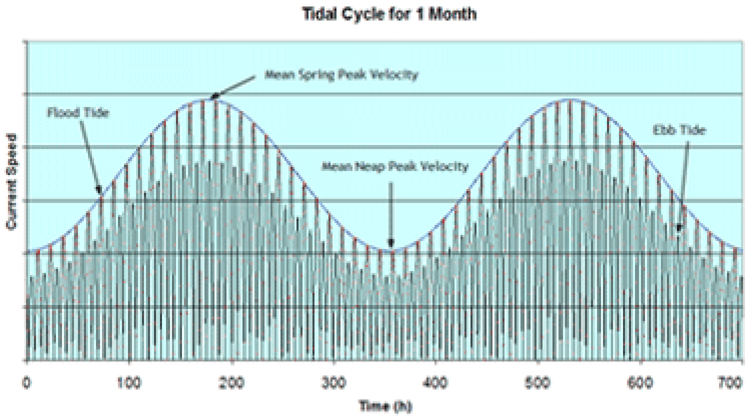
Tidal streams and tidal stream energy device design

This technical article introduces fundamental characteristics of tidal streams and links these to the power production of tidal stream energy devices.

Characteristics of tidal streams
Patterns of tidal stream velocity variations are described in the article on variability of wave energy and tidal stream energy resources, but suffice to say here that two periodic cycles dominate: semi-diurnal variations (twice per day) and the spring/neap cycle. Figure 1 shows a profile of current speed over one month and illustrates two limits of velocity often referred to: **the mean spring peak velocity** and **mean neap peak velocity**. One can see the former is the greatest velocity that can ever occur, while the latter is a restricted maximum when the spring/neap cycle is at a trough. In fact, this is a simplified illustration and at real tidal stream sites there may be some differences to the classic sinusoidal forms which are themselves time-varying.

Figure 1: Variation of current speed over one month



The way that tidal stream motions occur is in some ways similar to wind flows in open space, but there are some important differences due to the flow being constrained by the channel floor (seabed) and walls (land masses). Also tidal stream flow has a free surface, which gives it different properties to flow within pipes.
Consider the simple channel shown in Figure 2. Near the edges and the bottom, friction between the water and channel sides slows the flow and at the channel boundaries the velocity is zero. In effect, the wetted perimeter exerts a retarding force on the moving body of water, and in real tidal stream situations this is influenced by the shoreline **orography** (shape of the land), **bathymetry** (shape of the seabed) and the **roughness** of these surfaces.

Figure 2: Cross-section of a simple channel

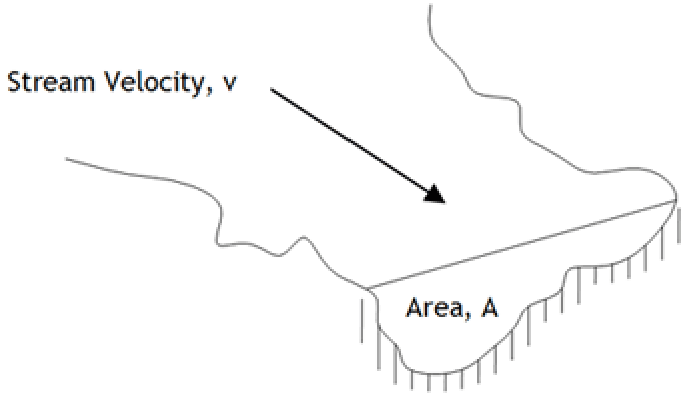
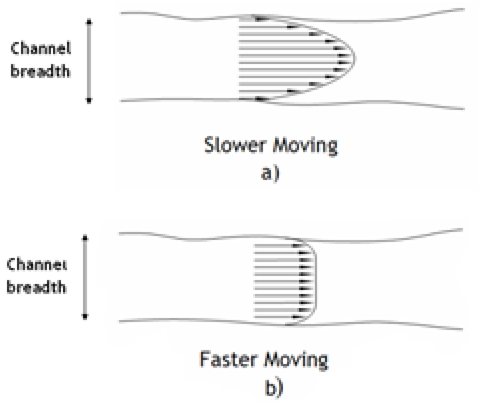


Figure 3 shows two channel **velocity profiles** (variation of velocity over a cross section of flow) in plan view. One can see that in either case the greatest velocity is away from the edges, towards the centre of the cross section. It might be supposed that the velocity profile would be less pronounced for slower flows than faster flows, but in fact the opposite is true. This is because when the flow rate is slow, viscous forces within the fluid tend to create a parabolic velocity profile, and at faster flow rates, inertia forces dominate the viscous forces and cause the profile to flatten off.

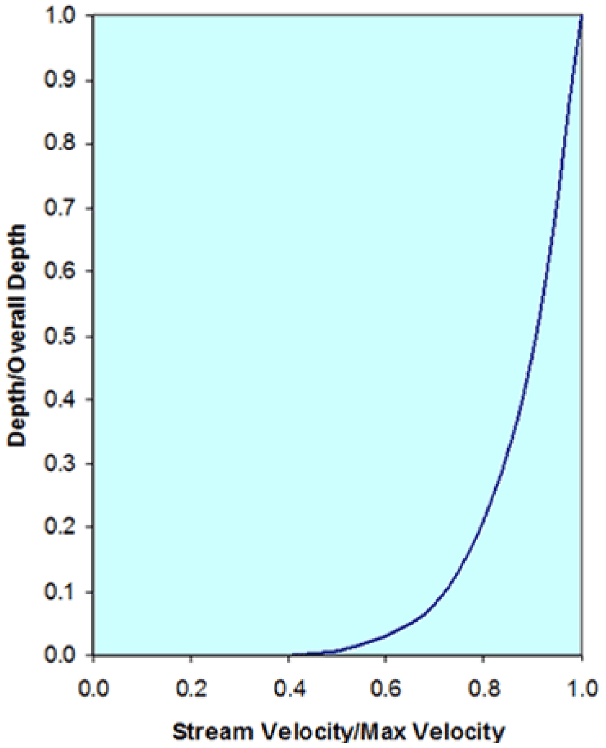
Figure 3: Velocity profiles (plan view) of tidal stream flows at different speeds



Having established how flow varies over a channel's breadth, we can consider how it varies over the water column. Readers familiar with wind energy will recognise the basic form of Figure 4, which is a **shear profile** from the seabed to water surface. The gradient function of this curve is affected by the seabed surface roughness and is not well known for tidal stream situations, but in some studies to date has been found to approximate to the 1/7th power law (that is, the same as some wind farm sites). Key observations from Figure 4 are that the velocity is always greatest close to the water surface, and falls off rapidly close to the seabed. Halfway up the water column the velocity is ~80% of the surface velocity.

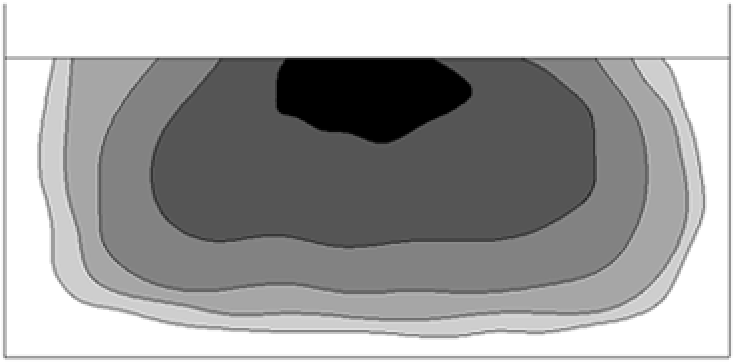
Figure 4: Shear profile showing variation of stream velocity with height. The power law is as follows: $v(z) = v_1(z / z_1)^{1/7}$,

where v1 is the velocity at a known elevation z_1, and v(z) is the velocity at some elevation in question z



Putting these frames of reference together, we can begin to imagine how velocity varies over the water column height and across the channel. Figure 5 is a simplified illustration of this. Since every tidal stream channel has a unique orography and bathymetry, it is important to appreciate the distribution of velocity when considering possible deployment locations. Note that the directions of flow, and therefore the velocity profile, may differ between the flood and ebb tides (i.e. the pre-dominant directions are not exactly 180° apart). Furthermore, turbulence intensity levels (short term fluctuations in flow speed) may need investigation. Turbulence can be expected some distance downstream of local bathymetric features (e.g. rocks, seabed shelves), and intensity levels may be higher near the seabed and channel sides. Acoustic Doppler Profiling and/or other survey techniques may be necessary to establish velocity distributions and turbulence intensity levels at real sites.

Figure 5: Variation of velocity over cross-section of a channel. Each region indicates a band of velocities, black being fastest, white slowest



Energy content of tidal stream flows and extraction by tidal stream devices

The kinetic energy of a flowing tidal stream per unit time, which is the same as the power (Ps), can be readily calculated in terms of the velocity (v), cross-sectional area (A) perpendicular to the flow direction, and the density of water (p, which for sea water is approximately 1025 kg/m3). Providing the velocity is uniform across the cross-sectional area (approximately true for small areas), at any instant in the tidal cycle $Ps = ½ p A v^3$.

This function is convenient to quickly estimate e.g. the maximum power of a site's tidal stream resource, but because the velocity changes constantly, a time-weighted calculation is needed to determine the energy resource.

The cubic relationship between velocity and power is the same as that underlying the power curves of wind turbines, and like in wind power, there are practical limits to the amount of power that can be extracted from tidal streams. Some of these limits relate to the design of tidal stream devices and others to further characteristics of the resource. This means that some constraints are the same as in wind power, but others are not.

To help explain the limits related to the resource, Figure 6 shows a horizontal-axis turbine (which is one of several options for tidal stream generation devices) in three situations: a) in open space (how wind turbines are sited over land or sea), b) within a wide channel, and c) in a narrow channel. These cases have a successively greater number of flow boundaries: the ground (seabed), water surface, and channel sides. We can approximate the open space situation to unconstrained free-stream flow if the turbine is sited some distance from the ground, such that the flow velocity is reasonably well developed. In this case, it can be shown there is a maximum amount of energy which can be extracted, due to the need for the flow to retain some kinetic energy downstream of the turbine. This is known as the **Betz** limit and is approximately 59% (for details see e.g. Massey, Mechanics of Fluids). Note that this is a physical limit independent of a device's ability to convert the tidal stream energy into electricity – i.e. it applies before any mechanical or electrical efficiency is accounted for.

Figure 6a: Turbine rotor in open space

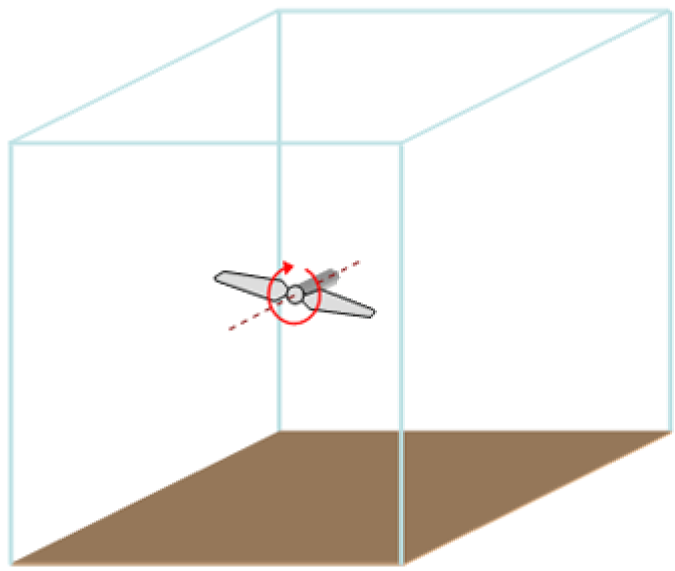


Figure 6b: Turbine rotor in wide tidal stream channel, far from seabed, water surface and channel sides

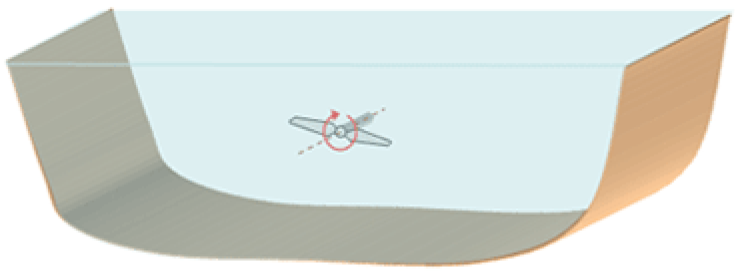
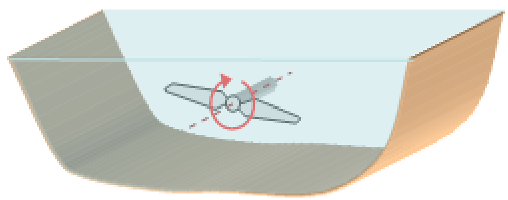


Figure 6c: Turbine rotor in narrow tidal stream channel, close to seabed, water surface and channel sides



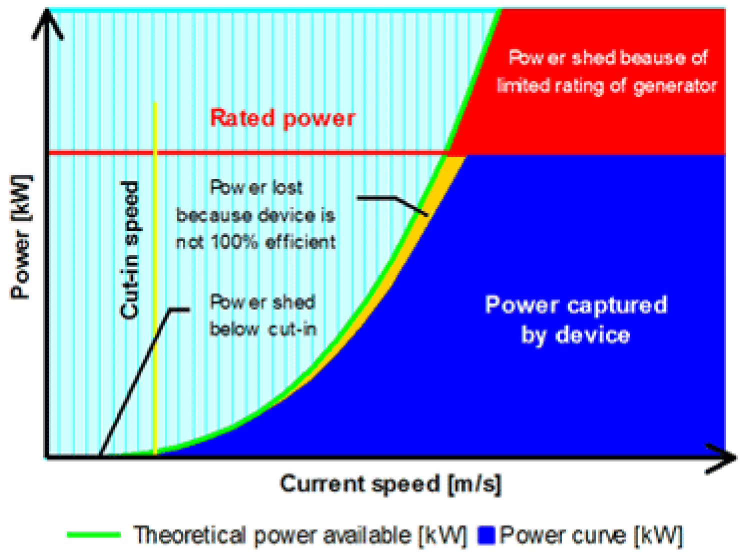
The case of a wide channel can also be approximated to free-stream flow if the area of flow intercepted by the turbine is relatively small compared to the distance this area is from both the seabed and water surface, (that is, the rotor diameter is relatively small compared to the water depth). Thus we might again expect the Betz limit to apply. However, for situations where the rotor is close to either the seabed, channel sides or surface, so that the stream is blocked to a significant degree, Betz will not hold. Actually what happens to tidal stream flows in such situations is complex and depends strongly on the geometry of the fixed flow boundary(ies) and the remaining unobstructed area. In some cases the flow may be prevented from diverging around the turbine and slowing to the extent it would do in a free stream. Indeed, it is possible to create an artificial duct around a turbine to deliberately create a region of greater velocity, and this is a feature of some proposed turbine designs. However, the possible subsequent benefit of using a smaller rotor to capture an equivalent amount of power must be weighed against the cost of creating the duct itself. A further area to note in relation to device/resource interactions is the effect of extracting energy from a tidal stream on the downstream flow. In most situations one would expect a wake behind a turbine (a region of relatively slow, turbulent flow), and indeed the ability of the flow to recover wakes is one condition of its approximation to a free stream. But investigators have also noted that for any site, only a finite proportion of the total energy can be extracted without significantly altering the site's general flow speed, which could have economic and environmental consequences. This proportion is the **Significant Impact Factor (SIF)**, and is mentioned in the articles on the tidal stream resource. The SIF is unique to particular sites and may vary between 10% and 50% of the energy in the flow.

Power generation of tidal stream devices

Moving now to the limits of power capture relating to the tidal stream device itself, Figure 7 illustrates ranges of velocity where power can and cannot be captured. This is a repeat of the graph shown in the previous energy capture performance article, and a commentary is given there, but it is worth recalling that at all speeds the power captured is always less than the maximum given by the power $\propto$ velocity^3 relationship.

To understand why this is so, it is necessary to look closely at the process of converting the tidal stream's kinetic energy to electrical power. Essentially, this happens in a number of steps, considered here in the case of a horizontal-axis turbine, for example.

Figure 7: Example tidal steam energy device power curve



Firstly, some of the linear momentum of the moving water is converted to angular momentum of the rotor blades, which delivers mechanical power to the rotor shaft. The shaft power is the product of torque applied to the rotor (τ) and the speed of rotation (ω), ($P_s = \tau\ \omega$), and is expressed as a fraction of the tidal stream power flux by the coefficient of performance (C_p).

Note that the torque and speed are strongly influenced by the design of the rotor. A rotor with many blades taking up much of the swept area (a configuration known as high solidity) will produce high torque at low speeds, but also reach maximum power at a relatively low rotational speeds.

Conversely, a turbine with few blades (low solidity) produces low torque at high speeds and is more suitable for electricity generation at 50 Hz.

In situations where the Betz limit applies (see above), the maximum value of C_p is 59%.

In practice, however, the actual performance of a turbine is less than this, firstly because it is impossible to create an aerodynamically perfect (lossless) rotor. In operation, performance is also reduced due to either the blades turning so rapidly that the turbulent region created by one blade is moved into by the following blade, or the rotational speed being so slow that much of the flow simply passes through the swept area without a blade interfering with it. Hence C_p is a function of rotational speed.

To achieve the correct balance, there needs to be time for the stream to become re-established between the passage of successive blades. This points to the relationship between the rotational speed and free-stream velocity (v_{fs}), which it is convenient to refer to as the **tip speed ratio** (Λ).

This is the linear speed of the blade tips (v_t) divided by the free-stream velocity, ($\Lambda = v_t / v_{fs}$).

Figure 8: Power coefficient (C_p) against tip speed ratio (λ) for an example horizontal axis turbine

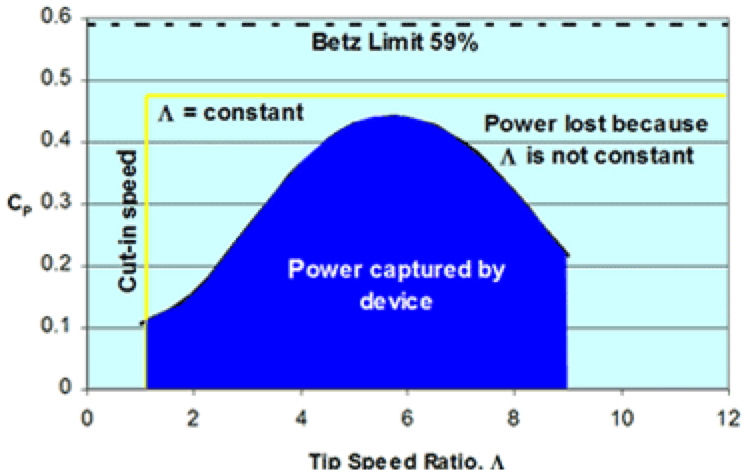


Figure 8 shows how the power coefficient of an example horizontal-axis tidal stream turbine relates to the tip speed ratio.
We can see that the maximum C_p occurs for a certain value of Λ
If a turbine could operate at a fixed tip speed ratio then the power produced would be constant, as indicated by the yellow line of Figure 8; one would naturally choose Λ to give a constant maximum C_p .

But in practice, this is not possible, since to achieve a constant tip speed ratio would require the tip speed and therefore angular velocity to change proportionally with free stream velocity, over the entire range of v_{fs}.

It is unattractive to let the rotor turn very fast since this would mean that the blades experience large forces, and the likelihood of structural failure (or costs of avoiding it) would increase. Speed of rotation also affects the blades' energy capture performance, because each blade experiences drag due to the pressure difference across it. At moderately fast speeds, **cavitation** can possibly occur; this is when the water pressure local to the blade surface falls below the vapour pressure, causing

bubbles to appear, rapidly expand and then collapse. The resulting small shock loads can damage the blade surfaces and reduce their efficiency. The implication is that for a rotor of any particular diameter, there is a maximum permissible tip speed.
Notwithstanding these constraints, there is scope for generating power close to the maximum C_p over a range of v_s by **varying the blades' pitches** (feathering).

This permits control of the blades' aerodynamic efficiency, and has been proposed for some designs of tidal stream turbine. Below the rated speed, the objective is to generate as much power as possible, and varying the pitch angle allows the aerodynamic efficiency to be maintained as the free-stream velocity changes. Above the rated speed, pitch control can be used to shed power and control the forces experienced by the rotor. An alternative power control strategy common in wind turbines is **passive stall**, whereby fixed-pitch blades are designed so that when a particular free-stream speed is reached, a region of turbulence created behind the blades overcomes the lift force and causes the rotor to slow.

Although rotor efficiency (transfer of the tidal stream's power flux to shaft power) is best maintained by varying the rotational speed, it may be noted that the opposite is true for generation efficiency (conversion of the shaft power to electricity); constant rotational speed is most straightforward to generate at constant voltage and frequency. An approach which facilitates the two ideals is to de-couple the rotor and generator by using a frequency converter, although this is at the expense of some electrical loss. If such a system is used, it is possible to employ a synchronous generator, but otherwise, it may be that an induction machine is necessary, due to the need to apply damping in the drive train to accommodate cyclic variations in torque developed by the rotor. Direct-drive generators (mitigating the need for a gearbox) have also been proposed for some tidal stream devices.
Depending on the power train configuration, after the stage of transferring the tidal stream's power flux to shaft power, the remaining steps of energy transfer may include the following:

1. Increase the shaft rotational speed/reduce the torque (gearbox);
2. Convert the shaft power into electricity (generator);
3. Convert the generation voltage and frequency to the grid voltage and frequency (frequency converter).

The efficiency of each stage (**η_1, η_2, η_3**) will be less than 100% but can be expected to be reasonably high at around 95% each. The electricity generated at any instant (P_e) is the product of the tidal stream power flux, rotor coefficient of performance and the applicable power train efficiencies:

$$P_e = P_s C_p \prod_i \eta_i,$$