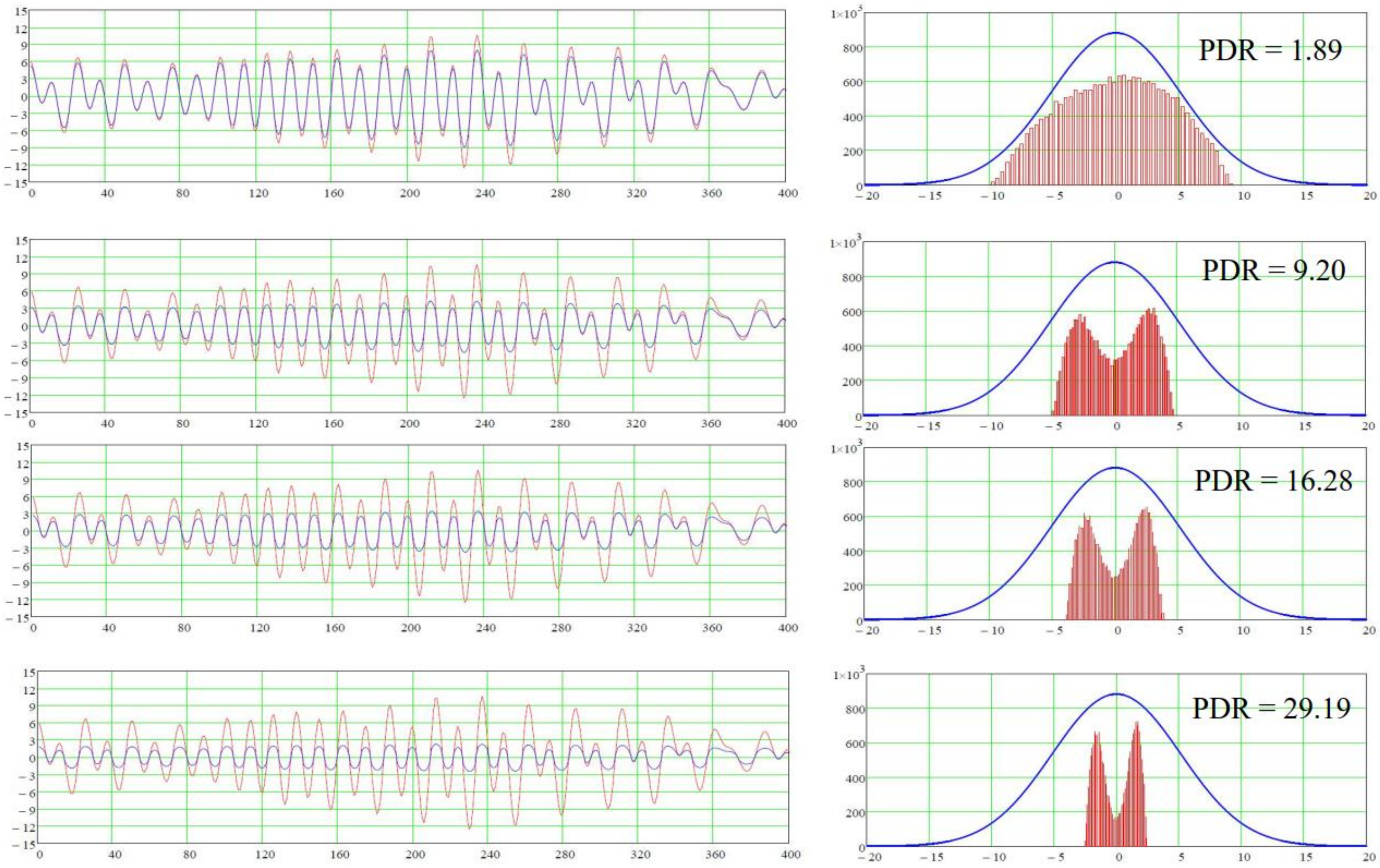

Figure 5. Signals, resulting histograms and power-density ratios for various square-law drag coefficients.

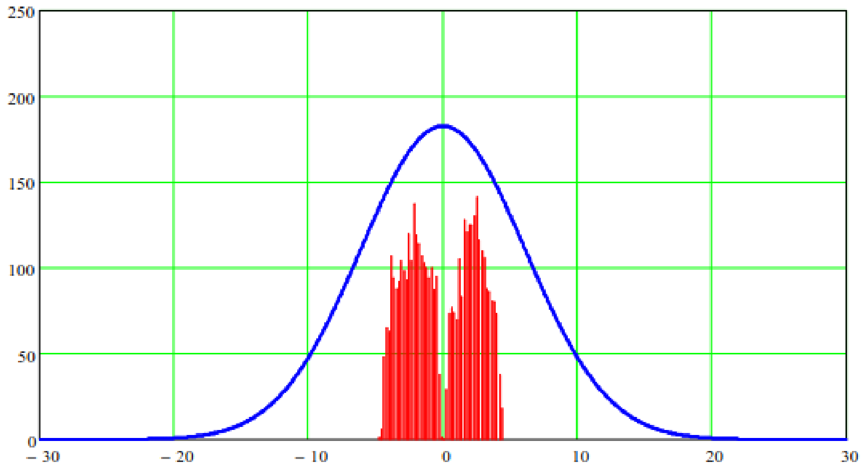

Figure 6. The velocity histogram from an acoustic Doppler current profiler in the Pentland Firth. This uses information from all data points but needs better pattern comparison than a human eye.

The final method to make a rough engineering estimate of the impedance of the ocean source goes back to the definition of increased head to reduced flow rate. If we have numbers for the present head difference along the Firth we can compare it with the higher head at places where some major obstruction to flow, such as the Republic of Ireland, has reduced the East-West velocity to zero. We could imagine that in ancient times there was once a similar tidal stream plant through Ireland but that it has silted up.

Provided that there is no funnelling acting like the Bristol Channel we could calculate the ratio of amplitude increase to the complete flow reduction. The tidal range at Clare Island goes up to 4.57 metres. We can get similar numbers from Spain and Portugal. Data from Proudman Laboratories is that in the Pentland Firth the maximum September spring amplitude is about 1.25 metres. The maximum flow rate in the Pentland Firth is about two million cubic metres a second. The ratio of head change to flow reduction suggests that impedance of a Pentland Firth width of the Atlantic is 0.0084 kg/m4 sec.

Electrical engineers know that impedance is power divided by the square of flow rate so, if we knew the present losses, we can estimate the present resistive impedance of the Pentland Firth and how many turbines should be installed to get the best match to the reactive impedances of the Atlantic in series with the North Sea. It is a great many.

High sweepage rotors

Horizontal axis turbines reduce fluid velocities at the tower, the nacelles and the blade roots but increase them round the blade tips. The torque on the blades gives an exactly opposite torque on the sleeve of fluid going down stream. The result produces wake turbulence shown in figure 7 which would be excellent for food blenders. Turbulence behind wind turbines serves to recharge the flow with energy from higher velocity air above but this does not happen with high sweepage tidal rotors.

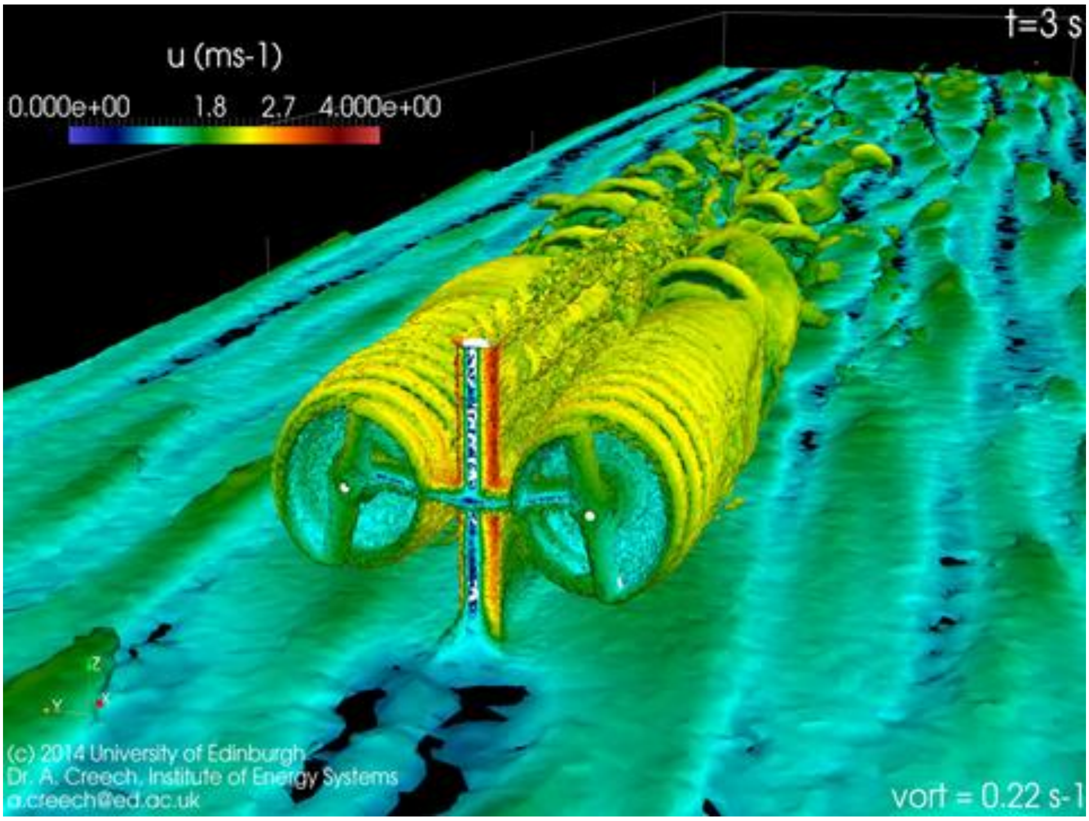

Figure 7. A simulation by Angus Creech [3] of Peter Fraenkel's installation in Strangford Lough.

Figure 8 shows an artist's impression of close-packed vertical-axis rotors. The power take-off is by a quad ring cam inside the stationary yellow annulus. It acts as a slew-bearing as well as a pump and is accessible even during generation. Rotor diameter has to be more than three times the water depth. The 200 metre red rings and 11 metre silver blades, will move at eight metres a second, below the speed of fast marine predators. The rings suppress tip vortices. Geometry is defined by well streamlined diagonal cables and radial spokes made from carbon fibre. This gives the high structural efficiency of a bicycle wheel. Each blade will have its own pitch control from a spline actuator, also removable at sea. This allows instant disconnection of the power input but prevents stall. We hope from [4] that contra-rotation will recover some of the vortex energy in the wake and that pitch-control can recover some from larger turbulence eddies.

Forces on turbine blades depend only on their shape, their area, fluid density, fluid velocities and the angle of incidence. Blades do not know about horizontal and vertical axes. Horizontal axis blades do not have very large changes through a rotation cycle but suffer wide changes of velocity and angle of incidence along their span and so have large shape and pitch changes.

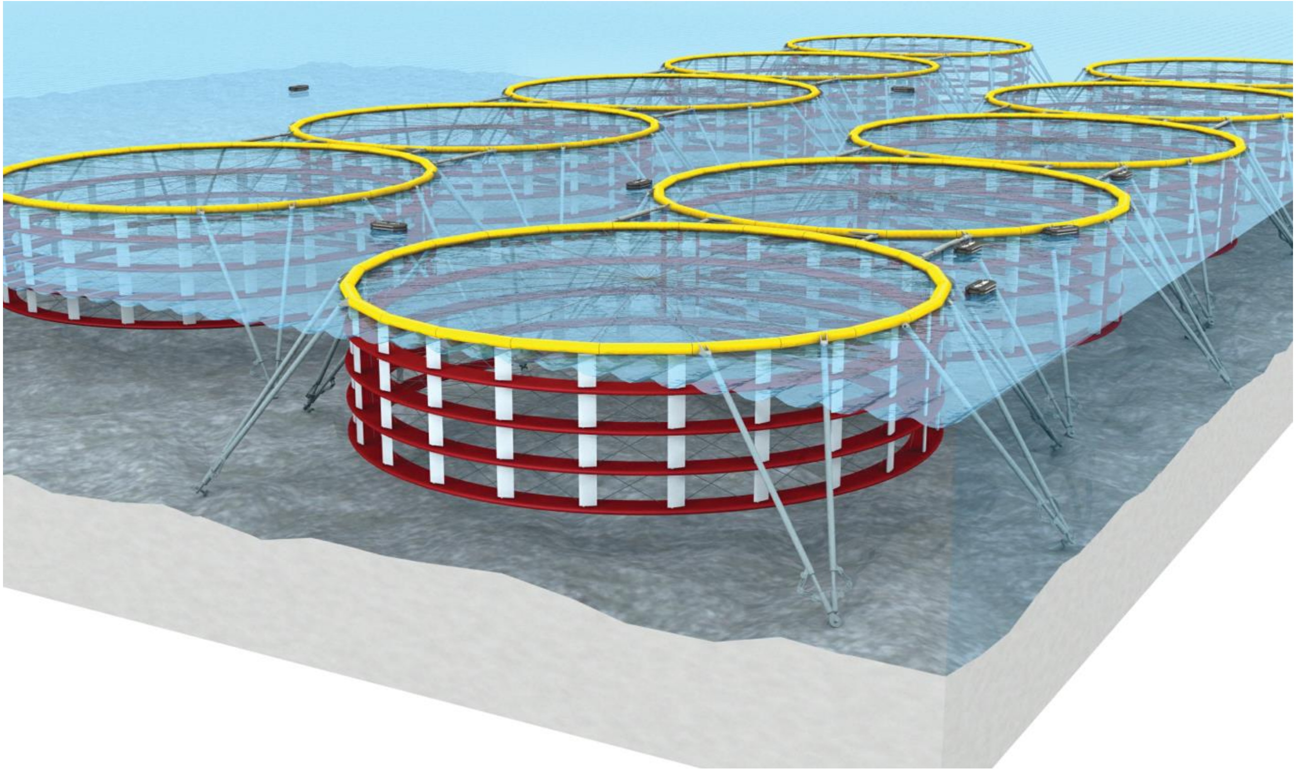

Figure 8. An artist's impression of close-packed vertical-axis contra-rotating rotors. © John MacNeill.

Vertical axis blades suffer a reversal of bending stress twice per rotation but supporting the blades at both ends gives a very large reduction in bending moment relative to a conventional cantilever blade. This would be forcefully confirmed if two stretcher bearers were ordered to stand at the same end of the stretcher. Vertical axis blades have nearly the same flow conditions along the blade span. They do not suffer stress alterations from gravity or buoyancy. With no taper or twist they may be cheaper to make.

Each rotor is located to the sea bed with 12 sloped legs made from post-tensioned concrete with adjustable near-neutral buoyancy. Hydraulic rams across the gaps and at the ends of the sloped legs will allow load-sharing and may even generate some energy from wave action. All 12 legs will have an automatic mechanical attachment to a conical steel fabrication pulled down into a conical hole in the rock by grouted Macalloy bars. Two of the legs will have wet-mating 33 kV connections to a bus running between two rows of rotors. Gaps between rotors are as small as we dare but enough to allow the passage of RNLI Atlantic 85 inshore rescue vessels.

Each rotor will sweep 10,000 square metres, ***twice*** per rotation. Readers are invited to calculate the power if there is a head difference of 0.4 metres on both the upstream and downstream sections of a rotor and if the water velocity is 3 metres a second. You should then subtract losses of blades, spokes and rings from drag and the losses of power conversion. Pairs of rotors with fuel for Diesel power can act as an extremely agile tug with Voith-Schneider propellers and a 100 MN bollard pull for self-installation and removal. If waves and safety rules allow, brave pedestrians and cyclists can travel on the upper deck. The lower downstream head will mean that the wake velocity will be slightly *higher* than the input one, *not* one third.

Rectangles can fill a higher fraction of a flow passage than circles. Provided that we can have good control of blade pitch angle through a rotation cycle the hydrodynamic performance can match that of horizontal axis turbo-machinery. Vertical axis blades have two idle pauses for each rotation but these occur when they are close to near neighbours. Being near another idle blade causes no problems and so we can have much smaller rotor gaps. They can present the same, well-controlled pressure drop across 95% of the frontage and so make the wake turbulence *lower* than that of the input flow. Ross McAdam [5] has shown with a tank test that high sweepage fraction machines can deliver a performance coefficient more than double the Betz prediction.

Recommended actions

Scottish energy planners must decide if they really would like tens of GW of clean, predictable renewable electricity and what they should do with any excess above Scottish demand. One possibilities is selling it to southern neighbours, which would need large changes to the grid. A second is producing synthetic liquid fuels from electrolytic hydrogen and an environmentally nice carbon source. Flotta seems a good place to do this.

We need to get robust information about the driving head along the Pentland flow direction. This may be possible from tidal gauge measurements by Cartwright [6] [7] or by installing patterns of acoustic Doppler current profilers with pressure sensors. Unlike now, all data should be made available to the public.

We need an energy audit for the Pentland Firth and its approaches including islands, headlands and depth changes as well as bed friction. The Cartwright measurements show 48 GW along the entering the Western approaches to Scotland. It is hard to account for all of this with low coefficients of bed friction alone. While we are highly confident about the astronomical forcing function and the bathymetry from Admiralty charts we only have real velocity measurements from very few points. The greatest uncertainty concerns water levels. It is possible that wrong information about bed friction and flow losses has been used with accurate astronomical forcing predictions to calculate water levels which have then been then been used to calculate bed friction coefficients which are in excellent agreement with models but totally wrong.

We need to consult the shipping industry and RNLI about acceptable reductions in the width of navigation passages and necessary navigation markers. We can start with a wide gap metres and build confidence about how much to reduce it.

We should calculate any increases in transport costs due to longer travel distances so that fair compensation can be negotiated. Geometry shows that these are small but not zero.

The Black and Veatch 2011 report imposed a Significant Impact Factor (SIF) of 10% as a limiting velocity reduction and a similar one for water levels. Energy planners may ask in whose name and by whose authority this limit was imposed. I happen to know that it was by a former student of mine, Ian Bryden. He chose this figure because it was the accuracy of the instruments available at the time and he argued that at this reduction nobody would be able to detect the presence of tidal installations from velocity change. He was using the word ‘significant’ in the statistical sense of a detectable threshold.

There are many places in the world with very much lower water velocities than the Pentland Firth where the heavens have not fallen and biology goes on successfully. Depending on the values of the source impedance there will be a reduction in total flow rates but there can also be local velocity *increases* in some places particularly below the rotors and in shallows at the ends of the turbine rows. It may be possible to get the two effects in balance. Velocity changes can affect sediment movement and feeding times for seabed organisms. We must ask marine biologists for advice about the optimum rates and effects of sub-optimum ones. Instead of ‘significant’ we should use the word ‘tolerable’.

We need an estimate on the amount of energy present in turbulence and the cell size of the eddies.

As well as lower velocity there will also be lower low-tide water levels downstream, nice for wading birds if not their prey, and a higher chance of vessels going aground. Higher high tides are of more concern but the amounts will be well below wave amplitudes in storms. We need to find how often the turbines would have to be taken off-line to prevent coastal flooding along the coast of Caithness.

We should minimise leakage between turbines and use the word ‘sweepage’ rather than ‘blockage’.

To match turbine installations to the Atlantic we need a more rigorous way to measure flow impedance or a more respectable way to calculate it from first principles than the increased tidal range in nearby ‘blocked’ channels.

Although the design of close-packed vertical-axis turbines is well advanced and the necessary digital hydraulics is now entering the commercial phase, there is a need for development and testing of seals, sea-bed attachments and high-voltage wet-mating connectors.

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