

3. Tidal Stream

Tidal stream technologies are designed to extract energy from fast flowing water in tidal streams.

3.1. History and Development

Tidal stream energy conversion devices are a recent addition to the aquatic renewable energy industry.

The power of tidal streams has been known since the earliest days of seafaring. It is only recently, with the development of offshore engineering technologies and the drive to find renewable energy resources, that tidal stream energy has become technically feasible.

Developments of tidal stream technology began in the early 1990s, and by the beginning of the 21st century a wide range of designs were being proposed, developed and tested.

3.1.1. Level 2

Tidal stream technologies generate electricity using the flow of water created by the tides and accelerated by coastal topography. As is the case with early stage wind and wave technologies, a number of tidal stream concepts have been, and continue to be, proposed. Most are based on rotating rotors, either horizontal or vertical-axis. No tidal devices are commercially available. A number of devices have been, or are being, tested on a small scale, and some machines have been tried as full-scale prototypes.

Tidal power research programs in industry, government and at universities in the UK, Norway, Ireland, Italy, Sweden, Canada and US over the last half dozen years have established an important foundation for the emerging tidal power industry. Today, a number of companies, backed by private industry, venture capital and European governments, are leading the effort to commercialise technologies to generate electricity from tidal streams. The results show that large-scale energy generation from currents requires entirely submerged turbines and large and robust offshore systems - which are only now becoming technically feasible.

There are many similarities between wind and tidal current generating systems, both in terms of devices and the nature of the driving force. The most straightforward way to develop tidal stream energy is to borrow from horizontal axis wind turbines, where the technology, components and know-how have been developed over the last 30 years. A tidal stream turbine is similar to a wind turbine, except that the density of seawater is 800 times greater than air, and seawater flow rates are typically one fifth those of air. A properly rated tidal turbine would have a rotor diameter about half that of a wind turbine of the same rated power.

Compared to wind technology, tidal stream systems are in their infancy and there have been only a small number of prototype scale demonstrations of plants with an installed capacity of over 100 kW. It is expected to take several years before items of equipment are produced for

purchase and installation. Three of the most significant technology demonstrations have taken place during the past few years and two of these are ongoing. None of the demonstration units is a pre-production prototype and all research teams plan to build and test larger systems before going into production. There is very little published data on the performance of tidal stream systems either at model or prototype scale. Consequently, most of the available information is sourced from company literature and the world wide web.

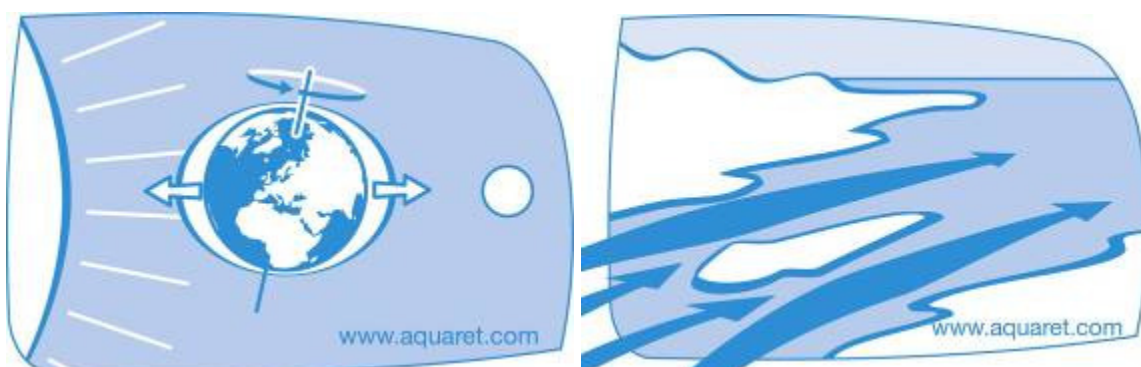
Many engineers and developers now favour technology which makes use of kinetic energy in flowing tidal currents. The most thoroughly documented early attempt to prove the practicality of tidal current power was conducted in the early 1990s in the waters of Loch Linnhe in the West Highlands of Scotland. This scheme used a turbine, held mid-water by cables, which stretched from a sea-bed anchor to a floating barge.

The mid-to-late 1990s was primarily a time of planning and development and it was not until the beginning of the 21st century that further systems became ready to test. In 2000, a large vertical-axis floating device, the Enermar, was tested in the Strait of Messina. Marine Current Turbines Ltd has been demonstrating a large pillar-mounted prototype system called Seaflow in the Bristol Channel, between England and Wales.

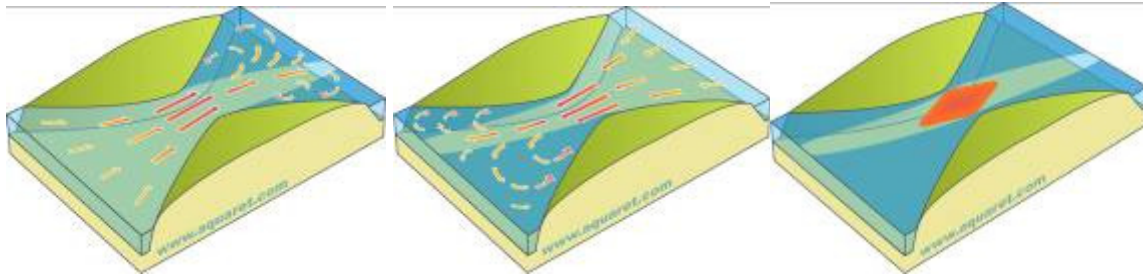
In Norway, the Hammerfest Strøm project demonstrated that pillar-mounted horizontal-axis systems can operate in a fjord environment. In the USA, the first of an array of tidal turbines were installed in December 2006 in New York's East River. Once fully operational this should be the world's first installed array of tidal devices. In 2007, The European Marine Energy Centre (EMEC), which was established in 2004 to test full-scale marine energy technology in a robust and transparent manner, became fully equipped. The tidal test berths are located off the south-western tip of the island of Eday (Scotland).

3.2. Energy Source and Location

As with tidal range impoundment plants, tidal stream technologies rely on the tides created by the gravitational pull of the moon and sun on the seas. Impoundment uses the rise and fall of sea level, and the potential energy of heads of water trapped in a basin, but tidal stream uses the kinetic energy of the currents flowing in and out of tidal areas.



The tidal current resource follows a sinusoidal curve with the largest currents generated during the mid-tide. The ebb-tide often has slightly larger currents than the flood-tide.



In most places the movements of seawater are too slow and the energy availability is too diffuse to permit practical energy exploitation. The strength of the marine currents generated by the tide varies, depending on the position of a site on the Earth, the shape of the coastline and the bathymetry. Along straight coastlines and in the middle of deep oceans, the tidal range and marine currents are typically low. Generally, the strength of the currents is directly related to the tidal height of the location.

There are also some locations where the water flows continuously in one direction only, and the strength is largely independent of the moon's phase. These currents are dependent on large thermal movements and run generally from the equator to cooler areas. The most obvious examples are the Gulf Stream and the Strait of Gibraltar, where in the upper layer, a constant flow of water passes into the Mediterranean basin from the Atlantic.

3.2.1. Level 2

Data on marine currents are sparse but work is being undertaken to remedy this. A major study by the European Commission evaluating the tidal current resource for 106 locations around Europe, with predefined characteristics making them suitable for tidal stream energy exploitation, estimated an exploitable resource from those sites of 48 TWh a year (IT Power, 1996). The aggregate capacity of this selection of sites amounted to an installed capacity of marine current turbines of more than 12,000 MW.

The UK government has estimated 320 MW of installed capacity for the United Kingdom by 2010 (ETSU/DTI, 1999). A more recent study by Black & Veatch (2004) suggests an estimated UK extractable resource of 22 TWh for tidal stream, using a modified and more accurate methodology. Although the UK tidal stream database is fairly limited at this stage, there is no other country with more detailed information. In 2005, the Electric Power Resource Institute (EPRI) evaluated the techno-economic feasibility of tidal in-stream energy conversion (TISEC) in North America with valuable results. Other countries with an exceptionally high resource include Ireland, Italy, the Philippines, and Japan.

The map below presents the mean tidal amplitude for 237 locations along the European coastline. These locations are situated 50 to 100 km away from the shoreline, and the distance from one location to another is approximately 100 km. It is the analytical result of a study performed by the European Environment Agency (<http://www.eea.europa.eu/>).

3.2.2. European Resource Map

Tidal stream resources are generally largest in areas where the water depth is relatively shallow, where a tidal range exists, and where the speed of the currents is amplified by the funnelling effect of the local coastline and seabed; for example, in narrow straits and inlets, around headlands, and in channels between islands. Entrances to lochs, bays and large harbours often have high current flows. In particular, large marine current flows exist where there is a significant phase difference between the tides that flow on either side of large islands. A good in-stream tidal site is one that has bathymetry and seabed properties that will allow a tidal stream device to be sited, has minimum or no conflicts with other uses of the sea space, and is close to a load and grid interconnection.

The map below indicates the level of resource across Europe.

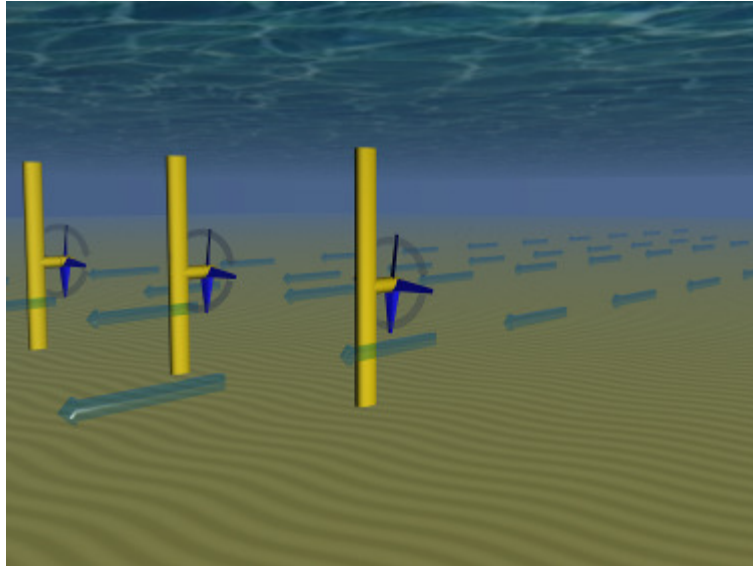


Compared with wave or wind technologies, the siting requirements for tidal turbines are far more site-specific. As with wind energy, a cube law relates instantaneous power to fluid velocity. A marine current of 2.5 metres per second (5 knots), not an unusual occurrence at such locations, represents a power flux of 8 kW per square metre. The minimum velocity for practical purposes is 1 metre per second (2 knots), 0.5 kW per square metre. In practice, locations are needed with mean spring peak tidal currents faster than 4-5 knots (2-2.5 m/s), or the energy density will be inadequate to allow an economically viable project.

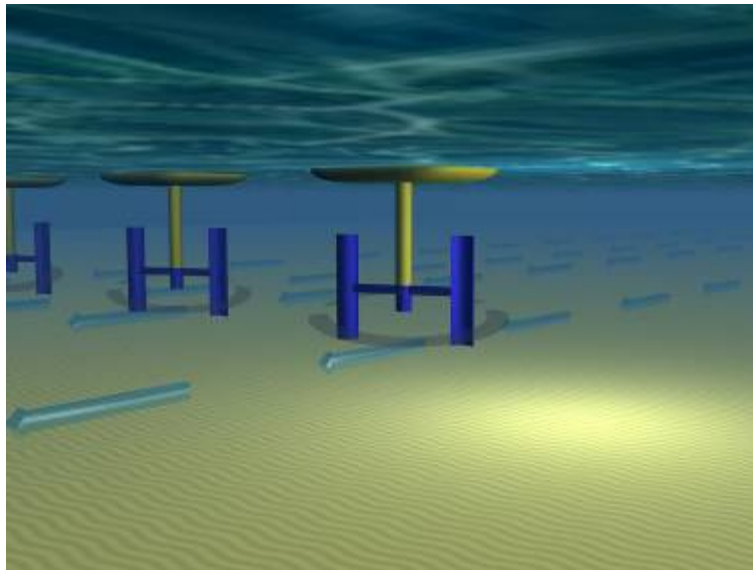
3.3. Technology Types

Tidal stream technologies are designed to harness the kinetic energy of the fast flowing water in tidal areas. Research and development in this emerging field have led to the design of several types of device to capture this energy:

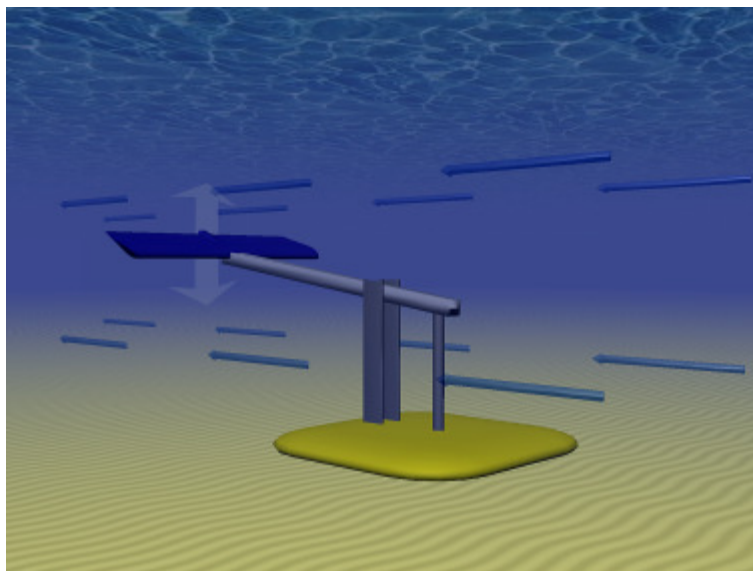
Horizontal axis turbines work much the same as a conventional wind turbine and some look very similar in design. A turbine is placed in a tidal stream which causes the turbine to rotate and produce power. Some turbines may also be housed in ducting/cowling to create secondary flow effects by concentrating the flow and producing a pressure difference.



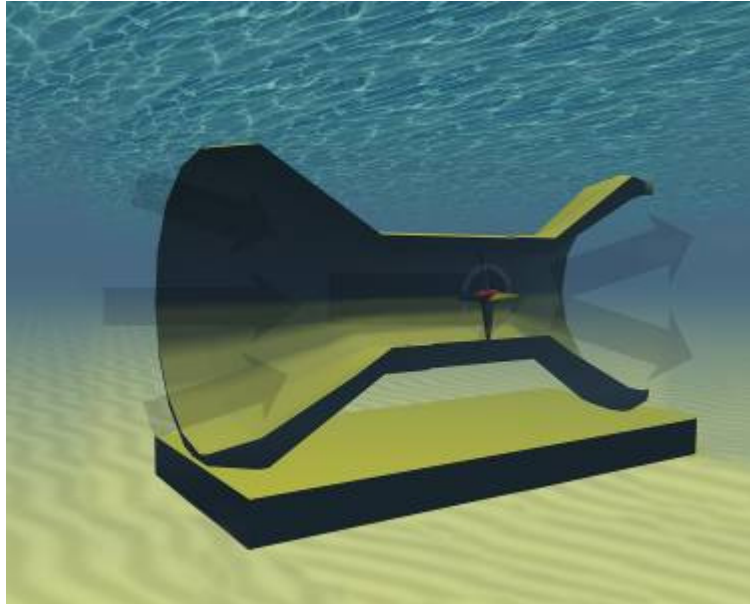
Vertical axis turbines use the same principle as the horizontal axis turbines only with a different direction of rotation. A turbine is placed in a tidal stream which causes the turbine to rotate and produce power.



Reciprocating devices (oscillating hydrofoils) have hydrofoils which move back and forth in a plane normal to the tidal stream, instead of rotating blades. The oscillation motion used to produce power is due to the lift created by the tidal stream flowing in either side of the wing. One design uses pistons to feed a hydraulic circuit, which turns a hydraulic motor and generator to produce power.



Venturi effect tidal stream devices – The tidal flow is directed through a duct, which concentrates the flow and produces a pressure difference. This causes a secondary fluid flow through a turbine. The resultant flow can drive a turbine directly or the induced pressure differential in the system can drive an air-turbine.



3.3.1. Level 2

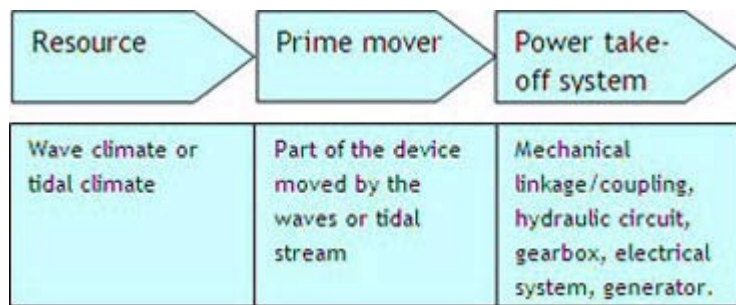
The physics of the conversion of energy from tidal currents is similar in principle to the conversion of kinetic energy in the wind. Many of the proposed devices have a superficial resemblance to wind turbines. There is no consensus on the form and geometry of the conversion technology itself. Wind systems are almost entirely horizontal-axis turbines and many developers favour this geometry for tidal conversion, but vertical-axis systems have not been rejected.

There are three basic steps involved in the energy transformation by a tidal stream energy converter:

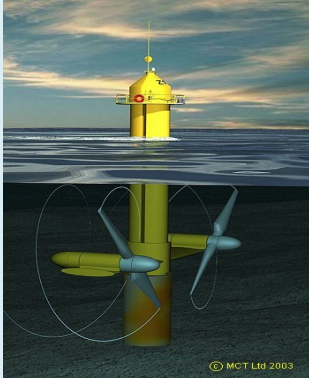
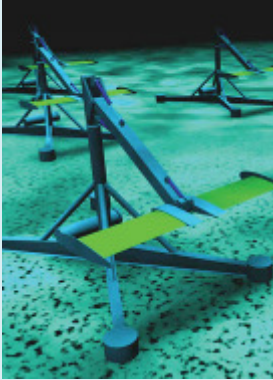
- The turbine rotor (or any other type of prime mover that extracts the energy from the flow) is driven by the current. This converts the energy of the current into rotational energy of the shaft.
- The gearbox converts the low rotational speed of the turbine shaft to the desired speed of the generator shaft.
- The generator converts its shaft energy to electric energy which is transmitted to the shore via a cable on the sea bed.

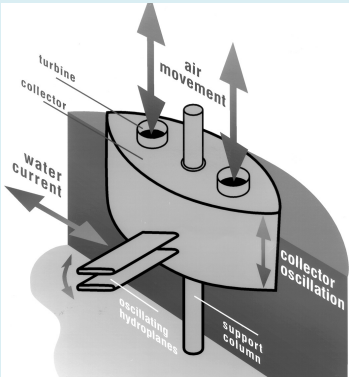

Essentially, the energy converted into electricity by a tidal stream device is a function of the resource it is placed in (i.e. local tidal conditions), the device's prime mover, and the device's power take-off system (i.e. everything between the prime mover and the electrical terminals for connection to the grid). This is a dynamic system; changes to one aspect can have a significant effect on another.

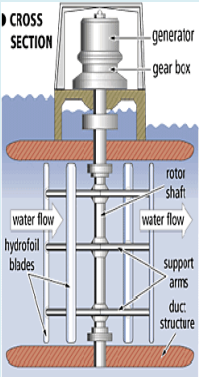

Key factors influencing the performance of marine renewable devices





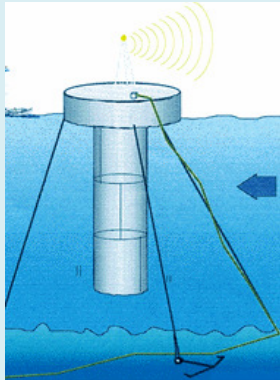

Although it is possible to make general observations about the performance characteristics of tidal stream devices and identify requirements for high performance that are common to many design variants, to understand performance characteristics in detail it is necessary to look closely at specific device designs. Because of the many ways that tidal stream devices can be configured, their performance characteristics vary widely.


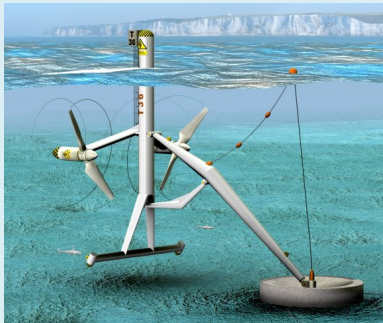
Device Name, Lead Organisation, Website, Country	Technology Type	Brief Description and picture
<p>Seaflow / Seagen</p> <p>Marine Current Turbines Ltd</p> <p>www.marineturbines.com</p> <p>UK</p>	<p>Horizontal Axis Turbine</p>	 <p>SeaGen consists of twin horizontal axial flow rotors of 15m to 20m in diameter (the size depending on local site conditions), each driving a generator via a gearbox much like a hydro-electric turbine or a wind turbine. The turbines are expected to be rated from 750 to 1500kW per unit and can be grouped in arrays. They have a patented feature by which the rotor blades can be pitched through 180° in order to allow them to operate in bi-direction flows – that is on both the ebb and the flood tides. The twin power units of each system are mounted on wing-like extensions either side of a tubular steel monopile some 3m in diameter and the complete wing with its power units can be raised above sea level to permit safe and reliable maintenance. The monopile can be installed at water depths less than 30 meters. The turbines and accompanying power units can be raised up the support pile to permit access for maintenance.</p>
<p>Stingray</p> <p>Engineering Business Ltd</p> <p>www.engb.com</p> <p>UK</p>	<p>Oscillating Hydrofoil</p>	 <p>Stingray is designed to extract energy from water that flows due to tidal effects - tidal stream energy. It consists of a hydroplane which has its attack angle relative to the approaching water stream varied by a simple mechanism. This causes the supporting arm to oscillate which in turn forces hydraulic cylinders to extend and retract. This produces high pressure oil which is used to drive a generator. EB has recently completed its programme to design, build, install offshore, test and decommission a full scale demonstrator of its Stingray tidal stream generator.</p>



Device Name, Lead Organisation, Website, Country	Technology Type	Brief Description and picture
<p>AWCG Engineering Business Ltd www.engb.com UK</p>	<p>Oscillating Hydrofoil</p>	 <p>The Active Water Column Generator features hydroplanes acted upon by moving water to move a part-sealed collector up and down. As it moves, air is drawn in and expelled from top of chamber powering an air-based turbine. A scale model of this concept was built and tested in dry docks in 1999, but little research has been carried out into the concept since that time.</p>
<p>Sea Snail Robert Gordon University and AREG http://www.rgu.ac.uk/cree/genera1/page.cfm?pge=10769 UK</p>	<p>Horizontal axis turbine</p>	 <p>This research project is focused on the novel design of the turbine support frame more so than on the operation of the turbine itself. Testing of a half-size frame prototype has taken place off Orkney, with a full size prototype, capable of generating 750 kW of electricity planned. The 330-tonne prototype can be taken down to any depth on the sea floor and back on command. It is expected to be useful for smaller sites and enable planning of future developments by ease of recording site data. The fundamental operating principle of the Sea Snail is based on the familiar upturned aerofoil found on most racing cars. A number of hydrofoils are mounted on a frame in such a way as to induce a down force from the stream flow. As the flow speed increases, so does the overturning moment on the turbine and the down force on the foils. Provided that the ratio of surface areas is such that the down force generated exceeds the overturning moment, then the Sea Snail will remain in position.</p>



Device Name, Lead Organisation, Website, Country	Technology Type	Brief Description and picture
<p>Ocean Turbine</p> <p>Blue Energy</p> <p>www.blueenergy.com</p> <p>Canada</p>	<p>Vertical axis turbine</p>	 <p>This turbine acts as a highly efficient underwater vertical-axis windmill. The basic design involves multiple 25kW vertical axis Davis Hydro turbines installed as a tidal fence array. Four fixed hydrofoil blades of the turbine are connected to a rotor that drives an integrated gearbox and electrical generator assembly. The hydrofoil blades employ a hydrodynamic lift principal that causes the turbine foils to move proportionately faster than the speed of the surrounding water. The turbine is mounted in a durable concrete marine caisson which anchors the unit to the ocean floor, directs flow through the turbine further concentrating the resource supporting the coupler, gearbox, and generator above. These sit above the surface of the water and are readily accessible for maintenance and repair.</p>
<p>Polo</p> <p>Edinburgh University</p> <p>www.mech.ed.ac.uk/research</p> <p>UK</p>	<p>Vertical axis turbine</p>	 <p>The design consists of a vertical-axis rotor, with the generation plant at the surface in a sealed compartment at atmospheric pressure. The rotor uses variable-pitch blades where pitch is set by control of the moment about the pitch axis. Hydrostatic bearings use a set of compliant master-slave pads to allow large geometrical distortion. The arrangement allows all the generation plant to be at the surface in an accessible, sealed compartment at atmospheric pressure.</p>

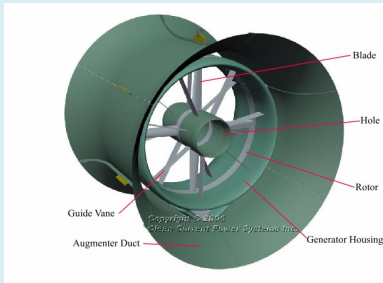
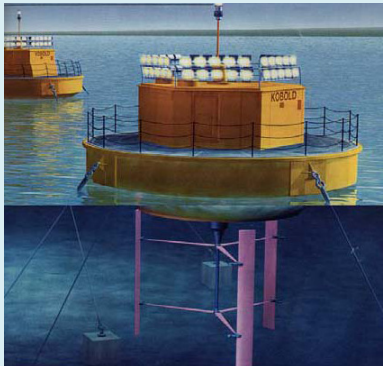
Device Name, Lead Organisation, Website, Country	Technology Type	Brief Description and picture
Rochester Venturi <i>HydroVenturi Ltd.</i> www.hydroventuri.com UK	Venturi effect device	 <p>In one type of RV system a submarine venturi can be used to accelerate the water and create a subsequent pressure drop which then pulls air into the device. The air sucked into the water can be used for remediation in addition to driving a turbine/generator pair sited onshore or on a platform. RV technology does not necessarily require impounding large bodies of water to extract energy economically, nor does it require submarine turbines or submarine moving or electrical parts. Expensive maintenance operations that typically arise when complex mechanical systems are submerged in a marine or river environment can thus be avoided.</p>
Underwater Electric Kite <i>UEK Corporation</i> http://uekus.com/ USA	Twin horizontal axis turbine	 <p>The Underwater Electric Kite is a twin horizontal axis turbine. The outer diameter of the augments ring is 6.2 m. The turbine diameter is 4 m. The turbine is named because it moves like a kite: anchored to the bottom by a cable and controlled by a computer, it rises or descends searching for the layer of water where the tidal current runs fastest. The design features a self-contained moderately buoyant turbine-generator suspended like a kite within the tidal stream. The 120kW system also works in tidal basins and rivers. The rated power is 400 kW at 3 m/s.</p>

Device Name, Lead Organisation, Website, Country	Technology Type	Brief Description and picture
<p>Exim Seapower www.seapower.se Sweden</p>	<p>Vertical axis turbine</p>	 <p>EXIMTM Tidal Turbine Power Plant (TTPP) by Seapower is based on the Savonius Turbine under a buoy which is anchored so that it cannot rotate with the stream. This drag type vertical axis turbine turns slowly but yields a high torque and was originally designed for converting kinetic energy of ocean currents into rotary energy. It is S-shaped. A prototype turbine has been used in tests to find the best site for a tidal generator to supply the Shetland grid. Dual rotors with 1 meter in diameter and 3 meters high; altogether 6 meters high. The rated power is 44 kW at 2.4 m/s water speed.</p>
<p>Gorlov Turbine GCK Technology www.gcktechnology.com/GCK USA</p>	<p>Vertical axis turbine</p>	 <p>The Gorlov Helical Turbine (GHT) was specifically designed for hydroelectric applications in free flowing low head water courses. It demonstrates superior power efficiency in free currents compared to other known turbines. The GCK Gorlov Helical Turbine is a cross flow turbine with three airfoil-shaped blades. The Gorlov Helical Turbine rotates at twice the velocity of the water current flow. The turbine design itself is an improvement of the Darrieus design. The standard model is 1 meter in diameter and 2.5 meters in length and the rated power of the device 1.5 kW at 1.5 m/s water speed and 180 kW at 7.72 m/s. The blades are similar in appearance to an aeroplane wing twisted into a helix. Water flowing into the blade causes a thrust force, and the blade's wing-shape generates lift and drag.</p>



Device Name, Lead Organisation , Website, Country	Technology Type	Brief Description and picture
<p>TidEl generator</p> <p><i>SMD Hydrovision</i></p> <p>http://www.reuk.co.uk/TidEl-Tidal-Turbines.htm</p> <p>www.smdhydrovision.com</p> <p>UK</p>	<p>Horizontal axis turbine</p>	 <p>TidEL differs from most tidal turbines in that it floats and is restrained by mooring chains to the sea bed rather than being fixed to piles driven into the sea bed. It has two horizontal axis counter rotating turbines. The turbine diameter is 18.5 meters and the crossbeam separating them 22 meters. The unit will incorporate two buoyant 500kW generators joined together by a cross beam giving a total power capacity of 1MW (at 2.3m/s flow rate). The fixed pitch turbine blades will be 15 metres in diameter - three 8m blades on a 2.5m hub.</p>
<p>TidalStream</p> <p><i>J.A. Consult</i></p> <p>http://www.teleos.co.uk/Home.htm</p> <p>UK</p>	<p>Horizontal axis turbine</p>	 <p>TidalStream concept is designed for deep water; too deep to economically mount turbines rigidly to the seabed and too rough for surface floaters to survive. Instead, the turbines are mounted on semi-submersible spar buoys tethered to the seabed gravity anchorages by swing-arms. A key feature is that the turbines use technology and components developed from the wind industry, that already exist and that have been developed over the last 20 years. It is basically the support structure that is truly new and innovative.</p>

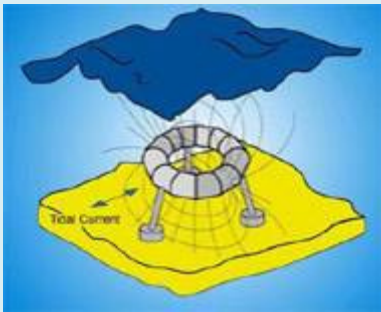
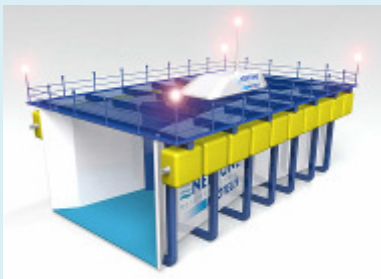
Device Name, Lead Organisation, Website, Country	Technology Type	Brief Description and picture
RTT <i>Lunar Energy</i> www.lunarenergy.co.uk/productOverview.htm UK	Horizontal axis turbine	 <p>Lunar Energy calls their technology Rotech Tidal Turbine (RTT). It consists of a five bladed horizontal axis bi-directional turbine with a symmetrical venturi duct. The RTT 1500 variant will have a duct with a diameter of 21 m and an overall length of 27 m. The turbine diameter is 16 m. The venturi draws the ocean currents into the RTT in order to capture and convert energy into electricity. At the rated speed of 3.1 m/s the power will be 1.5 MW. Use of a gravity foundation will allow the RTT to be deployed quickly and with little or no seabed preparation at depths in excess of 40 metres. The design is load bearing and self-supporting without the need for extensive seabed preparations which allows for a rapid installation process.</p>
Open-Centre Turbine <i>OpenHydro</i> http://www.openhydro.com/technology.htm UK	Horizontal axis turbine	 <p>OpenHydro has developed the Open-Centre Turbine, which is a twin horizontal axis open centre turbine. It incorporates a permanent magnet generator. There is an outer fixed permanent magnet rim and an inner single-piece rotating disc. The outer rim is the generator stator and the turbine is the generator rotor. The efficiency of the generator is 95%. The turbine diameter is 15 m and the rated power of the device 1.52 MW at 5 knots (2.57 m/s). The Open-Centre Turbine is designed to be deployed directly on the seabed. Installations are silent and invisible from the surface. They present no navigational hazard.</p>


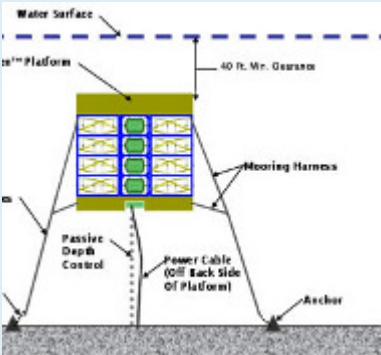
Device Name, Lead Organisation, Website, Country	Technology Type	Brief Description and picture
<p>Free Flow Turbine</p> <p><i>Verdant Power</i></p> <p>www.verdantpower.com/what-technology</p> <p>USA</p>	<p>Horizontal axis turbine</p>	 <p>The technology applied in Verdant Power's Kinetic Hydro Power Systems is the Free Flow Turbine, a three-blade horizontal-axis turbine designed to capture energy from the natural flows of tidal or river currents. The rotor diameter is 5 m. Free Flow Turbines are installed and operate fully under water, invisible from the shore. They are scalable to various sizes depending on site characteristics, and can be grouped into small or large clusters to produce village- or utility-scale power. Free Flow Turbines rotate at a slow rate, allowing for safe fish passage and causing minimal environmental impact. The rated power of the device 35.9 kW at 2.1 m/s water speed.</p>
<p>Blue Concept</p> <p><i>Hammerfest Strøm AS</i></p> <p>http://www.hammerfeststrom.com/</p> <p>http://www.e-tidevannsennergi.com/</p> <p>Norway</p>	<p>Horizontal axis turbine</p>	 <p>The turbine blades feature pitch and switch as the current change direction. The rotor diameter is 20 m. The current drives the propeller, with its blades automatically adjusted to their optimum orientation in the prevailing current. The rated power is 300 kW. Each propeller is coupled to a generator from which the produced electricity is fed via a shore connecting cable to a transformer and then into the grid. The nacelle is in a fixed position while the turbine blades turn along their own axis. Automatic control allow for unmanned operation and optimum energy output. Tilted structure minimizes flow disturbances, vibrations and unfavourable dynamic effects. Gravity based foundation allow for minimum installation resources and leaves the sea bottom in original condition when removed.</p>

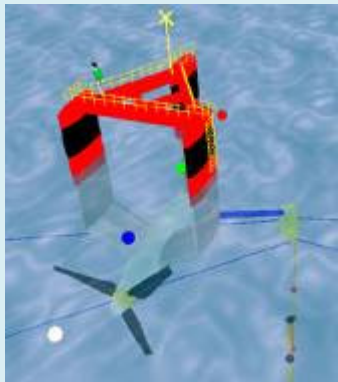
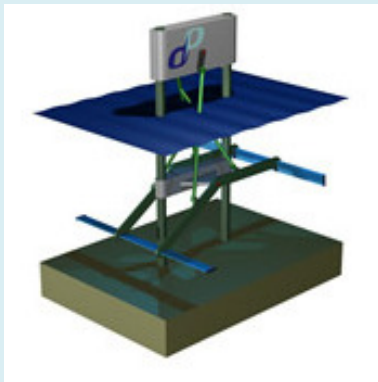
Device Name, Lead Organisation, Website, Country	Technology Type	Brief Description and picture
<p>Tidal turbine generator</p> <p>Clean Current Power Systems</p> <p>http://www.cleancurrent.com/</p> <p>Canada</p>	<p>Ducted horizontal axis turbine</p>	 <p>Clean Current's tidal turbine generator is a bi-directional ducted horizontal axis turbine with a direct drive variable speed permanent magnet generator. The rated power is 65 kW. This proprietary design delivers superior water to wire efficiency, a significant improvement over competing free stream tidal energy technologies. Operability is enhanced by a simple design that has one moving part - the rotor assembly that contains the blades. There is no drive shaft and no gearbox. The bearing seals will be replaced every five years and the generator will be overhauled every 10 years. The service life of the turbine generator is 25-30 years.</p>
<p>ENERMAR</p> <p>Ponte di Archimede</p> <p>www.pontediarchimede.it/language_us/progetti_det.mvd?RECID=3&CAT=003&SUBCAT=&MODULO=Progetti_ENG&returnpages=&page_pd=p</p> <p>Italy</p>	<p>Vertical axis turbine</p>	 <p>The patented Kobold turbine is a cross flow, three bladed, vertical axis device. Turbine 1 is 5x6 meters; the 2nd turbine is 6x6 meters. The platform has a diameter of 10 m and a height of 2.5 m of which 1.5 m is below the surface. The rated power is 70kW at a water speed of 2.5 m/s. This system rotates independently of the direction of the current and has high torques which permits spontaneous starting even under intense conditions without the need of an ignition device. The system has a global efficiency of 23%. This level of efficiency is comparable to that of wind turbines which have been under development for more than thirty years.</p>

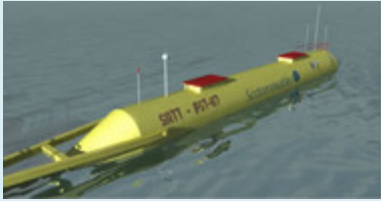
Device List

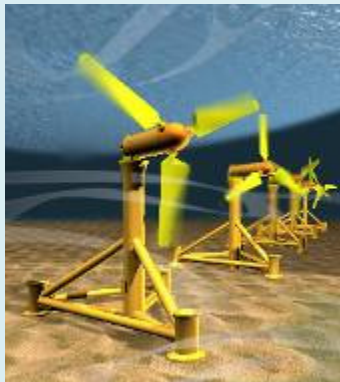
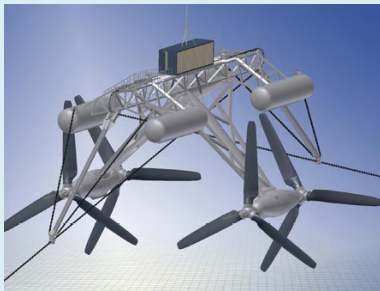
Device Name, Lead Organisation , Website, Country	Technology Type	Brief Description and picture
<p>Tidal Delay</p> <p>Woodshed Technologies Pty Ltd.</p> <p>www.woodshedtechnologies.com.au/news.html</p> <p>Australia / UK</p>		 <p>The Tidal Delay technology relies on the restraining or delaying feature of natural landforms, such as peninsulas or isthmuses, which gives rise to differences in water level on each side of the land. Connecting points across this landform with water carrying 82 pipes installed with turbines and generators enables the stored potential energy in the system to be harnessed.</p>
<p>bioStream</p> <p>BioPower Systems Pty Ltd</p> <p>http://www.biopowersystems.com/biostream.php</p> <p>Australia</p>	<p>Oscillating Hydrofoil</p>	 <p>The tidal power conversion system is based on the highly efficient propulsion of Thunniform mode swimming species, such as shark, tuna, and mackerel. The bioSTREAM mimics the shape and motion characteristics of these species but is a fixed device in a moving stream. In this configuration the propulsion mechanism is reversed and the energy in the passing flow is used to drive the device motion against the resisting torque of an electrical generator. Due to the single point of rotation, this device can align with the flow in any direction, and can assume a streamlined configuration to avoid excess loading in extreme conditions. Systems are being developed for 250kW, 500kW, and 1000kW capacities to match conditions in various locations.</p>


Device Name, Lead Organisation , Website, Country	Technology Type	Brief Description and picture
Hydro-Gen <i>Hydro-gen</i> http://www.hydro-gen.fr France	Horizontal axis turbine	Hydro-Gen is a big floating paddle, wheels included, in a catamaran type turbine. The frame is optimised to allow tapping a maximum of water in move in order to get a maximum of kinetic energy which is transformed into mechanical energy by the wheel motion, and transformed into power energy through a generator mechanically driven by the wheel. The machine is moored at its two ends. There is little impact on the environment. It can be moved, towed, and beached.
Tide Current Converter <i>Neptune Systems</i> http://www.neptunesystems.net/ Netherlands	Horizontal axis turbine (Enclosed Tips)	 <p>The concept is based on the direct interaction between a magnetic, electric and fluid flow field. In marine application, the sea water itself is the conductive fluid. A static antenna-like structure generates the magnetic fields and at the same time taps the electrical power from the fluid current. The configuration resembles a dynamo, the sea water being the rotor and the antenna the stator.</p>
Proteus <i>Neptune Renewable Energy Ltd</i> http://www.neptunerenewableenergy.com UK	Vertical axis turbine	 <p>The Neptune Proteus Tidal Power Pontoon consists of a 6m x 6m vertical axis cross flow turbine mounted within a patented, symmetrical diffuser duct and beneath a simple steel deck and buoyancy packages. The vertical shaft connects to the gearbox and generator/alternator on the top of the pontoon with associated valves and electrical processing and control machinery. The power pontoon is easily moored in the free stream, minimising environmental impact and operates efficiently for both flood and ebb currents. The rotor is maintained at optimal power outputs by sets</p>

Device Name, Lead Organisation, Website, Country	Technology Type	Brief Description and picture
		of computer controlled shutters within the duct.
<p>EnCurrent Vertical Axis Hydro Turbine</p> <p><i>New Energy Corp</i></p> <p>http://www.newenergycorp.ca</p> <p>Canada</p>	Vertical axis turbine	 <p>The EnCurrent Turbine is able to extract 40% to 45% of the energy in the water. As water is approximately 800 times denser than air, the energy that can be extracted from moving water is appreciably higher than that which be extracted from the wind. One of the unique properties is that it is able to capture the energy from the water irrespective of the direction of the current. This property enables the EnCurrent Turbine to harness the energy contained in both flood and ebb tides.</p>
<p>OCGen</p> <p><i>Ocean Renewable Power Company</i></p> <p>http://www.oceanrenewablepower.com</p> <p>USA</p>	Horizontal axis turbine	 <p>Generating capacity of up to 250 kilowatts in a 6 knot current (varies with current speed). Unique proprietary turbine rotates in one direction only, regardless of current flow direction. Two cross flow turbines drive a permanent magnet generator on a single shaft. Assembled OCGen™ modules are deployed in arrays comprised of tens to hundreds of modules. OCGen™ modules are held into position underwater using a deep sea mooring system. A power and control cable connects each OCGen™ module to an underwater transmission line that interconnects with an on-shore substation.</p>

Device Name, Lead Organisation , Website, Country	Technology Type	Brief Description and picture
Evopod <i>Overberg Limited</i> http://www.oceanflowenergy.com UK	Horizontal axis turbine	 <p>Evopod uses a simple but effective mooring system that allows the free floating device to maintain optimum heading into the tidal stream. It can be accessed by boat for first line maintenance and has been developed specifically to address the need for a tidal current device that can operate in exposed deep water sites where severe wind and waves also make up the environment.</p>
Pulse Generator <i>Pulse Generation Ltd.</i> http://www.pulsegeneration.co.uk UK	Oscillating Hydrofoil	 <p>Pulse generators cause hydrofoils to oscillate up and down like a dolphin's tail. The mechanical system is very efficient at taking energy from the flow, and transmitting this energy to a generator. The generator is held above the water. This means that wind turbine style generators can be used, and that they are always accessible for maintenance and inspection. The system takes energy from a rectangular cross section of water. This allows it to take full advantage of shallow flows. Changing the amplitude of oscillation of the foils, means the system can be adjusted for different flow depths. This means that extra water available at high tide can be exploited.</p>

Device Name, Lead Organisation , Website, Country	Technology Type	Brief Description and picture
<p>SRTT (Scotrenewables Tidal Turbine)</p> <p>Scotrenewables</p> <p>http://www.scotrenewables.com</p> <p>UK</p>	<p>Horizontal axis turbine</p>	 <p>The concept in its present configuration involves dual counter-rotating horizontal-axis rotors driving generators within sub-surface nacelles, each suspended from separate keel and rotor arm sections attached to a single surface-piercing cylindrical buoyancy tube. The device is anchored to the seabed via a yoke arrangement and compliant mooring system. A separate flexible power and control umbilical then connects to a subsea junction box. The rotor arm sections are hinged to allow each two-bladed rotor to be retracted so as to be parallel with the longitudinal axis of the buoyancy tube, giving the system a transport draught of under 4.5m at full-scale to facilitate towing the device into harbours for major maintenance.</p>
<p>Swan Turbine</p> <p>Swanturbines Ltd.</p> <p>http://www.swanturbines.co.uk</p> <p>UK</p>	<p>Horizontal axis turbine</p>	<p>The concept was designed to allow simple installation and maintenance retrieval in both shallow and deep water and to minimise vibrations, increasing the maintenance period. A gearless low speed generator offers a high efficiency over a range of speeds with minimal maintenance demands through the use of novel structural and electromagnetic topologies.</p>

Device Name, Lead Organisation, Website, Country	Technology Type	Brief Description and picture
<p>Deep-gen</p> <p><i>Tidal Generation Ltd</i></p> <p>http://www.tidalgeneration.co.uk</p> <p>UK</p>	<p>Horizontal axis turbine</p>	 <p>Tidal Generation Limited (TGL) is developing a 1MW fully submerged tidal turbine. TGL exploits the resource in depths > 30m and minimises visual and shipping impacts. It is cheap to construct and easy to install due to the lightweight (80 tonnes/MW) support structure (i.e. 7.7 KW/te).</p>
<p>Hydra Tidal design</p> <p><i>Statkraft</i></p> <p>http://www.statkraft.com/</p> <p>Norway</p>	<p>Horizontal axis turbine</p>	 <p>The power plant consists of a floating steel structure kept in position by a conventional anchoring system. The demonstration power plant has a total installed generator capacity of 1 MW, and includes two engine rooms with one 500 kW generator each. The rotor diameter is 22 m, the device length is 38 m, the deepest point is 25 m, the widest point under water is 55 m, the width above the surface is 15 m and the height above the surface is 7.2m. One turbine is fixed on both sides of each engine room for a total of four turbines per power plant. Each turbine drives one-half of each generator. The generator consists of two rotating parts. Each generator part (stator and rotor) is contra-rotated and operates at variable speeds. One advantage of this configuration is that there is no need for gear, as the sum of stator and rotor speed secures efficient power generation. The engine room with generators, turbines etc, can be brought to the surface; all maintenance can be done on-site. A control room with transformers, control systems, communication systems, etc, is installed on top of the device, above the water surface.</p>

Device Name, Lead Organisation, Website, Country	Technology Type	Brief Description and picture
<p>Tidal Sails</p> <p><i>Tidal Sails AS</i></p> <p>http://www.tidalsails.com</p> <p>Norway</p>	<p>Horizontal axis turbine</p>	 <p>A tidal sail power plant uses a number of submerged sails affixed to cables, which span the tidal stream at a specific angle. The sails are moved by the tidal flow back and forth between two stations, driving a generator that produces electricity. Tidal sail power technology differs in a fundamental manner from any other proposed method of renewable electricity generation, and offers three basic key advantages compared to rotary converters. The effective catchment's area of tidal currents per generator is determined by the total sail area exposed to the tidal flow and can be made larger than that of a rotary system. The sails can span across any depth, as only the end stations moorings or mountings need to be fixed near the shore. The sails move slowly (at speeds less than the current) and horizontally, so that the mechanical stresses and friction are minimised.</p>

3.4. Lifecycle

There are four basic stages in the lifecycle of a tidal stream power scheme, as is with any other electromechanical piece of equipment used to produce energy. These are:

- Design & planning
- Construction & installation
- Operation & management
- Decommissioning

Each stage has its own special features and key aspects that need to be taken into consideration when planning projects of this nature.

3.4.1. Design and Planning

Compared to wind, tidal stream has the advantage of a better velocity distribution. Energy-producing flows are present for a greater percentage of time than for wind. In areas of high tidal flow, slack water is short-lived; there are very few calm days. This means that the capacity factor (i.e. ratio of average power to rated power) can be 50%, whereas for wind sites it rarely exceeds 40%. While this is also a function of the rating of the device, the broad conclusion is that tidal stream capacity factors are significantly greater than for wind energy.

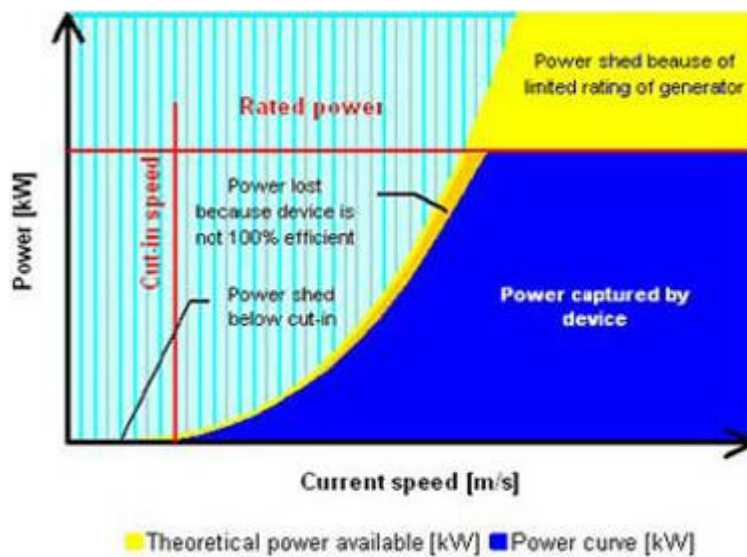
Providing the velocity is uniform across the cross-sectional area (e.g. for small areas) at any instant in the tidal cycle, the kinetic energy of a flowing tidal stream per unit time, i.e. the power P_s , can be calculated in terms of the velocity (v), cross-sectional area (A) perpendicular to the flow direction, and the density of water (ρ , which for sea water is approximately 1025 kg/m^3):

$$P_s = \frac{1}{2} \rho A v^3$$

This 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 characteristics of the resource.

3.4.1.1. Level 2

During operation, conditions of the tidal stream resource vary over time. Two parameters are relevant here: current speed and direction. With some devices direction is not a factor (e.g. vertical axis tidal stream devices), but even for devices that do have a directional dependency, the other parameter is generally important. The description of tidal stream power capture can be reduced to two dimensions: power and current speed. The figure below provides an example tidal stream device power curve and illustrates how the parameters are related.



Example tidal stream energy device power curve highlighting conditions where no power is generated

An ideal tidal stream device captures all the power in the tidal stream cross-section that it intersects. But this is not possible in practice; there are certain conditions in which devices cannot operate. At all speeds the power captured is always less than the maximum. This is because the prime mover can never be 100% efficient. The maximum amount of energy that can be extracted from the stream is $16/27$ (59%) of the theoretically available (i.e. the Betz limit) and, as for a wind turbine, this efficiency can only be approached by careful blade design.

More details on the most important components of the technology and their function, indicators that describe the size-range for single devices and park-scale installations, including all relevant dimensions, other geometrical factors/relationships, and performance indicators are provided herein—

3.4.1.1.1 Operation Principles

Main Components and mechanisms - Description of the “Wave-to-Wire” Chain

Tidal stream current turbines use similar principles to wind turbines in order to harness the kinetic energy in moving water. Accordingly, the main components of a tidal stream energy converter are (see Figure 1 below):

1. The prime mover which extracts the energy from the flow - a rotor of some sort;
2. The foundation which holds the prime mover in the flow and reacts the loads to the seabed;
3. The power train (i.e. gearbox & generator);
4. The power take-off system (power electrical and control system, and submarine cable to onshore grid connection point).

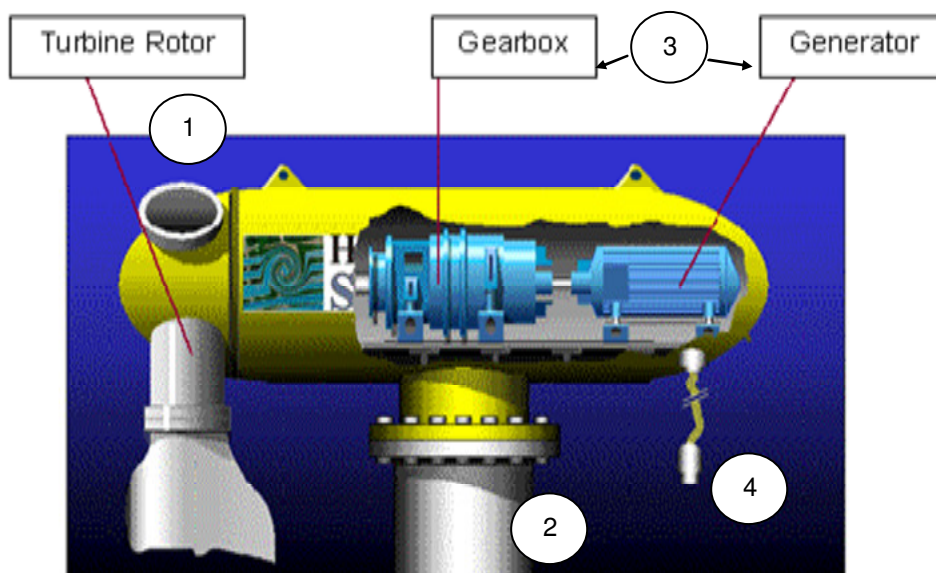


Figure 1: Basic components of a marine current turbine

Three steps are involved in the energy transformation:

- The turbine rotor is driven by the current. This converts the energy of the current into rotational energy of the shaft. The power is optimised by adjusting the angle between the rotor blades and the current.
- The gearbox converts the low rotational speed of the turbine shaft to the higher speed of the generator shaft.
- The generator converts its shaft energy to electric energy which is transmitted to the shore by a cable on the sea bed.

The kinetic energy of a flowing tidal stream per unit time, which is the same as the power (P_s), can be readily calculated in terms of the velocity (v), cross-sectional area (A) perpendicular to the flow direction, and the density of water (ρ , which for sea water is approximately 1025 kg/m^3). Providing the velocity is uniform across the cross-sectional area (approximately true for small areas), at any instant in the tidal cycle $P_s = \frac{1}{2} \rho A v^3$.

This function is convenient to quickly estimate 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 characteristics of the resource. This means that some constraints are the same as in wind power, but others are not.

During operation, conditions of tidal stream energy vary over time. For tidal stream, two parameters are relevant: current speed and direction. With some devices, direction is not a factor (e.g. vertical axis tidal stream devices), but even for devices that do depend on direction, the other parameter is generally most important.

The description of tidal stream power capture can be reduced to two dimensions, power and current speed. Figure 2 is an example tidal stream device power curve and illustrates how the parameters are related. This is an imaginary device, for illustration only; the graphs for real devices may differ.

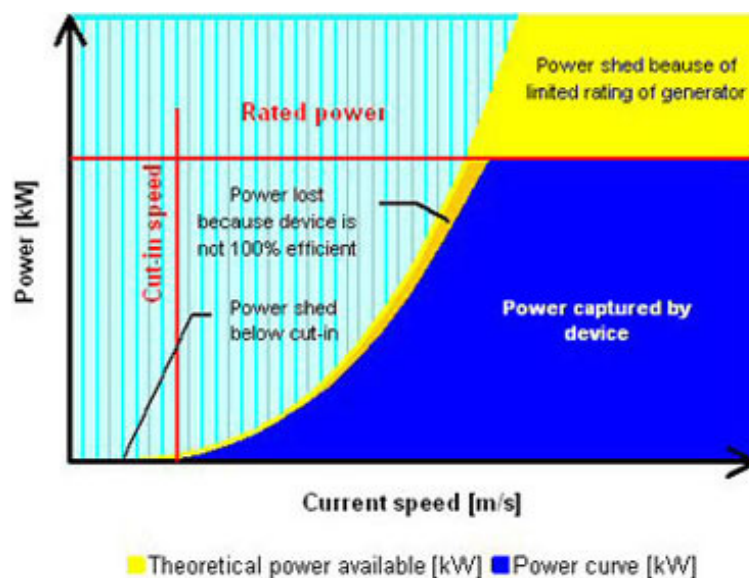


Figure 2: Example tidal stream energy device power curve highlighting conditions where no power is generated

An ideal tidal stream device would capture all the power in the tidal stream cross-section that it intersects. This is not possible in practice; there are certain conditions where devices

cannot operate and consequently no power is generated. These conditions are illustrated in Figure 1.

At all speeds the power captured is less than the maximum. This is because the prime mover can never be 100% efficient; there are a number of theories that indicate the maximum energy that can be extracted from a flowing stream; tidal stream situations are the subject of present research.

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) (namely, $P_s = \tau \cdot \omega$), and is expressed as a fraction of the tidal stream power flux by the coefficient of performance (C_p).

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 (i.e. a configuration known as high solidity) will produce high torque at low speeds, but also reach maximum power at a relatively low rotational speed. Conversely, a turbine with few blades (i.e. low solidity) produces low torque at high speeds and is more suitable for electricity generation at 50 Hz.

An unconstrained free-stream flow where the turbine is sited some distance from the ground, such that the flow velocity is well developed, has 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 Massey, Mechanics of Fluids). 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.

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. What happens to tidal stream flows in such situations is complex and depends on the geometry of the fixed flow boundary 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.

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. In operation, performance is reduced due to either the blades turning so rapidly that the turbulent region created by one blade is moved by the following blade, or the rotational speed being so slow that much of the flow 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 replenish between the passages of successive blades. This highlights the relationship between the rotational speed and free-stream velocity (v_{fs}), referred to as the **tip speed ratio** (λ). This is the linear speed of the blade tips (v_t) divided by the free-stream velocity, ($\lambda = v_t / v_{fs}$).

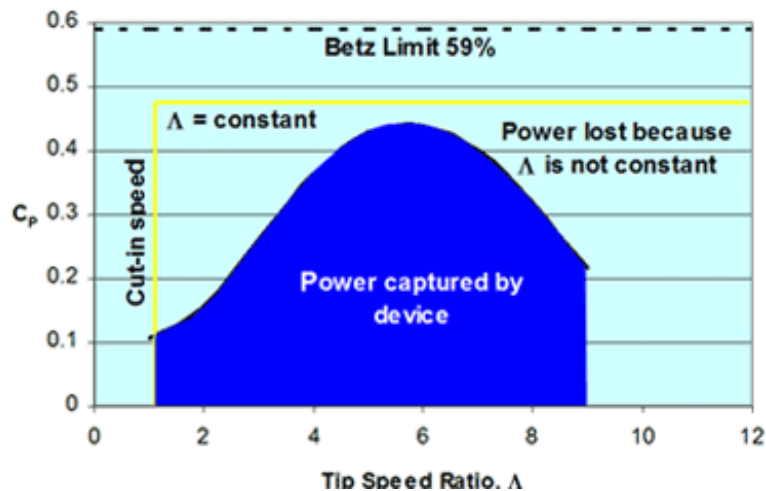


Figure 3: Power coefficient (C_p) against tip speed ratio (λ) for an example horizontal axis turbine

Figure 3 shows how the power coefficient of an example horizontal-axis tidal stream turbine relates to the tip speed ratio. 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 2; one would naturally choose λ to give a constant maximum C_p .

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

It is not practical to let the rotor turn very fast since this would mean that the blades experience large forces, and the likelihood of structural failure (or the 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 occur; this is when the water pressure local to the blade surface falls below the vapour pressure, causing bubbles to appear, rapidly expand and collapse. The resulting small shock loads can damage the blade surfaces and reduce their efficiency. The implication is that for a rotor of any 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** (i.e. 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 is **passive stall**, whereby fixed-pitch blades are designed so that when a particular free-stream speed is achieved, a region of turbulence created behind the blades overcomes the lift force and causes the rotor to slow.

Although rotor efficiency (i.e. transfer of the tidal stream's power flux to shaft power) is best maintained by varying the rotational speed, the opposite may be true for generation efficiency (i.e. 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. It is possible to employ a synchronous generator in this case, but otherwise, an induction machine may be 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 (i.e. mitigating the need for a gearbox) have also been proposed for some tidal stream devices.

Losses will occur within the power take-off system components. These can be reduced, but in practice there is likely to be an economic minimum beyond which increased costs deliver only modest performance improvements.

The device does not operate over the entire range of speeds and generation begins only after the speed has reached a certain level. This is known as the 'cut-in' speed, and reflects the lowest speed at which it is economic to capture power.

The device designer might also choose to limit the output at high speeds, as indicated by the 'cut-out' speed. Effectively the device sheds some of the available power in this range, and the choice of cut-out power is related to the generator rating. The designer must weigh up the extra cost of installing a higher-rated generator against the relative advantage of capturing more power. The cut-out region is not to avoid over-speed situations; since the maximum tidal stream speed is within the range, it would be possible to absorb power over and is highly predictable. This is unlike wind energy, where extreme wind speeds occur randomly and are often faster than it is economic to capture energy from.

Various designs are available for the power train linking the horizontally mounted turbine to the generator from which output is delivered through a marine cable laid across the seabed to the shore at voltages of 11 or 33kV.

There are a number of options but the primary generators are likely to be either induction generators or synchronous machines. Induction generators on their own will provide a cheaper generator than a synchronous machine. However the use of synchronous machines will permit the control of power factor and give a higher efficiency for lower-speed machines.

A key feature is the size and cost of the generator, which will increase with reduced speed, and the cost of the gearbox, which will increase with increasing gear ratio.

The power train's components, functions and operations of a tidal stream's turbine include:

	Component	Function	Options
I	Rotor	Extracts power from flow	<ul style="list-style-type: none"> •Horizontal axis •Vertical axis
II	Gearbox	Steps up rotational speed from rotor	<ul style="list-style-type: none"> •Planetary Gears •Hydraulics
III	Generator	Converts rotational power to electricity	<ul style="list-style-type: none"> •Induction •Permanent Magnet
IV	Foundation	Secures turbine to seabed	<ul style="list-style-type: none"> •Monopile •Gravity •Chain Anchors

Depending on the power train configuration, after 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 (i.e. gearbox);
2. Convert the shaft power into electricity (i.e. generator);
3. Convert the generation voltage and frequency to the grid voltage and frequency (i.e. frequency converter).

The efficiency of each stage (η_1, η_2, η_3) can be expected to be 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:

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

Dimensions and Performance

The most straightforward way to develop tidal stream energy is to borrow from **horizontal axis wind turbines**, where the technology, components and know-how have been developed over the last 30 years.

A tidal stream turbine like a wind turbine underwater; however, the density of seawater is **800 times** greater than air, and flow rates typically **one fifth**. A properly rated tidal turbine would have a rotor diameter about **half** that of a wind turbine of the same rated power.

Some of the factors affecting wind and tidal stream turbines are provided in the table below:

Feature	Effect / Implications of Feature on	
	Offshore Wind Turbine	Tidal Current Turbine
Fluid density	~1.25 kg/m ³	~1025 kg/m ³
Max velocity during normal operation	~25m/s	2-5m/s
Velocity for rated output	~12m/s	2-5m/s
Max velocity during life	50m/s +	As for normal operation
Variation of velocity with time	Stochastic, variable in magnitude and direction over timescales of the order of seconds to years.	Variation in magnitude & direction predictable for given location over periods of years.
Rotor diameter (typical)	90-120m	15-30m based on current designs
Limitations on rotor diameter	Mechanical integrity, primarily fatigue life due to self weight stresses	Mechanical integrity, cavitation at tip, water depth. Speed reduced as diameter increased. Limitation is on blade stress, primarily due to thrust forces being much greater resulting from higher density of fluid
Variation of flow pattern	Complex (turbulence)	Complex (turbulence + waves if top of rotor near surface)
Corrosion	Salt spray conditions	Immersion in salt water will require careful consideration of material combinations
Erosion	Unlikely to be a serious problem	Potential for serious problem; may exacerbate corrosion
Maintenance access	Weather dependent	Depends on deployment method but probably more difficult than offshore wind
Marine growth	Not an issue	Could be important for performance and maintenance
Rotor rotational speed	<15 rpm for large machines	7-20 rpm based on current designs

Compared to the largest wind turbines (i.e. rated power 2 MW), the power output and the size of a tidal stream turbine are extremely promising. The annual power output of wind turbines depends upon the annual wind speed variation which usually follows a Weibull distribution. Taking an annual average wind speed of 7 m/s and applying it to a 2 MW rated turbine, blade diameter of 60 m, the average output is of the order of 600 kW.

Assuming a marine current site with a mean velocity of 2 m/s with a maximum variability of 10%, the annual average velocity would be 1.8 m/s. This corresponds to a rotor diameter of 24 m producing a rated power as that of the wind turbine example.

With constant or highly predictable marine currents, a tidal stream turbine could not only rival the largest wind turbines in being more manageable in size, but also in generating highly predictable power.

In general, it is difficult to provide exact dimensions, geometrical factors and relationships of MCTs, as the devices developed to date are of various configurations, settings and sizes, and follow different technology concepts. However, as per a survey performed by EPRI in 2005 (EPRI TP-004-NA, *TISEC Device Survey and Characterization*), the following table

provides a summary of the eight devices examined with axis type, diameter of the rotor and rated power:

GCK	Lunar	MCT	OpenHydro	Seapower	SMD Hydro	UEK	Verdant
V axis Lift	H axis Duct	H axis Dual	H axis Rim Gen	V axis Drag	H axis Dual	H axis Dual	H axis
1 m dia	21 m dia	18 m dia	15 m dia	1 m dia	8 m dia	3 m dia	5 m dia
7 kW	2 MW	1.5 MW	1.5 MW	44 kW	1 MW	400 kW	34 kW

With respect to the size of the park-scale installations of these technologies, and according to relevant studies made by the corresponding device developer, an array of 22 tidal stream SST turbines will occupy an area of just **one square kilometre**. At 4 MW per turbine, this could provide an output of 88 MW.

The equivalent power capacity of **a nuclear power station** (e.g. 1232 MW) could be obtained from just **14 square kilometres of sea area**. A wind farm of the same power rating could require roughly **four times** the area of upland or sea area, i.e. 56 square kilometres, with a far less predictable energy output.

3.4.2. Construction and Installation

Tidal stream technologies are designed to be modular, in order that the devices might match the power demand and conditions in various tidal locations. They may in the future be installed as single devices or as an array of several modules in order to intercept a greater area of the resource. Future projects may have capacities in the range of a few hundred kW, for single module installations, to several GW, in multiple-module tidal stream power plants.

The key to success is how to support the rotor-transmission so that it follows the water flow and can be installed and maintained easily and inexpensively. The environmental drag forces on any tidal current energy conversion system are large compared to wind turbines of the same capacity. This introduces challenges to the designer. Designs exist for devices which are rigidly attached to the seabed or are suspended from floating barges, such as the early Loch Linnhe device. While there are some exceptions, it is generally accepted that fixed systems will be most applicable to shallow water sites and moored systems for deep water. .

In deepwater sites, where two thirds of the resource lies, submerged floating designs are necessary. These avoid the storm vulnerability of surface floating devices, and the impracticality of seabed-mounting. The major advantage of buoyant designs is that they can be floated into place, removing the need for cranes, barges or jack-up rigs which would have difficulty operating in the strong tidal flows, such as those found in the Pentland Firth.

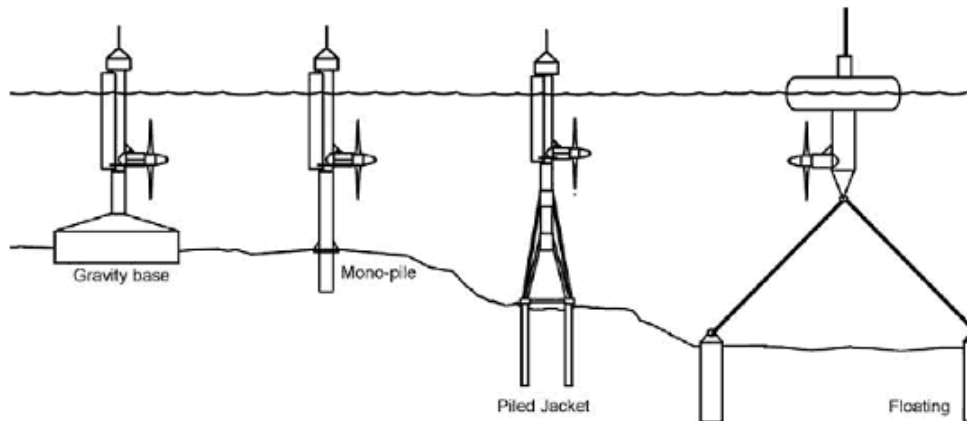
3.4.2.1. Level 2

A key requirement for tidal stream devices is the support structure concepts to hold them in place taking into consideration the harsh marine environment. Currently there are three options under consideration:

Gravity Structures are massive steel or concrete structures attached to the base of the units to achieve stability by their own inertia.

Piled Structures are pinned to the seabed by one or more steel or concrete piles. The piles are fixed to the seabed by hammering if the ground conditions are sufficiently soft or by pre-drilling, positioning and grouting if the rock is harder. In its simplest manifestation, the fixed piled structure may be a mono-pile (single pile) penetrating the seabed with the turbine fixed to the pile at the desired depth of deployment.

Floating Structures provide a potentially more convincing solution for deep water locations. The turbine unit is mounted on a downward pointing vertical column rigidly fixed to a barge. The barge is then moored to the seabed by chains or wire ropes which hang in a catenary and may be fixed to the seabed by drag, piled or gravity anchors, depending on the seabed condition.



Support structure concepts

<http://www.detini.gov.uk/cgi-bin/downutildoc?id=55>

Mono-pile installation is an established technique and seems to be the most favoured option. This is currently limited to depths less than 50 m considering the capabilities of available jack-up barges. The variable pitch devices mounted on a mono-pile will have rotating mechanisms to turn the devices during slack water to face the next tide tidal flow.

3.4.3. Operation and Management

It is important to have access to the turbine unit for maintenance. Maintenance and repair of tidal turbines would necessitate the use of a ship and could be difficult and hazardous as for wind turbines. Calm waters and good weather are essential for safe and quick maintenance. However, a number of measures could be taken at the design stage to reduce the frequency and difficulty of maintenance procedures. Tenacious lubricants, good quality seals and bearings and strong blades will reduce the frequency of routine maintenance.

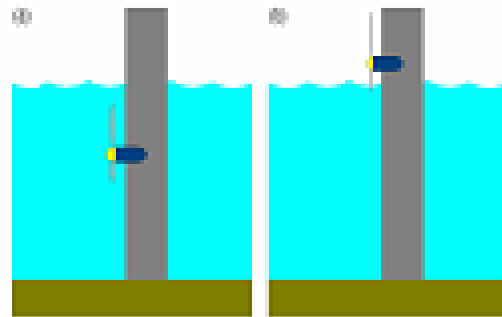
Some critical factors that affect the “survivability / vulnerability” of tidal stream energy devices, though they also constitute strong engineering challenges, are the following:

- Cavitation: Relatively high velocities at the tips of the rotor blades are likely to lead to formation of cavities which may be difficult to avoid at all points along the blade. Even though design to avoid cavitation in hydraulic pumps and propellers is well understood a different approach may be necessary for marine current turbines because of its larger plane or rotor area. Cavitation is also sensitive to water depth so some cavitation problems can be avoided by placing units in deeper water at potential cavitation sites.
- Biofouling: Many devices installed in the sea become artificial reefs, attracting a wide variety of marine organisms. These cover the structures and can cause significant fouling. Fouling of moving parts could affect the performance of devices. Several methods for preventing fouling have been proposed.

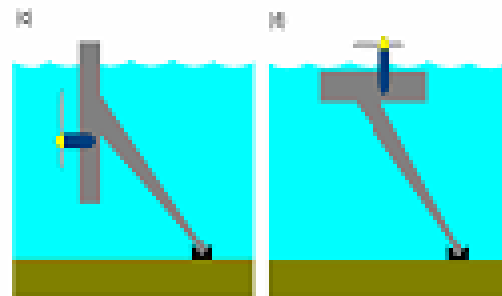
3.4.3.1. Level 2

There are numerous proprietary approaches to the provision of maintenance access to tidal turbines, some of them being subject of patent applications or grants. The maintenance access systems may be divided into three broad categories, which will have different costs relating to the type and size of boat/ship/crane and time taken to carry out the operations:

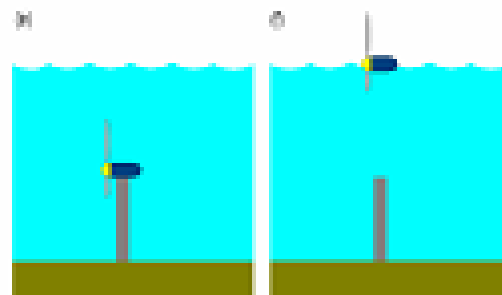
Changing the device geometry (a & b in Figure). The device may be mounted on a tower fixed to the seabed, with the tower extending above the water level. It is raised up the tower and clear of the water (e.g. by means of a jacking device) and may then be accessed from a boat or lowered onto a barge for transport onshore. MCT is an example of this approach.



Changing buoyancy (c & d in Figure). The device is mounted onto a semi-submersible structure that can be manoeuvred to the surface by changing the buoyancy, where it may be accessed from a boat or lowered onto a barge for transport to shore. Tidal Stream is an example of this approach.



Detaching important elements from the seabed-mounted part of the device (e & f in Figure). The device is mounted on a pylon fixed to the seabed, which does not extend above the surface, and it is detached from the pylon by divers or an ROV, lifted clear of the water by a heavy lift crane, and lowered onto a barge for maintenance there or onshore. An example is the Hammerfest Strom device.



3.4.4. Decommissioning

Once a tidal energy scheme has reached the end of its generating life the developer must decommission the scheme (or alternatively the developer may wish to continue using the site and install new tidal stream devices, as some wind farm developers do). It is necessary for the developer to remove the scheme from service and restore the environment to an acceptable state.

For a tidal stream farm, the devices would be removed from site at the end of their 20-year lifetime. For floating devices this is likely to be a relatively simple operation, as it will only require the removal of anchors from the seabed. Devices with a gravity-based foundation will be removed from the seabed. A mono-pile foundation may be left in the seabed after being cut off below the level of the seabed, or it can be removed using a vibration hammer.

Submarine cables are usually de-energised and left in-situ, as the removal of cables causes more damage to the seabed than leaving them in place.

Decommissioning of tidal stream devices is likely to result in less disturbance than decommissioning of other tidal devices. Whilst there will be the requirement for increased boat traffic, and temporary effects on noise level and air and water quality, the structures are much smaller in size and there is less solid construction to destroy. Floating devices which are simply moored or anchored to the seabed can be removed with relatively little effort, and it may be possible to leave the mooring bases on the seabed. Removal of fixed devices will result in greater disturbance, particularly in the case of mono-piles. It may be possible to leave gravity bases on the seabed, however, should they be removed this would result in significant seabed disturbance and sediment mobilisation. The removal of landward cables from tidal stream farms will result in a level of seabed and shoreline disturbance; usually these will be left in place in order to prevent excess damage to the environment.

3.5. Economical Factors

Tidal stream power schemes have a high capital cost and a very low running cost. As a result, such a scheme may not produce returns for years, and investors are thus reluctant to participate in such projects. Governments may be able to finance tidal power, but many are unwilling to do so also due to the lag time before investment return and the high irreversible commitment. For example, the energy policy of the UK (key principles 4 and 6 within Planning Policy Statement 22) recognizes the role of tidal energy and expresses the need for local councils to understand the broader national goals of renewable energy in approving tidal projects. The UK government itself appreciates the technical viability and siting options available, and has provided a grant scheme called the 'Marine Renewables Deployment Fund', while is also currently looking at increasing revenue support for tidal energy through the 'Renewables Obligation'.

There are three elements to the cost equation that determine cost effectiveness:

- 1) The 'effectiveness' of the technology at capturing energy (for example, the fact that all commercial wind turbines today use a horizontal rotor axis in preference to other configurations indicates the fundamental effectiveness of this approach);
- 2) The capital cost of the installed devices;
- 3) The operating cost of the devices.

The capital installed cost of tidal stream devices can be broken down into:

- the cost of the device itself;
- the cost of everything else required making it operational - foundations, cabling, installation, and grid connection.

3.5.1. Level 2

The device cost for an offshore wind turbine is about 50% of the capital cost. The device cost for horizontal axis tidal turbines is similar, as they also need blades, hubs,

transmissions and generators, support structures. And they need to be marinised for prolonged underwater use. Marinising may increase costs relative to wind, but marine and offshore oil and gas technology is well developed. Also forced cooling will allow components for tidal turbines to be more highly rated. Overall, it is likely that tidal turbines may have higher first costs than equivalently rated wind turbines, but due to better load factors no worse, or better, overall cost of energy.

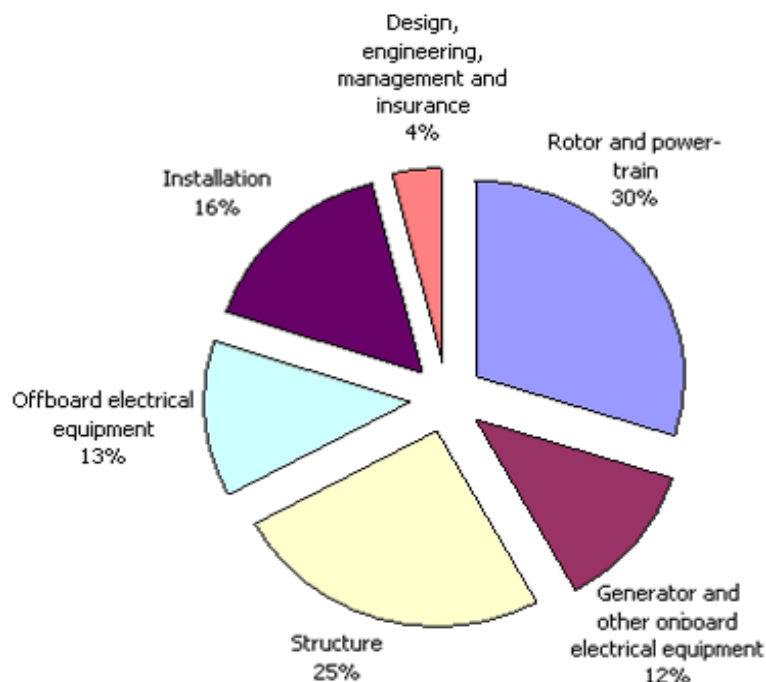
The “everything else” cost for tidal stream power is likely to dominate the capital cost; however this should be no more than for offshore wind for the best concepts. Power/area densities for tidal stream are roughly four times greater than for offshore wind, so cabling costs will be correspondingly less. Additionally:

Foundation costs are one of the largest unknowns.

The installation cost of tidal turbines - as for offshore oil platforms - will depend on the ingenuity of the concept designer. For any design requiring barges, floating cranes or jack-up rigs, costs will rapidly escalate.

Operating costs for all marine turbines are likely to be substantial. For maintenance, access in channels such as the Pentland Firth will be difficult and potentially dangerous, as will large equipment handling support.

The figure below shows the breakdown of installed costs for a tidal stream device. The structural costs are considerable, but in this case the largest cost item relates to the energy conversion systems. Note that this pie chart – which corresponds to a specific tidal stream energy device installed in a tidal stream farm of a certain size in a specific location – should not be taken as typical of tidal stream technologies as a whole. In fact, there are considerable variations between different device types and project locations. What’s more, future design improvements, performance/cost optimisations and learning effects could radically alter the relative weight of certain cost categories.



Capital cost breakdown for installation of a particular tidal stream energy device in a tidal stream farm of a certain size

Ongoing maintenance costs are expected to be modest, as they are with other large-scale marine infrastructures, e.g. bridges, ships, etc., and a non-polluting tidal energy regime will qualify for valuable carbon offset credits. According to a feasibility report on tidal current energy in British Columbia (2002), the future energy costs are expected to reduce considerably as both existing and new technologies are developed over the next few years. Assuming that maximum currents larger than 3.5 m/s can be exploited and present design developments continue, it is estimated that future tidal current energy costs between 5¢/kWh and 7¢/kWh are achievable.

Some more cost predictions for fully commercialised tidal stream power devices – based on relevant studies – are provided here.

Tidal Stream Energy Systems (TSES) Cost Projections

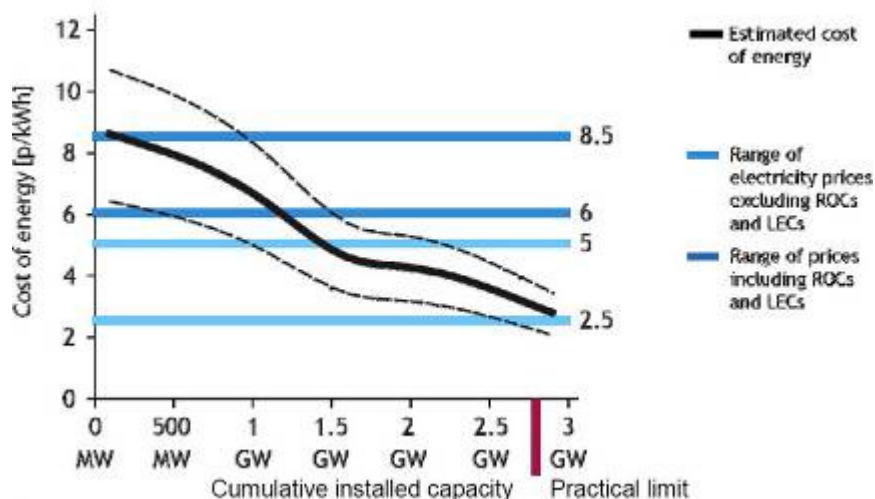
Evidence to date shows that tidal stream energy could become competitive **not just with offshore wind**, but **with onshore wind** - eventually achieving **3 p/kWh** at the best sites. Early estimates from the 1993 DTI report were higher at **10 p/kWh** for the best sites. However, these studies did not take account of learning curves – e.g. wind turbine costs have plunged with experience - and did not appreciate the proper rating of turbines (optimising rotor diameter to power ratios) and the dramatic effect of this on costs.

More recent studies, for example the 2001 AEAT study, estimated **4 p/kWh** for the first **1.5 TWh** of energy, with the cost rising sharply thereafter as the few shallow, high flow sites are used. However, this study assumed bottom-mounted devices, and did not account for the development of floating concepts such as the SST. The same study estimated **4½ - 5 p/kWh** for offshore wind.

The most recent study published by The Carbon Trust indicates a broadly saucer-shaped curve for the progress of costs over time. Initial costs will be high - of the order of **7 p/kWh** - because the technology is new, even though the best and most shallow sites are being developed. The cost then falls to **3 p/kWh**, after the first **12 TWh** of energy (or **3000 MW** of power capacity) is installed. Costs then rise again as only the lower flow sites are left.

In each study, an 8% discount rate has been applied, which is standard for the renewable industry, but ignores interest rates, and that some developers have access to cheaper financing than others. What is evident is that **tidal stream** offers *at least equivalent cost effectiveness to offshore wind*.

This graph presents a tidal stream energy cost reduction scenario developed by Carbon Trust (UK). A price of 21.6 p/kWh was used as starting point, and a 15% learning rate was assumed. ROCs stands for Renewable Obligation Certificates, while LECs stands for the Levy Exemption Certificates.



A recent EPRI study (EPRI TP-008-NA *North America Tidal In-Stream Energy Conversion Technology Feasibility Study*) provides the following as regards tidal stream plants capital costs and Cost of Energy (COE) – in 2005 US \$

Power Density (kW / m ²)	Capacity Factor (%)	Capital Cost (\$/MW)	COE (cents / kWh)
> 3.0	29 - 46	1.7 – 2.0	4 - 7
between 1.5 and 3.0		2.1 – 2.4	4 – 11
< 1.5		3.3 – 4.0	6 – 12

The COE is defined as the total plant cost, multiplied by the fixed charge rate, plus the annual operation and maintenance (O&M), all divided by the annual energy produced. It has been taken that the tidal plant capital cost is a function of the plant size, tidal flow profile, the bathymetry and the geotechnical properties of the seabed. The COE is a function of the power density of the tidal stream and the plant size.

3.6. Environmental Interactions

The greatest advantage of tidal (marine) current devices is that during their operational life they emit no greenhouse gas emissions and appear unlikely to produce pollutants. Tidal stream devices can be deployed in a range of sites and at a range of scales, from a single device to a farm of 30 or more devices or a number of such farms within an area. It is likely that the future will see a number of such farms deployed within a relatively small area in order to maximise the use of the available tidal resource. This means that the level of environmental effects resulting from tidal stream energy is likely to increase gradually over time, and the cumulative effects of a number of farms operating in one area may become significant. In addition, the types of environment affected will change over time, as technological improvements and economic requirements result in the movement of tidal stream farms from shallower water to deeper water and back again.

Currently, although much can be predicted, little is actually known about the environmental effects of tidal stream devices (no Environmental Impact Assessment of tidal stream devices has been made available). It is therefore difficult to predict the magnitude of the cumulative environmental effects resulting from the deployment of tidal stream devices and farms throughout the available tidal stream resource areas. The level of impact would be determined by, among other things, the quantity of units installed and the packing density.

A general matrix of the potential key environmental interactions can be found on the following pages.

Potential key interactions between tidal stream energy installations and the receiving environment

Development phase	Activity	Impact mechanism	Interactions with the physical environment	Interactions with the biological environment	Interactions with conservation (ecological designations, natural heritage, anthropogenic heritage etc.)	Interactions with the socio-economic environment
Preparatory works	Surveying	Disturbance of seabed through sampling	Minor impacts may result from baseline environmental surveys. For example, localised loss of substrates, plants and animals on the seabed through coring, boring and grab sampling, disruption to mammals from seismic and other vessel-based surveys.			Local contractors and scientific experts can be employed to conduct and support baseline surveys for example, vessel operators, consultants and divers etc.
		Noise disturbance through increased vessel activity and sonar / seismic surveying	No key interactions anticipated	Potential harm to fish species	Disruption of marine mammal behaviour	No key interactions anticipated
	Site preparation	Disruption of seabed and water column during and after dredging	Areas of the seabed may be dredged affecting seabed morphology and increasing water turbidity	Plants and animals may be removed and directly impacted by any dredging prior to construction	Protected migratory fish species and protected predatory bird species may be affected.	Temporary disruption to other sea users and navigation resulting from vessel activity and marine works.
Construction, installation and commissioning	Transporting tidal stream device /support structures to site	Physical presence of vessels and associated equipment/structures	No key interactions anticipated	No key interactions anticipated	Potential disturbance to marine mammals	Increased risk to other vessels from slow towing of large objects.
		Local business and employment opportunities	No key interactions anticipated	No key interactions anticipated	No key interactions anticipated	Potential economic benefits from utilisation of local resources, support companies and services
	Mooring and infrastructure installation	Disturbance to seabed and water column through installation of gravity anchors	Localised impact on seabed morphology – cuttings will become established on the seabed. These may subsequently be distributed over a wider area. Re-suspension of particulate matter into the water column	Direct localised impact on seabed habitats and species Gravity anchors may become colonised	Assuming all the relevant baseline studies have been efficiently completed, no impacts are anticipated	Loss of fishing grounds Fish may aggregate towards structures away from traditional fishing areas Additional hazard to navigation
		Disturbance to seascape and generation of noise through piling (if required)	No key interactions anticipated	No key interactions anticipated	Underwater noise may impact marine mammal species over significant distances	Unfamiliar vessels and superstructures associated with onsite fabricating and installation will be visible within the local seascape for extended periods of time
		Local business and employment opportunities	No key interactions anticipated	No key interactions anticipated	No key interactions anticipated	Potential economic benefits from utilisation of local resources, support companies and services
	Tidal stream device installation and commissioning	Introduction of moving parts into the water column	No key interactions anticipated	Potential interactions with fish species	Potential interactions with marine mammals and protected diving bird species	Potential for entanglement of 3 rd party moorings and fishing gear.

Potential key interactions between tidal stream energy installations and the receiving environment

Development phase	Activity	Impact mechanism	Interactions with the physical environment	Interactions with the biological environment	Interactions with conservation (ecological designations, natural heritage, anthropogenic heritage etc.)	Interactions with the socio-economic environment
Operation and maintenance	Extraction of energy from the tide	Reduction in tidal current energy downstream of the installation	Increased sediment settlement in predominantly downstream area Changes in local hydrographic conditions including tidal current profile over the seabed	Potential surface smothering of existing seabed species and habitats Potential alterations to seabed communities through reduction in water flow	No key interactions anticipated	No key interactions anticipated
	Sustained physical presence of tidal stream device, moorings and support structures at sea	Introduction of structures onto the seabed	Scouring may occur around structures on the seabed	Fish may aggregate around structures and increased predator activity may result.	Protected marine mammals may be enticed towards installation by aggregating food sources	Sustained additional hazard to other sea users Sustained exclusion of other vessels including fishing boats from around some installations
		Introduction of structures into the water column	Hydrographic conditions may be affected by the presence of structures in the water column	Fish may aggregate around structures and increased predator activity may result	Protected marine mammals may be enticed towards installation by aggregating food sources	Sustained exclusion of other vessels including fishing boats from around some installations Sustained additional hazard to other sea users
		Introduction of structures on the water surface	Wave action may potentially be reduced downwind of any large surface piercing structures Potential impact on coastal processes i.e. erosion and sediment transport	Birds may roost on surface piercing structures Potential changes to intertidal and sublittoral habitats resulting from any reduced wave action	Protected intertidal and foreshore community structures may be altered due to any reduced wave action and storm effects	Sustained presence of device(s) on the seascape Sustained exclusion of other vessels including fishing boats from around some installations Sustained additional hazard to other sea users Potential reduction in affects of coastal erosion and storm surge damage Potential effects on anchoring, sailing and other maritime activities within any wave shadow
	Generation and transmission of electricity	Production of Electro-magnetic Fields (EMF)	No key interactions anticipated	Electrical and magnetic interference with movements of fish species e.g. sharks and rays	EMF may affect protected species passing through the vicinity of the installation	Fisheries dependent on vulnerable species may be affected May be some implications for local divers
		Generation of underwater noise	No key interactions anticipated	Localised avoidance by some fish species	Protected species foraging and migrating within the water column may be harmed/disrupted Noise from installation during operation may affect the normal behaviour of marine mammals in the area	Potential effects on those dependent upon affected species Potential effects on local diving activities
		Reduction of greenhouse gas and exhaust emissions from fossil fuel combustion	Reduction in air pollution and atmospheric anthropogenic greenhouse gasses	Ecological effects resulting from greenhouse gas emissions and air pollution will be reduced		Local communities may benefit from any revenue generated from the development The social and economic impacts of climate change will be mitigated
		<ul style="list-style-type: none"> Local business and employment opportunities 	<ul style="list-style-type: none"> No key interactions anticipated 	<ul style="list-style-type: none"> No key interactions anticipated 	<ul style="list-style-type: none"> No key interactions anticipated 	<ul style="list-style-type: none"> Potential employment opportunities for local residents and benefits for the local economy

Potential key interactions between tidal stream energy installations and the receiving environment



Development phase	Activity	Impact mechanism	Interactions with the physical environment	Interactions with the biological environment	Interactions with conservation (ecological designations, natural heritage, anthropogenic heritage etc.)	Interactions with the socio-economic environment
Accidental events	Incident leading to chemical spill	Chemical pollution	Local/widespread changes in water and sediment chemistry	Species and habitats may be harmed and damaged by chemical pollution		Chemical pollution may affect other sea users for example; fish farmers, tourists and mariners etc.
	Incident leading to oil/fuel spill	Oil pollution	Transitory oil slicks on surface waters and risk of long-term seabed and shoreline pollution	Species and habitats may be harmed and damaged by oil pollution		Oil pollution may affect other sea users for example; fish farmers, tourists and mariners etc.
	Loss of equipment / structural components	Disruption to the seabed from sinking debris	Changes to the seabed profile and sediment composition	Localised disruption to seabed species and habitats.		Additional hazard to navigation, disruption of fishing grounds
Disruption of surface waters and shorelines from floating debris		No significant impact	Disruption to shoreline habitats through smothering and harm to species through ingestion/entanglement		Loss of amenity value, disruption to intertidal fisheries	
Decommissioning	Total removal of installation	Reversion to baseline hydrographic conditions	Dispersal of any accumulated sediments around installation Loss of any calming effects around installation and in coastal waters	Potential disruption to ecosystems established and adapted to post-installation hydrographic conditions	Protected intertidal and foreshore communities adapted to post-installation structures may be altered due to any increased wave action and storm effects Protected species foraging and migrating within the water column may be disrupted	Loss of benefits gained from any wave shadow effects to intertidal / inshore fisheries etc
		Local business and employment opportunities	No significant additional impact anticipated	No significant additional impact anticipated		Potential economic benefits from utilisation of local resources, support companies and services
	Replacement of tidal stream device	Local business and employment opportunities	No significant additional impact anticipated	No significant additional impact anticipated		Potential economic benefits from utilisation of local resources, support companies and services

3.7. Future Potential

Compared with other renewable technologies, there has been a little investment and research into utilising tidal (marine) current energy for power generation. However tidal current / stream energy is one of the most promising new renewable energy sources, and is deserving of further investment. Tidal energy power systems are expected to be very competitive with other conventional energy sources, and excellent cost advantages arise from there being no fossil fuel connected pollution or environmental expenses to remediate (but this has still to be clarified) nor are there fuel expenses (the kinetic energy of tidal currents is free). Furthermore, the knowledge to combine existing technologies to utilise tidal stream energy for power generation is now available at:

http://www.esru.strath.ac.uk/EandE/Web_sites/05-06/marine_renewables/background/marinecurrents.htm - 2.

Tidal stream devices offer the greatest potential for learning. As the devices are still a technology under development, further research and testing may lead to design developments that improve the operation of the devices. The devices are modular, and therefore a tidal stream farm will be constructed from a number of identical devices. As more and more devices are installed, experience will be gained through production, construction, installation and operation and maintenance. This will lead to cost savings, and the devices will benefit from economies of scale. This has been observed for other renewable energy technologies; there have been cost reductions for photovoltaic cells and wind turbines as the scale of manufacturing increases and installed capacities rise.

3.7.1. Level 2

In short, tidal current energy devices are needed and they are becoming technically possible. They should represent a major industrial growth area in the years to come, although there will be room to succeed for only a few of the numerous solutions currently being promoted, as many will fall by the wayside. The key to arriving at this result is to gain the operational experience to develop the reliability of the systems, to value-engineer them in order to get costs down, and to ensure that they can reliably deliver electricity from the seas with minimal environmental impact.

A number of issues that exist nowadays in the tidal stream energy industry and need to be addressed are the following:

- Tidal data and selecting sites: Insufficient site-specific data and so selecting sites based on tidal current atlases can be problematic
- Selecting technology: As the industry is fairly new, technology confidentiality makes comparison of the available technology difficult
- Planning permission: Gaining site permission is a very complex process involving numerous governing bodies each with their own criteria and agenda

- Environmental Impact: There are a number of environmental impacts that technology implementation and energy extraction could cause to the local environment, the extent of which is yet unknown
- Transmission issues: Once the power is extracted from the tidal currents, delivering it to the customer is at the moment a very costly and complex process due the distances and sub sea cabling issues.

It is likely that tidal stream devices (turbines) will initially be deployed in island or coastal communities with strong marine currents and which are isolated from national grid systems, where they are most likely to offer a cost-effective alternative. However, marine currents have the potential to supply significant quantities of energy into the grid systems of many countries. As interest grows, tidal stream energy is likely to play an increasing role in complementing other energy technologies and contributing to the future global energy supply mix.

Because tidal stream devices are still in prototype stages of development, at the moment they seem to be too expensive to be economic. Indeed, right now they are considerably more expensive than other forms of renewable energy, and certainly more expensive than other forms of conventional energy. This is not a fundamental problem with the technology, but rather a reflection of their state of development. Most units are prototypes, which cost perhaps ten times more than the first production machines are likely to cost. These prototypes are often installed as single units rather than the multi-unit farms expected in fully commercial projects. Thus there are currently no economies of scale in manufacture, project development or system infrastructure of tidal stream devices. The success of this industry is reliant on the technology developers proving their concepts technically, and then moving into a manufacture and project development phase to steadily increase the number installed and benefit from 'learning by doing' and economies of scale.

3.8. Case Studies

Tidal stream devices have been built in a number of countries. However, currently there are no commercial schemes world-wide, but a number of demonstration projects are being implemented. The most worth noticing are:

- Hammerfest Strøm developed the first grid connected tidal turbine which was installed on September 2003 in the Kvalsundet off Hammerfest (Norway), at 50 metres depth. The turbine has three 10-meter blades that turn with the tides to produce up to 300 kW of electricity, and it rests on 20-meter tripods anchored to the sea floor.
- The first in the world tidal turbine generator in open-sea was installed 1 mile off the coast of Lynmouth, Devon, in spring 2003 by MCT Ltd. The location was selected because of its 5+ knot spring tide tidal streams and easy accessibility. The 300kW 11m diameter turbine prototype (*Seaflow*) is fitted to a steel pile which was driven into the seabed.

- The Verdant Power's Roosevelt Island Tidal Energy (RITE) 175 kW demonstration project (6 free flow turbines - 5 with 35 kW generators and one equipped with a dynamometer for monitoring project operations) was licensed and commenced testing in mid-2006.

To add to this, the MCT SeaGen 1.2 MW commercial prototype has been fabricated and is currently being installed in Strangford Lough, Northern Ireland. The first developer that used the EMEC tidal test site in the Orkney Islands was OpenHydro, with their open centred turbine installed in late 2006. Additional tidal systems are scheduled for installation and testing there for 2008.

Case studies are presented on the following pages

Case Study - Hammerfest Strøm

Project Name	Hammerfest Strøm
Location	Norway
Installed capacity	300 kW
Technology Type	Tidal stream horizontal axis turbine (Blue Concept)
Project Type/Phase	Prototype testing
Year	Installation, 17 September 2003

Project Description

Hammerfest Strøm AS, a Norwegian company, in collaboration with ABB, Rolls Royce and Sintef, as well as Statoil, developed the first grid connected marine turbine rated 300 kW. The prototype was installed on 17 September 2003, in the Kvalsundet outside Hammerfest, northern Norway, at 50 metres depth. The submerged structure weighs 120 tonnes and has gravity footings of 200 tonnes. Its three-bladed turbine have been made in glass fibre-reinforced plastic and measure 10 metres from hub to tip.

By rotating the propeller blades around their own axis at slack water when the current turns, the mill is ready for the reversing current (pitch control) keeping the nacelle fixed. Each propeller is coupled to a generator from which the produced electricity is fed via a shore connecting cable to a transformer and then on into the grid. The turbines are designed to be maintenance-free for three years, but divers can go down if needed.

Locality and installation

Kvalsund county

- 1088 inhabitants;
- electricity consumption ~21 GWh.

Environmental and natural conditions

- the narrowest width of the strait is 400 meter;
- the mean velocity at the locality is 1.8 m/ sec;
- the depth is 50 m, allowing a sailing depth of 19 meter;
- an artery for ship traffic;
- abundant fish life;

- extensively used by the locals for rod fishing and trolling;
- sea mammals (e.g. seals, small whales) are common;
- many kinds of diving sea-birds have been observed including several protected species on the red list.

Thorough site surveys were completed to monitor the physical conditions of the energy capture and of the local eco-systems to assess their impact. Surveillance will continue as a part of the planned research work in Kvalsundet. Results will provide answers to some pressing questions to facilitate the commercial exploitation of tidal and other marine currents.

In order for surface vessels to maintain a stable position in the stream, two moorings are readied on the Kvaløy shore, one to the east and one to the west of the mill site. The required moorings on the mainland side are secured with anchor chains. For installation of the structure, which is the first sub-sea phase, a floating crane is used. When the crane lifted the structure off the transport barge in Kvalsundet, the first phase in the construction of the world's first tidal stream power plant was started.



Deployment of the first grid connected marine turbine in Kvalsundet (Norway)

The turbine has been in operation since 2003 with good results. It supplies 700 MWh per year – corresponding to the electricity consumption of 35 Norwegian homes. The only interruptions to production were to clean the rotor wings. According to the Norwegian Institute for Nature Research (NINA), no negative effects on marine life have been reported after several years of experimental operation in Kvalsundet.

The first generation of commercial mills is designed with twice the output of the prototype. The objective was for the tidal power plant in Kvalsundet to have 20 units which will deliver 32 GWh per year.

In the spring of 2007, Hammerfest Strøm signed a contract with the Scottish energy company Scottish Power to develop Norwegian technology for tidal energy in the UK. Scottish Power and Hammerfest Strøm have together founded the tidal power company Hammerfest Strøm UK. The goal is to install a full-scale tidal turbine in the UK in 2009. This

is an important step on the path to commercialisation and mass production of tidal power technology.

Project Partners

The project consortium consists of partners with state-of-the-art competence from leading Norwegian research institutions and industrial companies. By integrating theoretical competence with practical experience, solutions are technically and economically sound, based largely on established technology.

Hammerfest Strøm AS is a Norwegian tidal water energy technology company established in 1997. It has been engaged in research and development of state-of-the-art tidal energy technology, and has obtained patents and rights to commercial use by delivering turn-key stream turbines. Hammerfest's two largest owners are Statoil, the Norwegian oil and gas company, and Hammerfest Energi, a power utility located in northern Norway.

Norwegian technological research institutions, such as SINTEF Energy Research and the Norwegian University of Science and Technology (NTNU), participate in the tidal power project of Hammerfest Strøm, together with many corporate R&D units. Outstanding among the latter are Statoil, ABB (Offshore Systems and Corporate Research), Rolls-Royce (technology, and products for ship thrusters), Selmer Skanska (technology for sub sea structures and their construction) and Venturos, all important partners technologically as well as financially.

SINTEF was on site with data acquisition and monitoring equipment, surveying the operation and securing the orientation of the propeller axis in line with the recorded current. StatoilHydro has played an important role in the development of technology for the tidal power turbine. They have applied their experience and expertise from subsea technology in the oil and gas industries to develop technologies for sustainable energy.

Cost and Financing

According to a statement from Harald Johansen, the managing director of Hammerfest Strøm, the project cost to date is \$6.7 million (50 million NOK) and will cost almost \$15 million, a total investment of 100 million NOK, to complete installation of all 20 turbines. The production cost of the electricity is 4.3 to 5 cents/kWh, three times that of typical hydro-generated electricity in Norway.

Further Information

<http://www.hammerfeststrom.com/content/view/48/78/lang.en/>

<http://www.e-tidevannsennergi.com/>

Case Study - Race Rocks

Project Name	The Race Rocks Tidal Energy Project
Location	Race Rocks, BC, Canada
Installed capacity	65 kW
Technology Type	Horizontal axis bi-directional ducted turbine
Project Type/Phase	Part-scale model testing
Year	2006

Project Description

The Race Rocks Tidal Energy Project is Canada's first free-stream tidal power project. Located at Race Rocks Ecological Reserve, offshore of Vancouver Island in British Columbia 10 nautical miles southwest of Victoria, the project will allow the world-famous marine park to tap into surrounding ocean currents and convert tidal energy into electric power. The multi-year demonstration project involves the installation, operation and monitoring of a 65kW free-stream tidal turbine generator in the water.

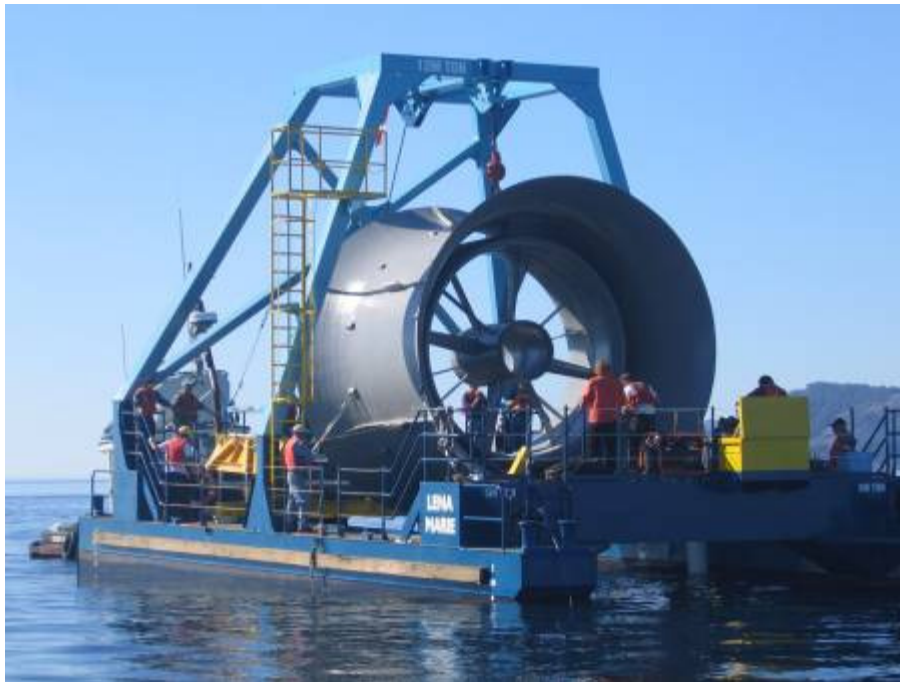
The key objectives of the project are to:

- Provide electricity to replace two diesel generators.
- Reduce greenhouse emissions.
- Reduce environmental impact of generating electricity – measure changes against baseline.
- Demonstrate the efficiency of the tidal turbine generator.
- Demonstrate power conditioning capabilities.
- Demonstrate maintenance processes.
- Study behaviour of sea mammals and fish in relation to operation of the turbine generator.
- Demonstrate safety procedures.
- Contribute to the educational experience of Pearson College students.
- Demonstrate the ability to install the system in an extreme tidal environment.
- Demonstrate the performance of the support structure during turbine operation.

Clean Current's tidal turbine generator is a bi-directional ducted horizontal axis turbine with a direct drive variable speed permanent magnet generator. This proprietary design delivers high water-to-wire efficiency. Operability is enhanced by a simple design that has one moving part - the rotor assembly that contains the permanent magnets. There is no drive

shaft and no gearbox. The turbine generator has a design life of 10 years (major overhaul every 10 years) and a service life of 25-30 years.

The Clean Current tidal turbine generator (TTG) was installed in 20 metres of water near Race Rocks during the period July to September 2006. The prototype tested is 3.5-metres in diameter and can produce enough electricity for 10 houses. Full scale models will be 14 metres (or more) in diameter and of more than 1 MW in capacity (according to the site's tidal velocity regime). The hydraulic and electrical performance of the TTG was tested using an offline load bank for two months.



Installation of the turbine, September 27, 2006

After testing was completed on December 5, 2006, the TTG was connected to the control system that feeds electricity into the battery storage at Race Rocks. Clean Current's testing at Race Rocks has validated its performance claims for the direct drive permanent magnet generator and the flow enhancement duct design. The tidal turbine generator has successfully extracted power in flows up 6.6 knots. The company is disappointed with the performance of the water lubricated bearing system.

The tidal turbine generator was successfully extracted on May 24, 2007. The unit is being carefully inspected and will be refitted with a new bearing system. The same bearing system will be designed into the commercial scale unit. The retrofit will also include an improved augments duct design and an improved antifouling coating. All of the lessons learned at Race Rocks will be incorporated into the commercial scale design.

Project Partners

The project is a partnership between Clean Current Power Systems Incorporated, the Lester B. Pearson College of the Pacific, EnCana Corporation and Sustainable Development Technology Canada.

Clean Current is a private British Columbia-based company that designs and licenses technology that efficiently converts the energy of tidal currents into electricity. The Race Rocks Tidal Energy Demonstration Project was an important step in the company's technology development plan aimed at early commercialization. To ensure success Clean Current enlisted technical assistance from AMEC Americas Limited and AMEC Dynamic Structures Limited (both subsidiaries of AMEC PLC), Powertech Labs Inc. (a subsidiary of BC Hydro), OceanWorks International, Xantrex Technology Inc., Robert Allan Ltd and Triton Consultants Ltd.

Pearson College is dedicated to protecting the marine ecosystems within the reserve and to increasing the awareness of students, visitors and the public about marine systems, ecological reserves and environmental issues. Students and staff worked elements of the tidal power demonstration project into their studies. Their scope is to develop support for alternate energy technologies to make the island energy-self sufficient.

EnCana, the largest producer and developer of natural gas in North America, invested \$3 million in the project from its environmental innovation fund. Sustainable Development Technology Canada is a foundation created by the Government of Canada that operates a \$550 million fund to support the development and demonstration of clean technologies — solutions that address issues of clean air, greenhouse gas (GHG) emission reductions, clean water, and clean soil to deliver environmental, economic and health benefits to Canadians.

Cost and Financing

The total Project Cost was \$C 4,000,000, and it was made possible by a \$C 3,000,000 investment from EnCana's Environmental Innovation Fund (EEIF). Clean Current and Pearson College, the core project partners, also won a grant of just under \$1 million in 2005 from Sustainable Development Technology Canada.

Further Information

Clean Current's website: <http://www.cleancurrent.com/technology/rrproject.htm>

<http://www.racerocks.com/racerock/energy/tidalenergy/tidalenergy2.htm>

Case Study - Roosevelt Island Tidal Energy (RITE) Project

Project Name	Roosevelt Island Tidal Energy (RITE) Project
Location	East River - New York, NY
Installed capacity	175 kW (first phase of the project)
Technology Type	Three-blade, horizontal-axis turbine (Free Flow Turbine)
Project Type/Phase	Commercial use
Year	December 2006

Project Description

Initiated in 2002, Verdant Power’s Roosevelt Island Tidal Energy (RITE) Project is being operated in New York City’s East River, along the eastern shore of Roosevelt Island. In three phases, the RITE Project will test, demonstrate and deliver commercial electricity from a tidal Free Flow system. The Project is progressing from an initial demonstration array of six Free Flow turbines to a complete arrangement of units that could generate up to 10 MW (~300 turbines), enough to power nearly 8,000 New York homes.

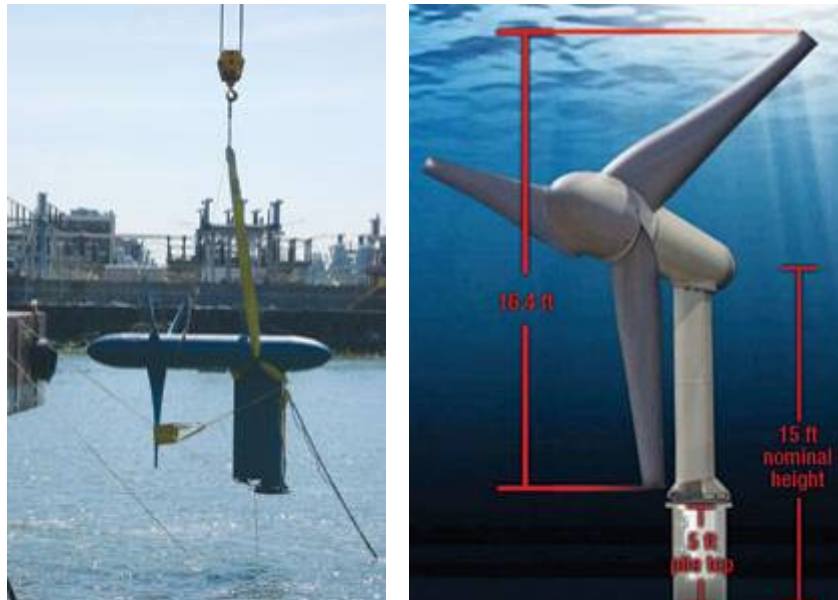
A world-first initiative

In December 2006, Verdant Power installed its first grid-connected Free Flow turbine at the RITE Project. The remaining turbines to make up the full six-turbine demonstration array were installed by May 2007. This stands as the world’s first grid-connected array of tidal turbines. The RITE Project has also accomplished the following:

- ~50 MWh of electricity delivered to customers (world leader);
- 7000+ hours of operation (world leader);
- Fully bidirectional tidal operation (world first);
- FERC allows Verdant Power to test energy delivery from RITE demonstration array with its “Verdant” ruling;
- Received overwhelming community support.

A key objective of the RITE Project is to test the transmission of electricity from the Free Flow system to end users. To help accomplish this, two end-users on Roosevelt Island agreed to receive electricity generated by the test array of Free Flow turbines installed in the East River: a Gristede’s Supermarket and the Roosevelt Island Operating Corporation (RIO) Motorgate parking garage.

On December 12, 2006, the first of this electricity was transmitted to the participating Gristede's Supermarket, marking the first time in history that such a technology has delivered energy to an end-use customer. This test transmission also demonstrated the ability of the Free Flow system to provide grid-connected power, with no switching or power quality problems, in the heart of one of the world's largest cities.



The Roosevelt Island turbines (installation and schematic diagram) - Verdant Power Inc.

The six axial-flow rotor turbines were installed in 30 to 40 ft of water in a section of New York City's East River about a mile long and 270 ft wide between Roosevelt Island and the Borough of Queens. The turbines, each averaging 35.9 kW of capacity, resemble wind turbines, with fixed-pitch blades 8.2 ft long and the centre line of the turbine 15 ft above the river bed. Mono-piles, steel pipes 24 in. in diameter filled with rebar and concrete, anchor the turbines in the bed.

RITE Project phases

The following works are foreseen in the three phases of the project:

1) Phase 1 (2002 - 2006):

- Prototype turbine development, demonstration & testing
- Site analysis
- Preliminary permitting

2) Phase 2 (2006 - 2008):

- Design & fabrication of next generation turbine
- Deployment and in-stream operation of six turbines (175 kW installed capacity)
- Permitting and licensing for full commercial operation

3) Phase 3 (2008 -2010):

- Design, fabrication and deployment of commercial scale turbine
- Full field build-out of RITE project (up to 10 MW capacity)

As part of Phase 2 of the project, Verdant Power has installed a field of six Free Flow turbines: five turbines with 35kW nameplate generators each (a total of 175kW), and one turbine equipped with a dynamometer. A key purpose of this second-phase installation is to evaluate and monitor the turbine array from a variety of environmental perspectives. These analyses include an assessment of any potential impact the technology may have on aquatic life.

Project Partners

Verdant Power – the project promoter and turbine’s manufacturer - was established in 2000 and is based in New York, NY. Emerging technology developers are coupled with utility industry veterans with advanced experience in constructing and operating electricity generation facilities, especially hydropower.

The other project partners include:

- *New York State Energy Research & Development Authority (NYSERDA)*: invests in renewable energy through programs that provide funds to emerging businesses for product and business development, product marketing assistance, incubators for start up industry and other support. NYSERDA also provides grants to companies that locate their operations in New York and manufacture renewable energy and associated technologies.
- *KeySpan Energy*: provides gas and electric service to more than seven million customers in the New York Metropolitan area, upstate New York, Massachusetts, New Hampshire, and Rhode Island. National Grid also generates electricity for customers located in New York City and Long Island. National Grid is the second largest electricity and gas company in the U.S. with a service territory that covers over 30,000 square miles.
- *New York City Economic Development Corporation (NYCEDC)*: encourages businesses to start, expand or relocate in NYC by creating policies that promote economic growth and offering programs and incentives to help them achieve success.

Cost and Financing

Officials of Verdant Power Inc. claim that this is an \$8-million project. Most of the costs were in obtaining regulatory approvals for the demonstration project; the RITE project also has incorporated over \$2 million in fish monitoring equipment. As an example of cost allocation, Trevcon Construction Inc. delivered and installed the turbines as prime under a \$1.3-million lump-sum contract.

The one-off prototype phase is expensive, with the price running between \$4,800 and \$5,000 per kW installed. Once commercialization is achieved, the price is expected to come down to around \$2,400/kW installed. According to Verdant Power's published projections for the RITE project (in 5MW capacity) the operating cost will be around \$ 0.07 - 0.09 per kWh free-flow.

Verdant Power has received an additional series of five NYSERDA awards since 2002, to commercialize the RITE project and build a related industry in New York State. NYSERDA awards supported approximately 25% of RITE project funding needs. Verdant Power has also worked with the New York City Economic Development Corporation and Keyspan Energy to provide additional local financing for the project's test phase and full-field build out.

Further Information

<http://www.verdantpower.com/what-initiative>

Case Study - Stingray

Project Name	Stingray
Location	Yell Sound, Shetland Islands.
Installed capacity	150kW
Technology Type	Reciprocating hydroplane device
Project Type/Phase	Part-scale model testing
Year	2002

Project Description

The Stingray project is the latest phase in the tidal stream energy programme established by The Engineering Business Ltd (EB), aiming at the design and building of a demonstration 150kW generator and testing it in a suitable tidal stream. Stingray is a system, developed and patented by EB, to extract useable electricity from tidal currents. It differs from other proposed devices in that it utilises an oscillating motion rather than rotation to capture the energy from the flowing water.

The programme started in 1997 with the Active Water Column Generator (AWCG), which subsequently developed into the Stingray concept. A technical and commercial feasibility study (Phase 1) in 2001 led to Phase 2 – the design, build, installation and operation of the Stingray demonstrator in Yell Sound in 2002. Phase 2 was extended into 2003 to consider aspects of the technology in more detail.

More precisely, the Stingray Project's phases included the following:

- 1) **Phase 1:** technical and commercial feasibility study (2001);
- 2) **Phase 2 – as-built:** comprises the demonstrator unit as tested in Yell Sound in the summer of 2002.
- 3) **Phase 3 – redeploy upgraded demonstrator:** rebuilding and reinstalling the Phase 2 demonstrator device to gather data on long term operability and to test more efficient operating approaches.
- 4) **Phase 4 – demonstration farm:** comprising 10 larger machines, the Phase 4 installation would demonstrate commercial potential, and allow EB to gain operating experience, to assess the interaction effects of multiple devices and to develop reduced cost mass production construction, installation and operating methods.
- 5) **Phase 5 – commercial farm: (incomplete)** comprising 10 larger machines, the Phase 5 installation would have been a commercial installation of Stingray machines, optimised for cost and performance for the specific location.

The key component of Stingray is the wing-like hydroplane. It is attached to a seabed-mounted supporting frame by a pivoted arm. As tidal currents pass over the hydroplane, lift and drag forces cause the hydroplane to lift. This causes the arm to lift, actuating hydraulic cylinders at the arm / frame pivot. The cylinders turn a hydraulic motor that drives an electric generator. When the hydroplane and arm reach their upper limit, the hydroplane angle is reversed such that the arm is driven down, and the cycle repeated.

During the project, a number of activities were undertaken, including:

- The design and construction of a working Stingray device.
- The design of the installation and maintenance methodology for Stingray.
- The site selection and acquisition, including assessing tidal flows, seabed geotechnical conditions, the environmental impact of Stingray and the requirements associated with obtaining permits and consents.
- The infrastructure requirements and power generation characteristics of the Stingray generator.
- The economics of supplying electricity to consumers using Stingray generators.

Table: Stingray specification

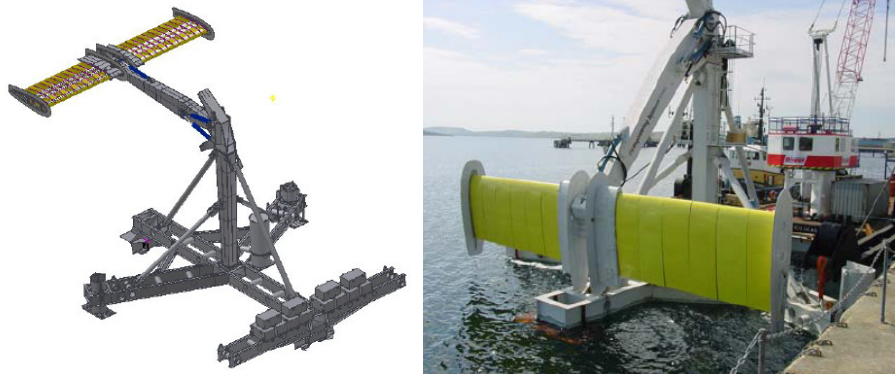
Maximum height	23.6 m with hydroplanes in highest position
Maximum width	15.5m
Arm length	11m
Arm operating angle	+/- 35 degrees
Hydroplane actuation angle	Relative to arm +/- 90 degrees
Rated power	150kW at 3 knots and above

The size of the Stingray structure was such that the existing EB workshop facilities could not be used for the main assembly. An order was placed in early June for use of the Amec Howdon Supply Base. Stingray assembly was undertaken by EB personnel, with welding by local fabricators and additional assistance provided by Amec.

A number of installation options were considered during Phase 1 of the project, including existing tried-and-tested technologies such as jack-up rigs, barge-mounted systems using technology transfer from existing EB systems, and new innovations. After thorough review, the existing systems were too expensive for a low-cost demonstration project, and the new innovations were impractical. The solution was to use EB's experience in deployment systems to develop a simple, cost-effective barge-mounted system with a wide operating window.

A concept design, incorporating a strand-jack lift system operating through a frame of lift beams, was identified. The Harry McGill barge, owned and operated by Briggs Marine Contractors, was selected for use as the installation vessel for Stingray. On 13th September

2002, Stingray was deployed to the seabed, in 30m of water. On-site testing commenced later the same day.



Stingray general arrangement (left) and commissioning in Shetland (right)

Marine operations were ended by the recovery on 25th September 2002. Although the operating period had been relatively short (12 days), a great quantity of data had been obtained for analysis. While permissions were in place to maintain the barge on station until mid-October, it would then have had to be moved off station and Stingray either removed, left on the seabed and operated from onshore control facilities via a subsea cable, or left on the seabed in a locked down position with no subsea cable or control system (wet stored) until the following Spring.

Although planning permission for the onshore facilities had been obtained by mid-September, the onshore control facilities and submarine cable could not be in place in time to allow initial onshore control to be undertaken while the barge was still on station. A decision was taken to remove Stingray rather than wet store it. This would permit modifications or reconfigurations to be made in light of any findings of the data analysis over the winter months.

Based on the data collected during its first deployment, Stingray was modified with improved hydroplane control and faster cycle times. These changes were tested when the 180 tonne Stingray was deployed for a second time off Shetland for a four week period beginning in late August 2003 to demonstrate total energy capture over one complete lunar cycle. This was Phase 3 of the project.

During the marine operations significant improvements in energy capture and power generation were made, compared to the Phase 2 operations. The mathematical performance model was validated by the test results, enabling a second-generation (500 kW) Stingray concept to be developed and cost models to be produced. Different control strategies were trialled before the optimum was found and fully tested.

The final stage in EB's development model for the Stingray was the completion of a 5 MW grid-connected Stingray tidal farm. In total, ten Stingrays were supposed to be installed, each rated at 500 kW. The first 500 kW Mach II Stingray was ready to be installed and

tested in 2005. Four more would have been installed in 2006, with the remaining five following in 2007. Although a location was not finalised, a site off the Shetlands looked likely for the farm. However, EB subsequently discontinued development of the Stingray as the funding available was “*not on the scale or basis that would allow EB to rapidly or profitably make Stingray a commercial reality*”.¹

Project Partners

The Stingray device was developed by the Engineering Business. This company has completed the programme to design, build, install offshore, test and decommission a 150kW part-scale model of the device. In September 2003, the Engineering Business joined with the New and Renewable Energy Centre (NaREC) in Blyth to create Tidal Energy Business.

Cost and Financing

Phase 2 of the Stingray technology’s development provided a baseline for capital costs but only limited information on reliability and operating costs over an extended period. More specifically:

- **Capital cost estimates:** The “as-built” demonstrator involved total capital costs of £1.87 million, comprising approximately £1,350,000 of materials costs (including marine operations) and £524,000 of EB time costs.
- **Operating cost estimates:** EB estimated that the annualised operating costs for the Stingray demonstrator would be about £160,000, roughly equally split between time costs and materials.

The research programmes have been part-funded by the DTI through a Smart award for the early AWCG work and the New and Renewable Energy programme for the Stingray project.

EB had budgeted £22 million for the ten-unit development (final Phase of the project). In addition, a £1m investment from NaREC would have allowed vital development work on the Stingray demonstrator to continue. Despite the significant support of the DTI, NaREC and Shetland, given the timescale and investment required, EB could not continue to sustain this project on a non profit basis.

Further Information

The Engineering Business Ltd: http://www.engb.com/services_09a.php
http://www2.env.uea.ac.uk/gmmc/energy/energy_pdfs/stingray_part1.pdf

¹ http://www.engb.com/services_09a.php

3.9. Test Your Knowledge

Learning Outcomes – Tidal Stream

Level	Tidal Stream
Basic ²	<p>On successful completion of this module you will be able to:</p> <ul style="list-style-type: none"> • Understand the physical processes that cause tides and tidal flows • Understand that the movement of water associated with tides is a renewable resource • Recognise that tidal energy resources are widely but not evenly distributed across Europe and that local topography affects tidal currents • Identify several different technology types used to extract energy from tidal streams • Recall the main technology types • Recall the basic steps involved in energy conversion by a tidal energy converter • Identify the different project phases such as Design and Planning, Construction and Installation, Operation and Management, and Decommissioning • Understand the importance of taking into consideration of all these project phases when evaluating the impacts and feasibility of a particular development • Recognise the equation used to calculate power in a tidal stream • Recall some of the foundation types that have been considered for tidal turbines • Explain how energy extraction leads to a number of possible interactions (both positive and negative) with the surrounding environment • Understand that the surrounding environment includes physical processes, wildlife and habitats, conservation interests, communities and social features, as well as commerce and economic activities • Explain how negative impacts can be minimised • Name specific examples where aquatic renewable energy is being extracted or has been tested
Intermediate	<p>On successful completion of this module you will be able to:</p> <ul style="list-style-type: none"> • Describe a few key developments in the use of tidal stream energy • Describe some of the factors which affect the speed of marine currents • Describe the different technology types used to extract energy from tidal streams • Outline the basic steps involved in energy conversion by a tidal energy converter • Describe some of the factors important for each phase of the project for the different technologies • Use the equation used to calculate power in a tidal stream to solve simple problems • Describe some of the foundation types that have been considered for tidal turbines • Outline the important factors in the operation and maintenance phase of the project • Describe the various impacts and opportunities associated with the technology • Outline the key types of environmental interactions associated with aquatic renewable technologies and to explain how these may change through a project lifecycle, in different locations and at different times • Outline some of the factors which influence the overall cost of the project for the different technologies

² **Basic** – Equivalent to EQF (European Qualification Framework) Level1 and Bloom’s Taxonomy “Knowledge” category. This level requires the student to have basic general knowledge of the subject, be able to recall important information.

Intermediate – Equivalent to EQF level 2 and Bloom’s Taxonomy “Comprehension” category. This level requires the student to be able to explain basic factual knowledge.

3.9.1. Quiz

Answers are given in the footnote³

Q1 Tidal stream as an energy source:

- a) Has been used for thousands of years
- b) Is currently being developed
- c) Has been used for hundreds of years and is now a fully commercial scale business sector
- d) Has not yet been tested

Q2 Tidal stream technologies use the following as an energy source:

- a) Wind, which is caused by the uneven heating of the earth's surface by the sun
- b) Water flowing in and out of tidal areas, caused by the gravitational pull of the moon and the sun on the seas
- c) Waves, which are caused by winds blowing over the surface of the sea
- d) Solar energy from the sun

Q3 Tidal stream technologies are designed to harness:

- a) The kinetic energy of tidal streams
- b) The gravitational potential energy associated with the rise and fall of tides
- c) The thermal energy of tidal streams
- d) The chemical energy contained within water molecules in the sea

Q4 Choose the two words which best complete this sentence.

Tidal stream resources are generally largest in areas where a relatively _____ tidal range exists, and the speed of the currents is _____ by the funnelling effect of the local coastline and seabed:

- a) large, amplified
- b) small, amplified
- c) large, reduced
- d) small, reduced

³ 1b, 2b, 3a, 4a, 5a, 6b, 7b, 8c

Q5 The following are types of tidal stream technology:

- a) Venturi effect device, reciprocating device (oscillating hydrofoil), horizontal axis turbine
- b) Attenuator, point absorber, overtopping device
- c) Weir and diversion type plant
- d) Solar panels

Q6 Reciprocating hydrofoils are:

- a) Devices that direct the tidal flow through a duct, which concentrates the flow
- b) Devices that have hydrofoils which move back and forth in a plane normal to the tidal stream, instead of rotating blades
- c) Devices that have turbine blades that rotate around a horizontal axis
- d) Devices that have turbine blades that rotate around a vertical axis

Q7 The following is an example of where tidal stream energy devices are being tested:

- a) Anatoliki, Greece using a 700kW “Pelton-2” turbine
- b) Yell Sound, Shetland Islands, Scotland device using a 150kW reciprocating hydroplane device
- c) La Rance Estuary, France using 24 x 10MW low-head bulb type turbines
- d) Scroby Sands, England using 30 x 2MWhorizontal axis turbines

Q8 The following is an impact associated with extraction of energy from a tidal stream:

- a) Reduced tidal range leading to potential decrease in number of intertidal species
- b) Changes in river flow patterns leading to potential disruption to protected migratory fish routes
- c) Reduction on tidal current energy leading to potential increase in sediment settlement downstream of the device
- d) Risk of bird collisions with moving turbine blades

3.10. Further Information

Reference documents

EC Joule II, ***The Exploitation of tidal and Marine Currents***, Commission of European Communities, 1996 [EUR 16683 EN, JOU2-CT93-0355]

The UK Parliament. 2001, “**Appendix 6 – Wave and Tidal Energy**” (Online)
<http://www.parliament.the-stationery-office.co.uk/pa/cm20001/cmselect/cmsctech/291/291ap07.htm>.

World Energy Council. 2001, “**2001 Survey of Energy Resources – Tidal Energy**” (Online)
<http://www.worldenergy.org/wec-geis/publications/reports/ser/tide/tide.asp>

IEEE Power Engineering Society, 2005. “**2005 Panel Session Harnessing the Untapped Energy Potential of the Oceans: Tidal, Wave, Currents and OTEC**” (Online)
http://www.ewh.ieee.org/cmte/ips/2005GM/oceans_2.pdf .

Emily Rudkin, Vortec Energy Ltd (post 2001), “**Survey of Energy Resources - Marine Current Energy**”, World Energy Council at: <http://www.worldenergy.org/wec-geis/publications/reports/ser/marine/marine.asp>

British Wind Energy Association: **Marine Renewable Energy**. [Webpage]; Available from <http://www.bwea.com/marine/>

Scottish Enterprise Marine Energy Group: **Harnessing Scotland's Marine Energy Potential**. [Webpage] 2004; Available from <http://www.scotland.gov.uk/Publications/2004/08/19742/41046>

AKWENSIVIE, F., et al., University of Strathclyde: **Marine Current Energy Baseload Supply Strategy for Scotland**. [Webpage] 2004; Energy Systems & the Environment MSc Group Project; Available from: http://www.esru.strath.ac.uk/EandE/Web_sites/03-04/marine/index2.htm

MARSH, G., **Energy from The Sea**. Refocus, 2005. 6(6): p. 30-32.

General articles about the technology

European Commission, **SEAFLOW, World's first pilot project for the exploitation of marine currents at a commercial scale**, [JOR3-CT98-0202], 2005
 Available online at http://europa.eu.int/comm/research/energy/pdf/seaflow_en.pdf

BAHAJ, A.S. and MYERS, L.E. **Fundamentals Applicable to the Utilisation of Marine Current Turbines for Energy Production**. Renewable Energy, 2003. 28(14): p. 2205-2211

BATTEN, W.M.J., et al. **Hydrodynamics of Marine Current Turbines**. Renewable Energy, 2006. 31(2): p. 249-256

CAMPOREALE, S.M. and MAGI, V. **Streamtube Model for Analysis of Vertical Axis Variable Pitch Turbine for Marine Currents Energy Conversion**. Energy Conversion and Management, 2000. 41(16): p. 1811-27

DTI, Development, **Installation and Testing of a Large Scale Tidal Current Turbine** [T/06/00210/00/REP; URN 05/1698]: Available online at:

<http://www.berr.gov.uk/files/file18130.pdf>

KIHO, S., et al. **Power Generation from Tidal Currents by Darrieus Turbine**. Renewable Energy, 1996. 9(1-4): p. 1242-1245

MYERS, L. and BAHAJ, A.S. **Power Output Performance Characteristics of a Horizontal Axis Marine Current Turbine**. Renewable Energy, 2006. 31(2): p. 197-208

SHIONO, M., et al. **Experimental Study of the Characteristics of a Darrieus Turbine for Tidal Power Generation**. Electrical Engineering in Japan (English translation of Denki Gakkai Ronbunshi), 2000. 132(3): p. 38-47