

TIDAL RESOURCE ASSESSMENT

Table 1 below summarises the site information that is required in order adequately to characterise a tidal stream site.

The data include the specific environmental conditions which determine the energy resource and therefore possible energy production. Other conditions that may affect the suitability of the proposed designs for the site and are important for specification of equipment, construction progress or which may result in operational disruption are also listed.

The various steps needed to undertake the calculation of the energy production of a tidal stream project are fairly well established. They are listed below but they have not been performed in any substantial quantity and furthermore they have not been validated against measured data.

- Define the tidal flow regime. This comprises the current exceedance curve, flow direction (i.e. the tidal ellipse) and velocity shear profile. These may not be constant across a site, owing to local bathymetry effects and sea bed features, and the natural spatial variations that occur in the global tidal flow across a large site;
- Define the device characteristic:
 - power curve;
 - power control and regulation strategy;
 - cut-in speed;
 - rated speed;
 - losses within the gearbox, power converter, electrical and transmission system;
 - availability.
- Define the turbine spacing, upstream/downstream and laterally, and establish any wake interference and device interactions;
- Establish the influence of the energy extraction on the global flow around the site. Assess the influence of the farm on upstream and downstream tidal levels, and establish to what extent the presence of the farm may cause the flow to divert to other routes;
- Determine whether there are any farm-to-farm interaction effects between adjacent installations;
- Feed back the influence of global flow modifications into the tidal flow models at each device location. Determine the annual energy capture for each device, and integrate to obtain the farm annual output.

This document is focused on the tasks defined by the first bullet point above and so only these tasks are considered in the following.

Flow exceedance curve

Key to establishing the energy capture potential of a site is an accurate model of the tidal flow regime, in order to establish a flow exceedance curve. Given the cube law relating flow velocity to energy, and the likely rated velocities typical for tidal plants (say 1.5m/s to 2.5m/s), errors of only 0.05m/s in estimation of the mean velocity can lead to errors of up to 6% in energy estimation. What is required, therefore, are accurate on-site measurements and an accurate tidal stream model that can predict the flow velocity (and its directional components) over a given year, at a given location.

Unfortunately, no such model currently exists. Previous tidal stream resource assessments around the UK and European waters (e.g. [1] and [2]) have used a simplified model based on the use of a double sinusoid to describe the 6.25hr flood-ebb cycle and the ~14-day spring-neap cycle. Given the other uncertainties which exist in the assumptions of resource modelling of this nature, the double sinusoid flow model is adequate for a broad-brush assessment of the likely total tidal stream resource in a region. It is not, however, sufficiently sensitive for an accurate energy capture assessment at a specific site, because true tidal patterns are much more complex. The recent UK Atlas of Marine Renewables [3] is also useful in identifying regions of high tidal stream speed for locating sites, and gives a picture of the tidal regime within each cell, however the spatial resolution means that it too is insufficiently accurate for local energy capture modelling.

Before looking at analytical models, it is worth considering some of the characteristics of tidal regimes. Tides are complex - almost 400 astronomical harmonic components have been identified which govern their motion. The motion follows a pattern which recurs over an ~18.6-year cycle, although a reasonably representative estimate of average energy capture can be obtained by looking at any single year within that pattern (it is important to consider a full year given the non-linear relationship between flow speed and energy output due to the cap introduced by the rating of any particular device). ([2] shows a typical annual tidal pattern for information). The complexity comes from the fact that:

- Flood and ebb tides are generally of different range, and the corresponding flow velocity will be of different strength;
- The first and second tidal cycles in a day also generally have different amplitudes;
- The local tidal flow pattern is not necessarily sinusoidal, but can be skewed and distorted;
- The amplitude of the 14-day spring-neap cycle varies continuously, peaking and troughing twice per year.

Tidal heights can usually be predicted to sufficient accuracy for navigation by using up to 30 of the dominant harmonics, and the procedure for deriving these for a given place and time is given in the Admiralty Manual of Tides [4] and the annual publications of tidal constants [5]. Whilst extensive tidal height tables for most major and many secondary ports around the UK are published, information on tidal streams is much more sparse. The Admiralty tidal atlases [6] give an overall impression of the tidal stream velocities around the UK, however they are not to a sufficient level of spatial resolution for tidal farm design, and generally cover only the mean spring and mean neap tides. The following flow modelling approaches are therefore envisaged:

- The assumption can be made that the peak tidal flow velocity in any low-water to high-water cycle is proportional to the tidal range of that cycle. This is probably sufficiently accurate for many sites. Using the Admiralty Harmonic Method (or other validated) tidal height prediction model for the site, and assuming that the flow is a succession of sinusoids 90° out of phase with the tidal height, the tidal flow time history can be derived for a given year. The amplitude of the flow sinusoids is calibrated using site measurements of the flow velocities at mean spring and mean neap tides, and estimates of the mean flood:ebb ratio.
- There are clearly many assumptions implicit in this model, and it is only valid for certain locations where the tidal flow is proportional to the tidal range; some sites

have a very low tidal range but high velocities, and it may be more difficult to fit the model to the measured data in these cases.

- To overcome these difficulties, a rigorous analytical tidal flow model based on harmonic decomposition of measured tidal stream velocity and direction should be developed. The Admiralty publishes a semi-graphical method for tides [7], however it is manual and calculation-intensive. Further development work is therefore required in this area.

Whichever route is adopted, at least 30 days' data from one or more bottom-mounted fixed-position Acoustic Doppler Current Profilers (ADCPs) is likely to be required in order to fully characterise the flow at a given site. The use of ADCPs can also provide valuable information on the turbulence intensity, spatial correlation of turbulence, and the wave influence of the wave climate on current flows. It may be prudent to collect substantially more data to demonstrate that 30 days' data is adequate and that the inclusion of more data produces no improvement in the result.

Work is required to develop standards for the field measurements, and experience on prototypes should provide guidelines and rules of thumb for planning the flow characterisation. For early machines, measurements should be taken over a period which encompasses a mean spring and a mean neap tidal range. The mean velocity over a period of several seconds should be sampled every few minutes. The x, y and z components of velocity should be recorded at 1m - 2m depth bins through the height of the water column. The number of ADCP measurement locations required will depend on the size of the site, and judgements are required as to the likely flow variations arising across the site from bathymetry and local features; again, experience from prototype testing is awaited.

The potential use of satellite interferometer measurements of tidal streams has also been identified by some investigators. The claimed spatial and velocity resolution is good, and may be adequate for energy capture modelling. Further investigation is required to determine whether this is likely to be a feasible route.

Velocity shear and flow direction

Tidal turbines operate in sheared flows, owing to the finite thickness boundary layer between the sea bed and the surface. Estuarial velocity profiles tend to follow a 1/7 power law from the surface, however there can be strong local site variations, with "S-shaped" profiles where the maximum velocity is not at the surface but a few metres below. The hub height velocity (and hence energy capture) at a particular site therefore depends critically on both the average velocity shear profile at that site, and the vertical position of the turbine within that flow. Some concepts may allow the latter position to vary at sites of high tidal range, such that the turbine follows the region of maximum flow in order to optimise energy capture. Other concepts however, for example gravity-based devices in deeper water, will be in a fixed position, closer to the sea bed.

Whilst many tidal stream flows are bi-directional (i.e. the flood and the ebb tides are at 180° to each other, +/- 5° to 10°), some are not. For devices that can yaw to face the flow, and for vertical-axis turbines, the flow axis is not an issue. Some device concepts, however, involve fixed orientation axial-flow turbines, and it is important to understand the flow direction in order to orientate the devices for optimum energy capture.

Table 1 Data required to characterise a tidal stream site

Data requirement	Purpose of data	Comments
Environmental conditions		
<p>Mean spring velocity (V_{ms})</p> <p>To be measured on both flood and ebb tides, when the corresponding tidal range is a mean spring tidal range.</p>	<p>An indirect measure of the energy intensity at a given site; also an indicator as to the load factor achievable and hence the economics of a site.</p> <p>Influences the rated velocity and hence rated power of a machine.</p> <p>Important in assessing the operating envelope of construction vessels (e.g. jack-up barges and dynamically positioned (DP) vessels).</p>	<p>As a guideline, most modelling suggests that currents having a $V_{ms} < 2.0\text{m/s}$ will not be economic to exploit, at least not with first generation machines.</p> <p>Sites with higher V_{ms} values (say $V_{ms} > 3.0\text{m/s}$) tend to permit load factors 40% or better, when using machines rated at a sensible (i.e. economic) power; sites with $V_{ms} \sim 2.5\text{m/s}$ tend to achieve load factors between of around 30%.</p>
<p>Mean neap velocity (V_{mn})</p> <p>To be measured on both flood and ebb tides, when the corresponding tidal range is a mean neap tidal range.</p>	<p>In conjunction with V_{ms}, the ratio of spring:neap peak tidal velocities can be established, and the ratio of flood:ebb tidal velocities. These are important parameters for calibrating an accurate tidal flow model for the site.</p>	<p>Tidal flow measurements to be taken at $\sim 1\text{m}$ depth bins through the water column from sea bed to the surface. If bathymetry is complex, or the site covers a large area, it may be necessary to repeat the data at a number of points across the site to establish the spatial variation.</p> <p>At least 14 days' data will be required at each site, in order to derive the constants required for the tidal flow model. For more accurate modelling, e.g. harmonic decomposition models, at least 30 days are required.</p>
<p>Maximum current surge velocity (V_{max})</p>	<p>To evaluate structural integrity under maximum structural drag loads combined with rotor thrusts at maximum current.</p> <p>Also necessary to ensure the rotor power regulation system can safely accommodate the maximum current. Shutdown currents may need to be defined for extreme cases.</p>	<p>Maximum 1-year and 50-year currents to be supplied in the site Metocean study, considering storm, wind wave and atmospheric effects.</p> <p>Typically, a site may see a maximum 50-year surge of 0.5m/s to 1.0m/s. This compares with mean spring peak velocities in the range 2.0m/s to 4.5m/s.</p>
<p>Flow direction (tidal ellipse)</p>	<p>For fixed-orientation horizontal axis turbines, this determines the optimum orientation for energy capture. Not relevant for vertical axis machines, or turbines which yaw into the stream.</p>	<p>Many tidal stream device concepts employ fixed-orientation axial-flow turbines. Whilst many tidal flows are approximately bi-directional (i.e. the flood and ebb are at 180° to each other, $\pm 10^\circ$), some are not, and it is therefore important to determine the optimum orientation for energy capture.</p> <p>Note that one tidal stream concept deploys a fixed-orientation turbine within a duct which it is claimed can accommodate flows up to 40° off-axis without loss of performance.</p>
<p>Tidal flow turbulence intensity and spatial turbulence correlation</p>	<p>Blade, rotor, hub and foundation fatigue integrity.</p> <p>For fatigue assessment of devices employing multiple rotors on one foundation structure, it is also necessary to measure the spatial correlation of turbulence across the rotor planes, to evaluate asymmetric fatigue and extreme load cases.</p> <p>Influence on energy capture also needs to address turbulence, but this secondary.</p>	<p>Tidal streams have a level of turbulence intensity, typically similar to that of offshore wind sites ($\sigma \sim 0.1$ to 0.12). Further work is required to confirm this is true for all types of site (e.g. estuarial, sea loch, oceanic, tidal races, sounds, rivers, saline and thermal streams). Further work also required to establish spatial correlation of turbulence at these sites.</p> <p>Need to identify local sea bed features that can increase turbulence and cause potential fatigue problems, e.g. headlands, large submerged pinnacles, steep sea bed hollows, sea bed shelves.</p>

Data requirement	Purpose of data	Comments
Current velocity profile	Energy capture assessment and fatigue load assessment.	<p>Measured estuarial flows follow a $1/7$ power law model, and thus ~75% of the energy in a flow is typically contained in the upper ~50% of the water column.</p> <p>Positioning of a device within the water column must balance energy capture with maintaining adequate surface clearance under the design wave trough occurring at LAT.</p> <p>Site specific velocity shear measurements are required, because simple models currently used may over-estimate the energy capture.</p>
Bathymetric effect	<p>Sea bed slope may influence the stability of jack-up barges.</p> <p>Local hollows or large boulders may influence the siting of turbine foundations.</p> <p>Steep sea bed slopes may affect the local incoming flow, influencing the device performance.</p>	Requirement to identify local bathymetric features that would render areas of the seabed unsuitable for installing devices. This should be done in conjunction with geophysical information
<p>Tidal heights:</p> <p>Highest Astronomical Tide (HAT)</p> <p>Lowest Astronomical Tide (LAT)</p> <p>Max. Still Water Level (positive surge) (MSWL+ and MSWL -)</p> <p>Min. Still Water Level (negative surge)</p> <p>Mean High Water Springs (MHWS)</p> <p>Mean Low Water Springs (MLWS)</p> <p>Mean High Water Neaps (MHWN)</p> <p>Mean Low Water Neaps (MLWN)</p>	<p>HAT (plus a specified construction stage design wave height) determines the maximum water depth for jack-up legs and lifting equipment for deployment of devices on the sea bed.</p> <p>LAT determines the minimum clearance between devices and the sea surface.</p> <p>Mean still water levels provide extreme cases for added mass in assessing structural dynamics. They also influence the design of access systems onto surface-breaking foundation structures.</p> <p>Mean high and low water levels determine the mean spring and mean neap tidal ranges (MSR and MNR respectively), which are important for inputs to the tidal flow model.</p>	Tidal heights are provided as standard data in site Metocean studies.
Wave climate	<p>Construction risk assessment (e.g. for jack-up stability and operating envelope of heavy lift craneage).</p> <p>Wave data are also required for structural loading calculations (fatigue and foundation extreme loads) and for installation/maintenance assessment, not for energy capture.</p> <p>Turbines will probably need to be shut down in storm conditions because (i) the wave-induced power oscillations may become too severe (+/- 80% of mean), and (ii) foundation loads may approach a</p>	<p>Wave climate to be provided in a site Metocean study.</p> <p>For construction assessments, seasonal sea state scatter diagrams are required, with wind roses at crane height. For fatigue design, a summary of total wave numbers as a function of H_s and T_p is required for the site. For extreme load assessments of the foundations foundation load assessment Typically directional sea states and a fatigue</p> <p>Modelling suggests that long-period swells can have significant effect on the power output profile of the generator. In general, high wave climate will lead to more overall energy, but this may be of lower value owing to the oscillatory nature. This is a matter for commercial negotiation on a project-by-project basis. case-by-case</p>

Data requirement	Purpose of data	Comments
	stability limit.	basis. There is still some uncertainty as to the effect that wave-induced motion will have on tidal stream devices, and data from the early prototypes will be required to assess it.
Terrain issues		
Seabed stability (sandbank movements, storm surge effects on foundations in soft soils)	Detailed geophysical and geotechnical data are required for the design of the foundations.	Seabed stability vital, especially for gravity foundations; local scour, heave and shifting of a foundation can lead to loss of performance and in the worst case loss of stability or rupture of the power cable. Detailed geophysical surveys of the sea bed are essential, and also physical sea bed testing and/or core sampling at points across the site.
Seismic conditions	Definition of design loads	Probably less relevant for tidal machines given they have stiffer foundations and are located closer to the seabed and will attract high levels of hydrodynamic damping. Not onerous for UK sites, however in parts of the world could become a more significant load case.

REFERENCES

- 1 EC-Joule programme study “The exploitation of tidal and marine currents” EC, 1996
- 2 Report prepared for Carbon Trust under the Marine Energy Challenge “UK, Europe and global tidal stream energy resource assessment”, Black & Veatch Consulting, Peer Review Issue Rev 1, September 2004
- 3 “Atlas of UK Marine Renewable Energy Resources: Technical Report” published in December 2004
- 4 UK Admiralty Manual of Tides NP120
- 5 UK Admiralty Tidal Tables, NP 201
- 6 UK Admiralty Tidal Stream Atlases, 20 Vols for UK and European waters
- 7 UK Admiralty Tidal Handbook No.1 - The Admiralty Method of Harmonic Tidal Analysis for Long Period Observations, NP122 (1)