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EUROPEAN COMMISSION

SEAFLOW

World's first pilot project for the exploitation of marine currents at a commercial scale

Contract JOR3-CT98-0202

Final Publishable Report

Partners

IT Power

Seacore

Gesamthochschule Kassel

Jahnel-Kesterman

2005 Directorate-General for Research EUR 21616

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Luxembourg: Office for Official Publications of the European Communities, 2005

ISBN 92-894-4593-9

Printed in Luxembourg

PRINTED ON WHITE CHLORINE-FREE PAPER

Contents

1 ABSTRACT

SEAFLOW has been a 5-year project to develop and test a commercially-sized marine current turbine. The turbine was installed in the summer of 2003 off Foreland Point, near Lynmouth on the North Devon coast of England, and has been successfully operated and tested since then.

The turbine is a 300 kW, horizontal-axis machine that resembles a 2-bladed wind turbine, but with the rotor underwater. The turbine is mounted on a steel pile fixed into a socket in the seabed, and the power train – the rotor, gearbox and generator - can be slid up and down the pile and out of the water for servicing.

The project has included identifying a site for the turbine and obtaining all the necessary permissions to install it, including conducting an Environmental Impact Assessment into its effects on marine life and processes, the landscape, and other sea users.

The project was co-ordinated by the renewable energy consultancy, IT Power. The other partners were Seacore, a marine construction company, ISET, a research organisation attached to Kassel University, and Jahnel-Kesterman, a specialist gearbox manufacturer. A parallel project funded by the UK Government Department of Trade and Industry, DTI, had IT Power as its co-ordinator and Seacore as a partner, but added Marine Current Turbines Ltd., Bendalls Engineering, and Corus as UK partners. This consortium developed the machine from an early concept stage to detailed designs, then manufactured or purchased the components, and assembled and tested the prototype. The installation was carried out by a jack-up barge that could stand on legs on the seabed, providing a stable platform for drilling and assembly. No underwater operations were required.

Early testing has confirmed much of the design philosophy, and the turbine has performed at least as well as predicted. New techniques have been developed to install the turbine in a deep, high current area, and much has been learnt about working in such environments. The project has increased understanding of the nature of tidal flows, and the behaviour of a rotor in tidal currents. SEAFLOW lays the foundations for the development of a new industry, exploiting what is could be a sizeable renewable energy resource. The partners plan to follow SEAFLOW with further, larger prototypes, and to move to commercial production in the medium term. A dedicated company, Marine Current Turbines Ltd, has been set up to achieve this.

2 PARTNERSHIP

SEAFLOW has been a co-operative effort of multiple partners and multiple funding agencies. The work originally started with the EC project on 1 September 1998. The UK Department of Trade and Industry, DTI, also initiated a project to support SEAFLOW, on 1 June 2001. The work also benefited from a German project, *Control and management of variable speed marine current turbines on variable-speed power trains for tidal turbines*, supported by the German Government.

This led to a consortium of 7 organisations working on SEAFLOW, with a wide complementary range of experience and skills. Both the EC and DTI projects were co-ordinated by IT Power, but only IT Power and Seacore were in both projects. The structure is summarised in Figure 1, and the partners are listed in the sections below.

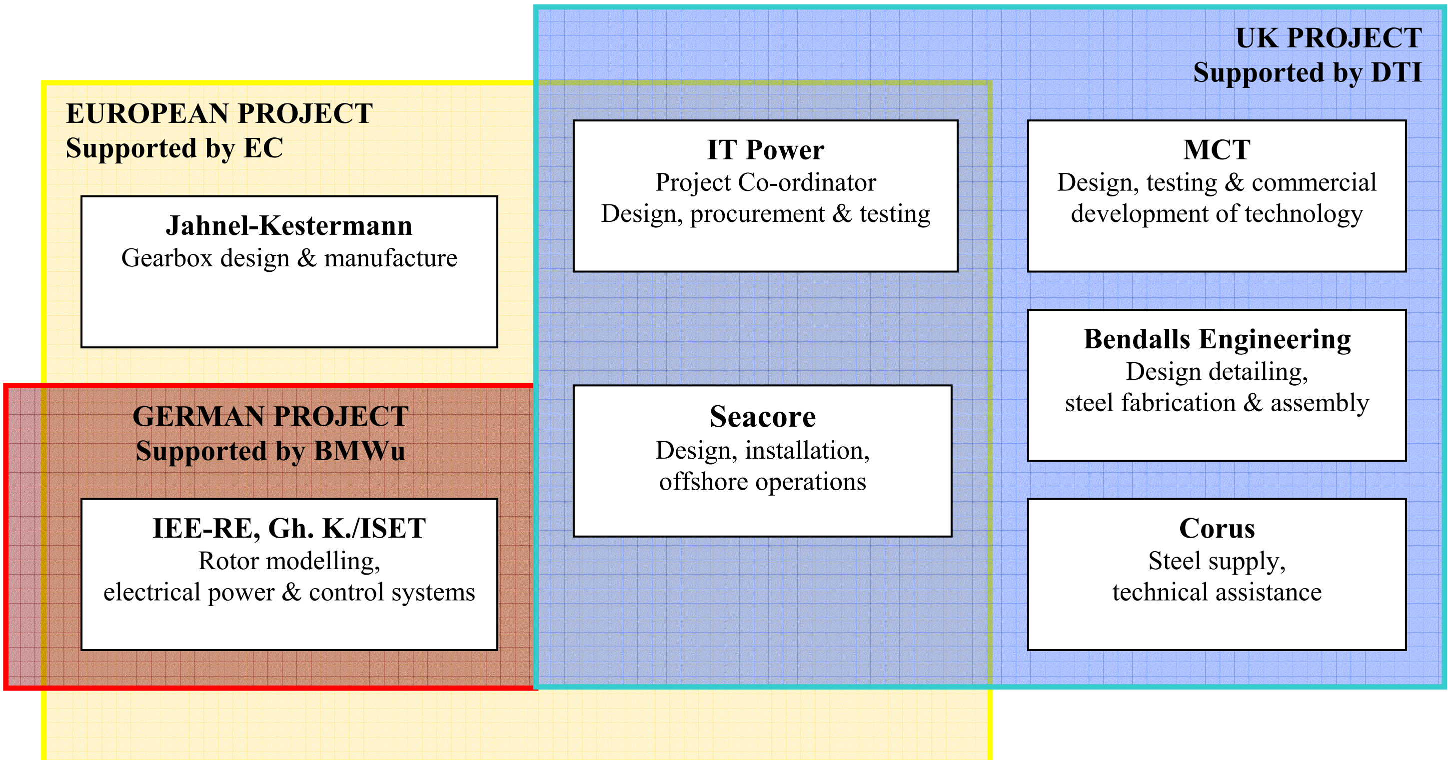

Figure 1: The relationship of the various projects and partners behind SEAFLOW.

The rather complex interlinking of the projects reflected the complexity of the work, and the need to raise a considerable amount of finance. The overall budget was around €5 million, of which approximately €1 million was grant from EC and €2 million was grant from the DTI. Some assistance was received in hardware from the BMWi project, to the value of around €100,000. The remainder was financed by the partners.

It was agreed that Marine Current Turbines Ltd., one of the partners in the DTI project, would be the ultimate owners of the Intellectual Property Rights arising from the project, as it will be developing the subsequent commercial technology.

2.1 EC COMPONENT AND PARTNERS

SEAFLOW, The World's First Pilot Project for the Exploitation of Marine Currents at a Commercial Scale. 1 September 1998 - 31 August 2003. Supported by the European Commission in the framework of the Non-Nuclear Energy Programme, JOULE III.

IT POWER LIMITED - "IT POWER", CO-ORDINATOR

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IT Power is a renewable energy consultancy, with over 20 years' experience covering most aspect of renewable energy, completing over 800 projects in almost 100 countries. IT Power has also undertaken a number of R&D programmes, including some of the pioneering early work in river-current and tidal turbines.

Within SEAFLOW, IT Power was responsible for the management of the project, design, operation and testing.

SEACORE LIMITED - "SEACORE"

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Seacore is a marine exploration and civil engineering contractor, specialising in site investigations and the installation of large-diameter monopiles. Seacore has installed several of the first offshore wind farms.

Within SEAFLOW, Seacore was responsible for structural design, installation, and maintenance.

UNIVERSITÄT GESAMTHOCHSCHULE KASSEL, INSTITUT ELEKTRISCHE ENERGIETECHNIK, RATIONELLE ENERGIEWANDLUNG - "IEE-RE, GhK"

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IEE-RE is a department of Kassel University that specialises in renewable energy research and teaching.

Within SEAFLOW, IEE-RE was jointly responsible with ISET for the electrical, control and instrumentation systems.

JAHNEL-KESTERMANN - "JaKe"

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Jahnel-Kesterman is a specialist gearbox manufacturer, making large gearboxes for a variety of markets. It has experience of both the marine and renewable energy industries, and is increasingly involved in wind turbine gearbox manufacture.

JaKe designed and manufactured the gearbox for SEAFLOW.

JaKe replaced ITT Flygt as the partner responsible for the power train in SEAFLOW in 2001.

2.2 UK COMPONENT AND PARTNERS

Development, Installation and Testing of a Large-Scale Tidal Current Turbine. 1 June 2001 – 31 August 2004. Project supported by the UK Government through the Department of Trade and Industry, DTI.

IT POWER - CO-ORDINATOR

Also co-ordinator of the EC project - see above.

SEACORE

Also a partner in the EC project - see above.

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MCT was originally established by IT Power to take forward the development of the SEAFLOW technology to a commercial product, but has subsequently become completely independent. MCT's shareholders include EDF Energy, Seacore and Bendalls Engineering. The partners have chosen to assign the know-how and IPR arising from the SEAFLOW project to MCT.

Within SEAFLOW, MCT was responsible for design of the rotor, operation and testing.

BENDALLS ENGINEERING - "BENDALLS"

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Bendalls Engineering is part of Carrs Milling plc, and is a large steel fabricator. Bendalls has traditionally specialised in pressure vessels and nuclear plant fabrications, but is diversifying into renewable energy.

Bendalls undertook detailing and manufacture of the structural steel components, and the assembly of the pod and rotor.

CORUS CONSTRUCTION & INDUSTRIAL - "CORUS"

Corus Construction & Industrial, Commercial Centre, P.O. Box 1, Brigg Road, Scunthorpe, N. Lincolnshire, DN16 1BP, United Kingdom

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Corus is a large, international steel company, with major manufacturing and research facilities.

Within SEAFLOW, Corus supplied all the steel, and gave expert assistance on various aspects of the design.

2.3 GERMAN COMPONENT

Control and management of variable speed marine current turbines on variable-speed power trains for tidal turbines. 1 March 2001 - 30 June 2004. Supported by the German Federal Government through the Energieforschung und Energietechnik (Fachprogramm) of the Bundesministerium für Wirtschaft und Technologie, BMWi.

INSTITUT FÜR SOLARE ENERGIEVERSORGUNGSTECHNIK – "ISET", CO-ORDINATOR

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ISET is a renewable energy research organisation associated with the University of Kassel.

ISET was responsible with GhK for the electrical, control and instrumentation systems in SEAFLOW.

3 OBJECTIVES

The main objectives of the project were to design, manufacture, install, and test a commercially-sized marine current turbine.

The SEAFLOW turbine had the following specifications:

The turbine was to have a rated output power of 300 kW from a horizontal-axis rotor. It was to be mounted on an epoxy-coated steel monopile, installed using a jack-up barge. It was to be installed in water depths of 20-30 m at a site with peak currents in the range 2-3 m/s, giving a rated energy output of approximately 1,000 MWh/year.

The test objectives for the project were:

- Confirmation of methodology for installing, maintenance and removal without underwater operations
- Investigation of marine growth
- Evaluation of stall-regulated rotor versus running at variable speed
- Assessment of static and dynamic loading, cavitation

4 TECHNICAL DESCRIPTION

4.1 CONCEPT DESIGN

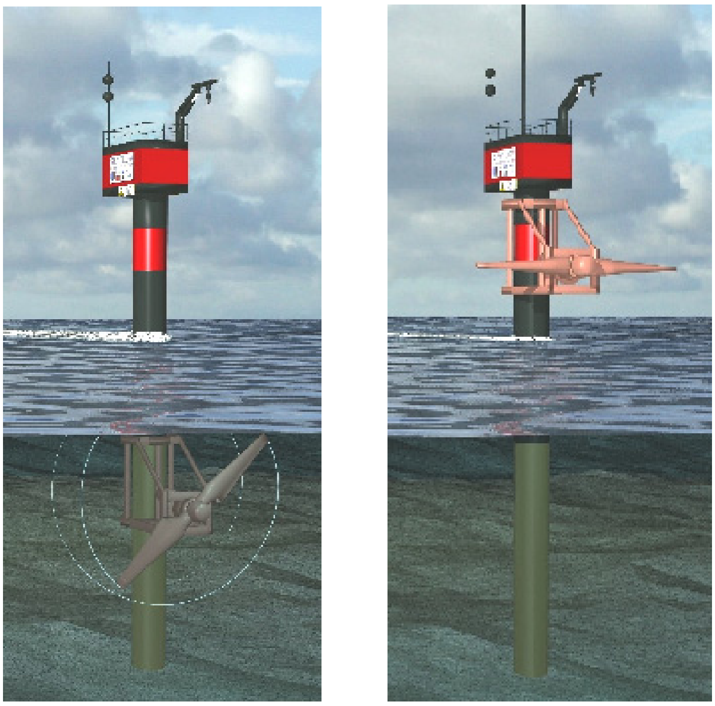


Figure 2: The SEAFLOW concept.

The basic concept of the SEAFLOW turbine was established around the following principles:

- It would be mounted on a monopile, giving a stable platform both to operate the machine and to access it.
- No divers or underwater operations should be required at any point in the life of the machine. Servicing would be by sliding the collar holding the power train up the pile and out of the water using a lifting mechanism integral to the turbine.
- Access should be by small boat or RIB (Rigid Inflatable Boat)
- Only the power train would be submerged. All the control and power electronics to be housed in a control pod on the top of the pile, above the sea surface

4.2 SITE SELECTION

The search for a site began with a study of available tidal information, such as UK Admiralty Tidal Atlases & Charts and ships' pilots. Various other studies were consulted, such as the CENEX study from EC CENEX project[1] and the UK Tidal Stream Energy Review[2]. Advice

[1] Marine Currents Energy Extraction: Resource Assessment; Tecnomare, ENEL, IT Power, Ponte di Archimede, University of Patras; Final Report of EU-Joule Contract JOU2-CT93-0355; 1995.
[2] UK Tidal Stream Energy Review; Engineering & Power Development Consultants, Binnie & Partners, Sir Robert McAlpine & Sons Ltd. & IT Power; Report for ETSU, Dept. of Energy, DTI, UK; ETSU Report No. T/05/00155/REP; 1993.

was sought from marine consultants, marine construction companies, harbour authorities, universities with marine or oceanographic departments, and marine sports groups.

4.2.1 CRITERIA

The key criteria for selecting sites were:

- 2-3 m/s maximum spring peak current (4-6 knots), in order to achieve an economic size of rotor
- Uniform flow with strong currents for long periods to maximise power available,
- Minimum depth 15 m to chart datum or lowest astronomical tide, to provide adequate space for a rotor
- Maximum depth 25 m, to remain within capability of jack-up barge,
- Close to the coast (preferably < 1 km),
- Near a suitable electrical network connection on the shore,
- Reasonably close to Seacore's base (to keep mobilisation overhead costs down), and to be accessible from IT Power,
- Not too exposed to open sea waves and wind, to reduce the risk of weather-induced delays and to maximise time available for installation and servicing,
- No major conflicts with other sea users,
- Avoiding sensitive environmental sites.

This preliminary study led to a shortlist of possible sites around the coast of England and Wales. While other good tidal sites were found off Scotland, Ireland, and the Channel Islands, these were not considered feasible as there would have been logistic problems working in these areas, which would have significantly increased the cost of the SEAFLOW installation.

4.2.2 GENERAL SITE SELECTION PRINCIPLES

Some general principles for tidal current turbine site selection were noted. The Mean Spring Tide current over most of the continental shelf is quite low, less than 1 knot (0.5 m/s). Higher currents are only found around certain features, such as:

- Channels or constrictions between islands - these provide some of the best sites, as the flow is fast and rectilinear.
- Headlands in the path of moderate flows - these are best when the headlands are large and not too sharp, otherwise the flows are fast but turbulent, and the high currents may be in different places on ebb and flood.
- Estuaries or other resonant water volumes - good sites with rectilinear flow, but combined with high tidal ranges.
- Narrow entrances to enclosed tidal lakes – these can have very high currents, but only over a small area.

Using these observations, large-scale maps can be used to predict possible sites, but in many places there is insufficient published data to verify whether an actual site is suitable. As marine current exploitation develops, there will be a need for a detailed inventory of potential sites.

On small-scale maps, areas that do have high currents appear very small, though in reality each one may be several kilometres long in the direction of flow, and have space for many turbines, potentially generating tens or even hundreds of megawatts. Many suitable areas are several kilometres from the shore, and would be suitable for development as tidal 'farms', though they would be prohibitively expensive for a single, isolated turbine. In this respect, the search for a site for SEAFLOW was unusual, and it will be easier to find sites for larger developments where overhead costs can be more easily absorbed.

4.2.3 SEAFLOW SITE

The outcome of the above work was a shortlist of four areas. These were: the Bristol Channel off North Devon, the north coast of Anglesey in North Wales, the West Solent between the Isle of Wight and the mainland in the south of England, and the Kent coast just north of Dover in south-east England. Consultations with various official bodies indicated that it would be difficult to obtain permissions for the Solent and Dover sites. Preliminary survey work showed that the Bristol Channel was much more favourable than Anglesey, so North Devon was chosen as the preferred site.

The Bristol Channel acts to constrict the tidal wave coming off the continental shelf, giving both large tidal ranges and high currents. These currents are faster further up the Channel, but the depths decrease. A survey site was chosen off Foreland Point, near Lynmouth, which is the northernmost tip of the Devon coastline. Being about halfway along the Channel, it has high currents in depths of 20-30 m.

A detailed survey was made of the bathymetry, seabed type, and current regime, confirming that it was a suitable location.

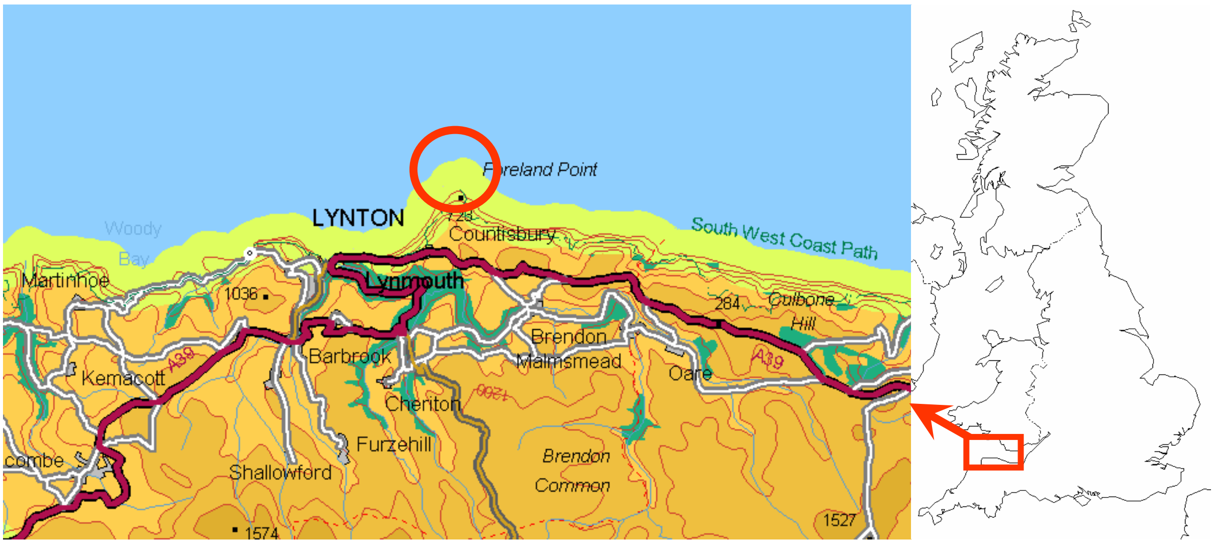


Figure 3: The location of the SEAFLOW site.

4.2.4 SITE PERMISSIONS

The regulatory framework governing construction at sea off the coast of England is complex. There are several relevant pieces of legislation and EC Directives that cover coastal waters, and these are administered by different government departments. When applications were made for licences for SEAFLOW, even the departments themselves were unclear as to which legal Acts applied, and how areas of apparent overlap were to be resolved. The situation has improved somewhat during the project, partly due to the SEAFLOW project itself, but primarily because of the advent of offshore wind farms. The various government departments have now created a single point of contact for marine licensing, but this was not the case when the SEAFLOW applications were made.

The consents to be obtained for a marine current turbine fall into four broad categories:

- Lease arrangements for the seabed,
- Navigation and shipping interests,
- Marine environment and usage,
- Cable and electrical connections on land.

Lease arrangements for the seabed are relatively straightforward, and are handled by The Crown Estate, which owns nearly all the seabed around the UK within the 12 nautical mile limit.

Navigation and shipping in UK coastal waters are the responsibility of the Department for Transport. While obtaining permission from DfT requires advertising the proposal and consultation, the scope of which is limited to issues of obstruction of navigation routes and safety.

The legislation covering the marine environment and usage is far more open, particularly in the way it is administered by the Department for Environment, Food and Rural Affairs, DEFRA. It involves widespread consultation with environmental groups, fishermen and other sea-users, so the process can be lengthy and involved if objections are raised.

The land-based consents for bringing a cable ashore and erecting switchgear are the responsibility of the local planning authority and the landowners.

Widespread consultation was carried out with all the official bodies who have a statutory input to the consents process, in advance of submitting formal applications. Discussions were also held with many other local organisations which potentially had an interest in the project. There was general enthusiasm for the tidal turbine concept, and the responses were nearly all positive.

Official applications for permission to install were made in 2001. A licence to install under the Food & Environmental Protection Act, FEPA, was granted by DEFRA on 20 March 2002. This had to be renewed in 2003 as the installation began just outside the twelve month licence period. Permission was granted by DfT under the Coastal Protection Act on 5 April 2002. A rental agreement was made with The Crown Estate dated 8 May 2003, after the other permissions were received, as this was conditional upon the granting of all other licences.

The Crown Estate required that the turbine should have third party insurance covering third-party liability to other sea users, and that the consortium should provide guarantees that the turbine would be removed at the end of the project. This guarantee was made by Seacore, which was considered to have sufficient financial stability to make the commitment. The insurance proved more of a difficulty, as the world-wide insurance market became unstable after the 11 September attacks in USA in 2001. Eventually, a special agreement with Seacore's normal insurance brokers allowed the consortium to obtain insurance, though at a rate somewhat above the original estimated cost.

The project applied for planning permission for laying a cable across the beach at Lynmouth to a substation just on the seafront, and this was granted by the Exmoor National Park Authority on 7 March 2000. In the event, the turbine was not connected to the grid, and this permission was not used.

4.2.5 ENVIRONMENTAL IMPACT

One of the pre-requisites for the FEPA licence was that the project produce an Environmental Statement, ES. This was completed in November 2001, and covered possible effects on waves, flow, seabed, sediment, water quality, marine habitat, fish and cetaceans, birds, fisheries, navigation and noise. It also had a major section on the visual impact and landscape, a photomontage from which is shown in Figure 4.

Figure 4: Photomontage of the turbine prepared for the Environmental Statement.

The conclusion of the ES was that the environmental impacts of the scheme were generally 'minor' or 'insignificant'.

The EIA and licence applications for SEAFLOW were groundbreaking, requiring the various authorities to think though the implications of marine current energy exploitation. Largely because of SEAFLOW, the UK government now includes 'tidal stream energy' as a defined area of interest for renewable energy resource, and the offshore marine permissions regime specifically includes tidal stream turbines.

4.3 TURBINE DESIGN

4.3.1 GENERAL DESCRIPTION

SEAFLOW resembles a wind turbine, but with the rotor totally submerged in the water when working. It has a 2-bladed, horizontal-axis rotor, 11 m in diameter. The rotor is directly mounted onto the shaft of a speed-increasing gearbox, which in turn drives a generator. The rotor is turned by the flow of water, and the generator produces electric power. The orientation of the rotor is fixed, but the blades can be pitched through 180° so that it can be used for currents in both directions, either on the ebb or the flood tide. As installed, the SEAFLOW rotor points up the Bristol Channel, facing directly into the ebb tide.

The turbine is mounted on a steel tube or 'monopile' which is fixed into the seabed. The power train (rotor, gearbox and generator) are mounted on a collar which can slide up and down the pile. With the collar out of the water, there is easy access to the working components for inspection and maintenance. Apart from the power train, all the other systems are housed in a pod on the top of the pile. This means they can be kept in a controlled, dry environment, which is especially important for the electrical and control components.

4.3.2 ROTOR

Rotor performance is the key to the successful exploitation of the technology, and the loads on the rotor are the starting point for the design of the turbine. It was therefore important to develop a means of modelling the rotor performance, and this was done by ISET (a renewable energy research organisation attached to Kassel University). ISET modified a Blade Element Model (BEM) program that had been developed and verified for wind turbines. The model was changed to work with seawater rather than air, and to include the effects of waves, velocity shear through the water column, cavitation, and pile interference.

The rotor diameter was set at 11 m as a compromise between achieving a 300 kW electrical power output, and the maximum depth in which the available installation equipment could work. An 11 m rotor was calculated to generate 300 kW on peak spring tides at Lynmouth, and could be installed in a sea depth of 15 m at lowest tide. This leaves 2 m clearance to the seabed, and a minimum of 2 m clearance to the surface, though usually more. One characteristic of the Lynmouth site is the high tidal range between high and low tide, which can be around 10 m on spring tides. This meant that the jack up barge installing the turbine had to stand in up to 25 m of water, which was close to the limit for the largest barges available to the project at that time. (Since SEAFLOW was installed, larger equipment - designed for installing offshore wind farms - has become available.)

Wind turbines need to be yawed in order to face into the wind, the direction of which varies. A tidal turbine has the advantage that the direction of the flow is predictable, and the ebb and flow are very often along roughly the same line. The SEAFLOW turbine can be changed from operating on a flood tide to an ebb tide simply by reversing the blades, pitching them through 180°. The ability to pitch also meant that the blade angle could be optimised in any given current, the blades could be feathered to brake the rotor gently, and the maximum power generated could be limited by angling the blades away from the optimum position. It was therefore decided to implement full-length blade pitch control.

The choice of 2 blades was made after considering both 2 and 3-blade options. Rotors with 3 blades have the advantage of being slightly more efficient, and they are also more balanced, inducing less fatigue load on the gearbox and the structure. However, 2-blade rotors are much easier to handle, as they can be laid flat on the deck of a ship. This is likely to be an important consideration for commercial turbines, where easy removal and replacement of the power train will increase the availability of the machines. 2-blade rotors are more simple mechanically (with only two blades, two pitch drive mechanisms etc.), and are therefore cheaper. For SEAFLOW it was also found that there was a greater safety margin between the forcing frequencies of the rotor and the natural frequency that could be achieve for the pile. The blades are made of composite.

4.3.3 POWER TRAIN AND ELECTRICAL SYSTEM

The rotor is mounted on the front flange of a gearbox, which steps up the speed to drive a nominal 1000 rpm generator. The gearbox has an epicyclic first stage, followed by two helical gear stages. The gearbox was designed and manufactured by the German partner Jahnel-Kestermann. The gearbox has a hollow main shaft to allow cables to be taken to the hub through a slipring unit, for instrumentation and the pitch control drives. The generator is an asynchronous type, and bolts directly onto a flange on the rear of the gearbox. Unlike in wind turbines, the gearbox and generator are not enclosed in a nacelle, but are out 'in the open', submerged in seawater.

The electrical power from the generator is fed by cables up to the pod, where it is conditioned by a frequency converter. This turns the alternating current from the generator to direct current and back again, and allows the speed of the generator to be controlled over a wide band.

A marine current turbine would normally be connected via a submerged cable to the local electrical network on the shore. This option proved too expensive for SEAFLOW, with the cost of installing a submarine cable being very high for just a single turbine. The cost could not have been recouped by selling the electricity, and no significant technical lessons would be learned from putting in a cable. It was therefore decided to run the turbine off-grid. The generated power is dissipated into a fan-cooled resistance heater. Running off-grid posed some problems for exciting the generator and providing backup power for ancillary systems, and a standalone power system consisting of a diesel generator, several battery banks and numerous inverters had to be provided. A schematic electrical system is shown in Figure 5.

4.3.4 CONTROL, INSTRUMENTATION AND COMMUNICATIONS

The turbine is controlled via an industrial PC in the pod, which is linked to all the systems involved in operating the turbine. The machine can be started automatically by the control PC, or manually by adjusting the parameters on a control screen.

The SEAFLOW turbine is a prototype machine intended to advance the understanding of power extraction from tidal flows, and is therefore comprehensively instrumented; a list of the main instrumentation is Table 1. All data is passed to a data logger, which is linked to the control PC.

Area	Measurement	Sensor
Environment	Current	Magnetic meter
	Water depth & waves	Pressure transducer
	Wind speed & direction	Anemometer
Forces etc	Blade bending moments & forces	Blade strain gauges
	Pile bending moments & forces	Pile strain gauges
	Pile movement	Pile accelerometer
Operation	Power, voltage, current etc.	Frequency convertor
	Pitch angle	Rotary shaft encoders
	Rotor position	Shaft encoder
Condition monitoring	Gearbox oil & bearing temperature	Temperature sensors
	Generator winding & bearing temperature	Temperature sensors
	Water in hub	Leakage sensors

Table 1: Main instrumentation

Communications to the machine are via a radio link to a land base in Lynton. The onshore receiver is connected to a computer with an ISDN line, which allows the turbine to be accessed remotely by telephone. It is therefore possible to control and monitor the turbine from the shore, or from a modem anywhere else.

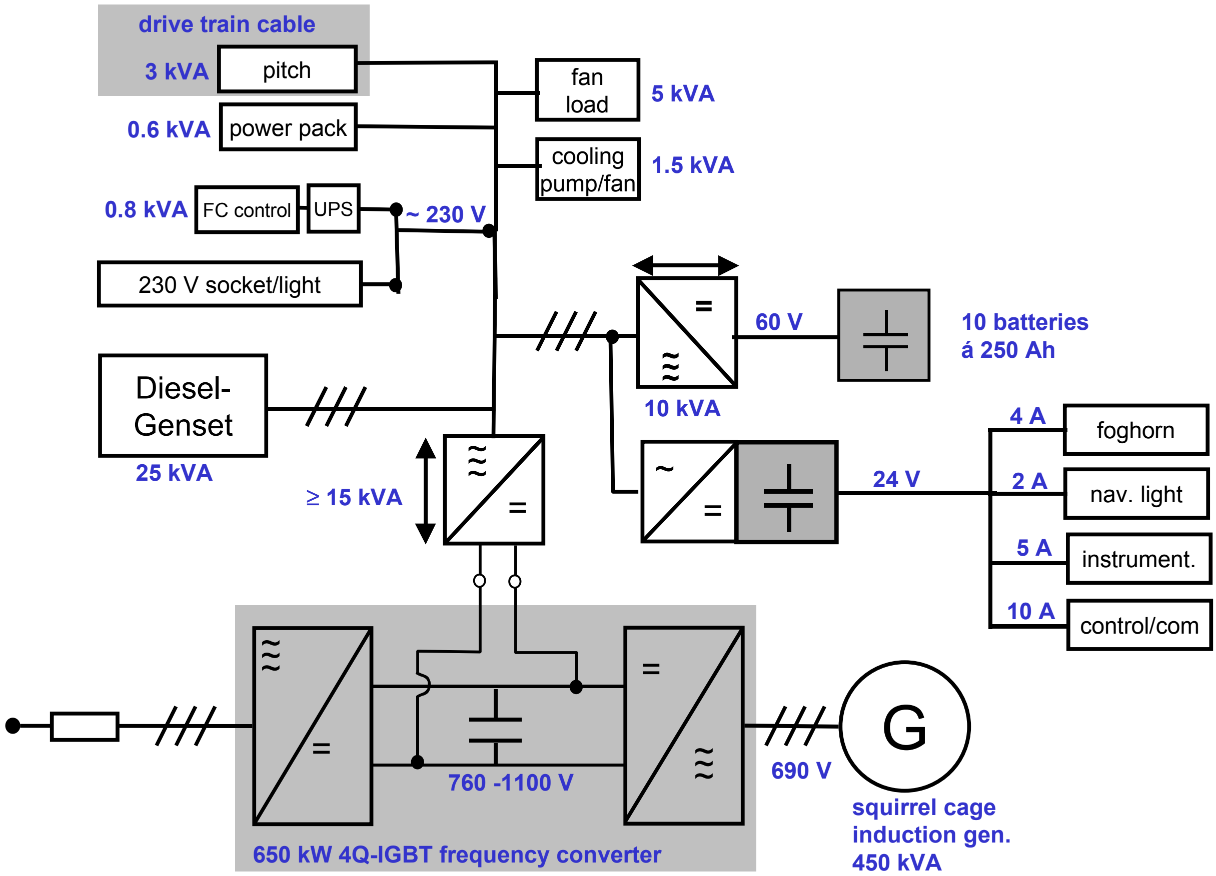


Figure 5: Electrical block diagram.

4.3.5 STRUCTURE AND FOUNDATION

The main structural element of SEAFLOW is the tubular steel pile. This carries weight of all the other components, the operating forces on the rotor, and environmental loads. A maximum diameter and weight were imposed on the pile design by the capabilities of the jack up barge used to install it. Working within these limits, the pile was designed to carry all the loads with an acceptable life. The pile is a steel tube 2.1 m in diameter, weighs 80 tonnes, and is 42.5 m long.

Geotechnic information from the site indicated that there was sufficient strength in the seabed to drill a self-supporting hole, or ‘socket’, into which the pile could be grouted in place. However, an attempt to drill such a socket in September 2002 found the material to be locally fractured and weak such that it collapsed into the hole, and the attempt had to be abandoned. This led to a revision of the foundation design, with a steel casing being used to line the socket. A further spigot was inserted, as a precaution, into the seabed below the casing, to provide sufficient foundation strength for the apparently weak material. This arrangement was installed in the summer of 2003, and an exceptionally good, strong foundation was achieved; it is possible that the first attempt was unfortunate in hitting a local weak spot.

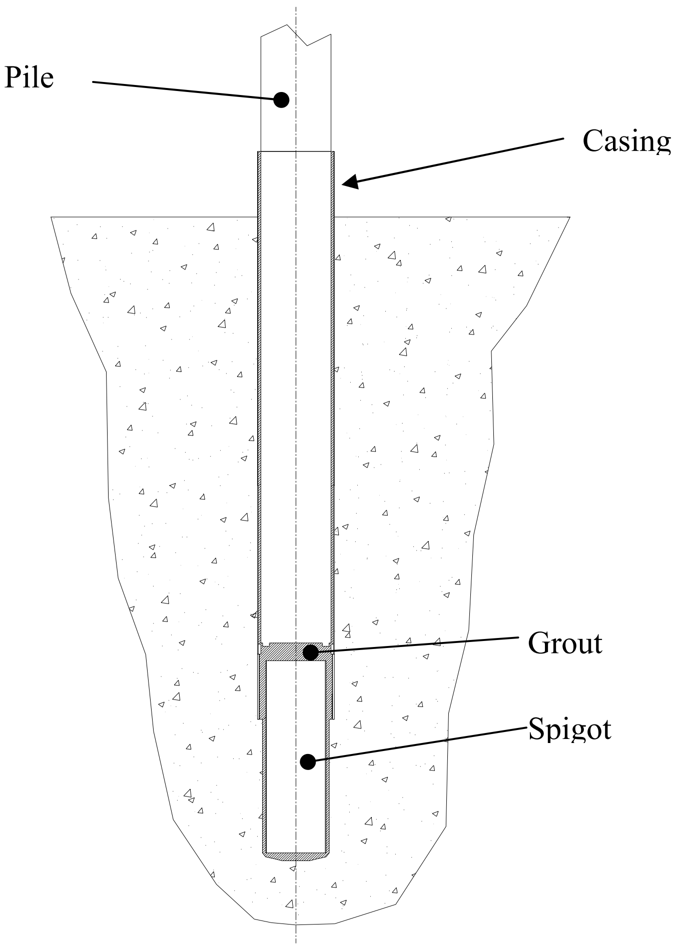


Figure 6: SEAFLOW foundation.

The collar that supports the power train is made of structural box and universal beam sections. It slides up and down the pile on plastic pads. The collar is attached to a steel tube which passes up through the pod. A lifting mechanism consisting of two hydraulic rams and an arrangement of pins and holes is used to jack the collar up or down in steps. The lifting tube also carries all the cables and services from the pod down to the collar; these services have to be disconnected from the top of the tube before the collar is lifted.

A second tube runs from the pod down an attachment point on the pile below the collar. This has a ladder attached to it, and is used to access the turbine. It is positioned towards off the centreline of the turbine so that a RIB can be brought up alongside it in a current, and staff can transfer safely from the RIB to the ladder.

The final structural element is the pod. This is a simple steel frame, clad with thin steel sheet. The pod houses the lift mechanism, the main electrical and control components, and all the ancillary systems. A foldable hydraulic crane is fitted to the roof of the pod for maintenance of the turbine.

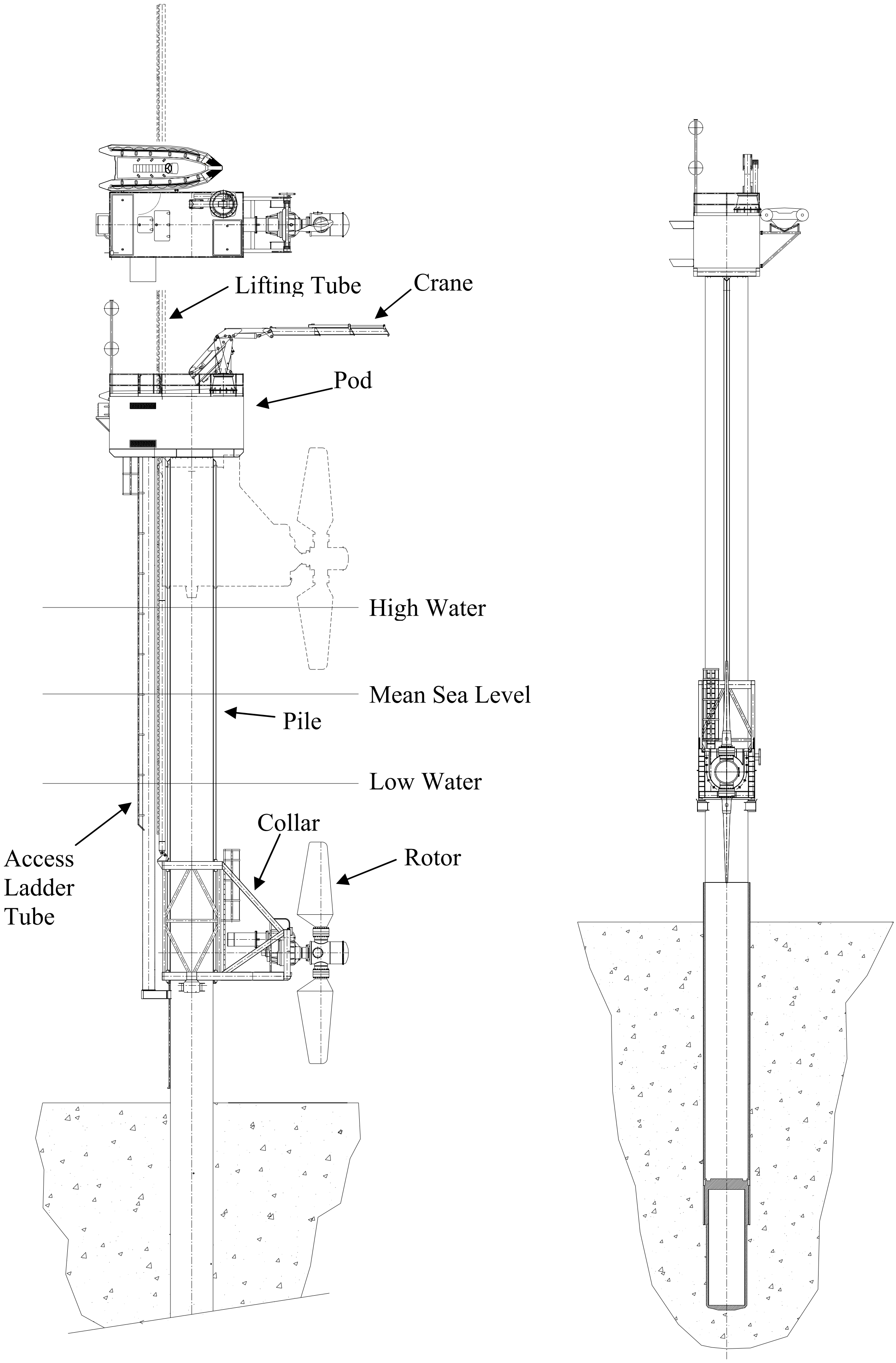


Figure 7: General arrangement of the SEAFLOW turbine.

4.4 MANUFACTURE, ASSEMBLY AND TESTING

The manufacture of the SEAFLOW turbine involved thousands of components and numerous manufacturers and suppliers. The main structural fabrications for the turbine were made by Bendalls Engineering, a partner in the UK DTI SEAFLOW project. This was done at Bendalls' factory in Carlisle, in the Northwest of England. All the steel for the project was supplied by Corus, the Anglo-Dutch steel manufacturer, which was also partner in the DTI part of the project.

The SEAFLOW turbine is located in an offshore environment, where conditions are rough and access is difficult. Reliability is crucial, and it was therefore important that, as far as possible, all the turbine components were tested and proven onshore. The full electrical power system was tested in ISET's 'Demotec' laboratory in Kassel. As shown in Figure 8, the various components were laid out as they would be installed in the pod.

Figure 8: Electrical system testing at ISET.

Figure 9: Submergence test for the power train on the quayside at Swansea.

In a quayside test, the complete power train was submerged to a depth of ~9 m, as shown in the photos in Figure 9. The cables between the power train and the pod were left connected so that the hub could be monitored for leakage, the pitch control could be operated underwater, and the system pressurised. The assembly was submerged for 24 hours, and then removed. The various components were opened, and no sign of leakage was detected.

4.5 INSTALLATION

Seacore is internationally recognised for installing large diameter monopiles, and took the responsibility within the project for designing and installing the monopile on which the turbine is mounted.

Tidal turbines present a challenge for offshore marine construction because of the need to work in water that is both deep and fast flowing; there is generally little call for construction work in such conditions. Currents impose significant drag loads on the legs of a jack up, and may also induce vibrations in the whole structure from vortex shedding off the round legs. Seacore undertook a number of detailed studies to assess these effects, and this led to modifications being made to the largest jack up barge Seacore then possessed, Deep Diver, to improve its strength and stability. Even so, Seacore had to impose limits on the operating envelope, which restricted both the depth in which the turbine could be installed, and hence the maximum rotor diameter. When Deep Diver was jacked up at the site, special farings were fitted to legs to lower the drag on them and to prevent any resonant vibrations due to vortex shedding; the top of these farings can be seen in Figure 10.

The SEAFLOW turbine was installed over the period 9 April – 2 June 2003. This was longer than expected, but was extended by several periods of severe bad weather. The foundation (see Figure 6) was made using a drill-drive technique to fix the casing into the seabed. In this way the installation method could cope with whatever ground conditions were found.

Figure 10: Seacore's Deep Diver jack up barge drilling the socket for the SEAFLOW foundation.

With the casing in place, a smaller diameter socket was drilled for the foundation bottom spigot. The spigot was then fixed by holding it in the socket, and injecting grout into the space around it. Finally, the pile was lifted into the casing, and the annulus between it and the casing was also injected with grout.

Figure 11: Semi-buoyant lift of pile into the casing.

After the grout had cured to achieve sufficient strength to hold the pile, the rest of the turbine was assembled.

Figure 12: The completed turbine, with collar raised.

The completed turbine is shown in Figure 12, just after Deep Diver had left site. In the photograph the collar is raised, though it would normally be submerged and not visible. Note the lifting tube projecting above the pod when the collar is raised. The maintenance crane is on the near corner of the pod roof. The cradle on the right side of the pod is for the RIB used to access the turbine. Stored on the roof of the pod are various platforms used to service the rotor, and a man basket.

4.6 COMMISSIONING, TESTING AND MAINTENANCE

Immediately after installation, there was an intense period of work to commission all the systems of the turbine. As with most prototypes, numerous small problems were encountered, and each had to be diagnosed and resolved in turn before the machine could be run.

The first phase of the testing was done with staff on the turbine, to gain familiarity with the operation of the device and to ensure that any significant problems could be rapidly identified and dealt with. Being present in the pod meant that operators had access to all the instrumentation, could hear the turbine and feel movements of the pile, and were present to resolve any problems that did occur.

Early testing involved running the turbine in moderate currents and reasonable weather, to ensure that the loads and dynamic response were within design limits. As the turbine was proved, it was run in progressively higher currents. For two series of tests, a special current meter (an ADCP or Acoustic Doppler Current Profiler) was deployed ahead of the rotor, giving readings of current speed through the water column from the surface to the seabed.

Regular testing in a variety of conditions has generated large amounts of data, and has greatly improved the understanding of the functioning of the turbine. The results are discussed below in Section 5.

Alongside the test programme, regular visits were made to the machine to ensure that everything was in good working order, to inspect the working components and structure, and to carry out both routine and necessary maintenance.

The only major repair needed so far has been to the gearbox. A lubrication problem led to some noise from one of the high-speed bearings. Internal inspection of the gearbox revealed some internal damage, so the rear of the gearbox was removed using the on-board service crane and transported to shore on a small workboat. The cause of the problem was readily identified by the gearbox manufacturer and rectified. The repair proved the usefulness of the pile-mounted turbine concept for easy access for both planned and unforeseen work.

5 RESULTS

The first, and most obvious, result of the project is that a working prototype tidal turbine has been installed. The machine has survived a winter at sea, including several gales, and continues to work well.

In line with the original objectives, the installation was achieved without the use of divers, with all operations carried out from the jack up barge. A robust foundation has been made with good structural integrity.

The turbine installation was completed in June 2003, and it took a couple of months, to August 2003, till the various systems had been commissioned and the turbine ran reliably. The EC support for the SEAFLOW project ran from September 1998 to August 2003, though the UK government sponsored component of the project continued through into 2004. The turbine was therefore only just producing results by the end of the EC contract period. This report has been delayed so as to include some comments on the first testing results, but considerable further work is planned for the summer of 2004. What is presented here is therefore a preliminary understanding of the machine.

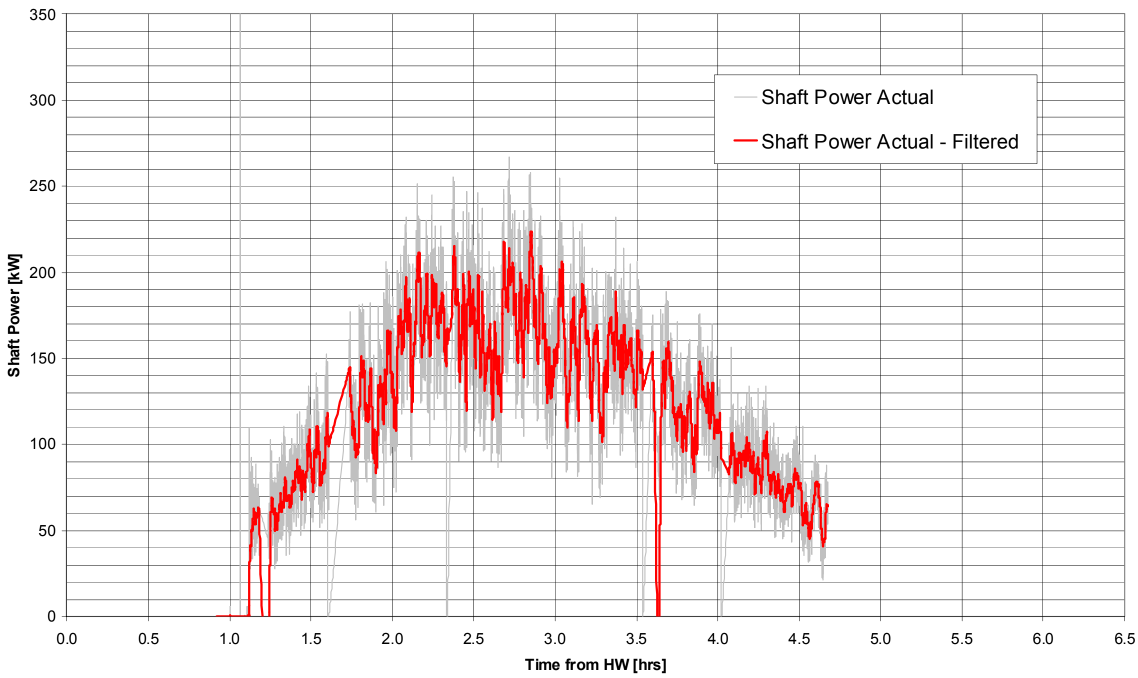
Various test runs have been conducted, including two periods of detailed testing during spring tides in the autumn of 2003, when a boat-mounted current meter was used to examine the flow into the rotor. Remote control of the turbine was not achieved in 2003, so the turbine was only run manually during the winter when weather allowed access to the pile. The turbine was run for a total of around 30 days during this period. More concentrated work began again in spring 2004 as the weather improved, with remote operation achieved in May. This will allow much more consistent testing to be undertaken in a wider range of conditions.

The turbine has a current meter attached to the collar, but testing has shown that this does not give adequate characterisation of the flow. The collar-mounted meter is influenced both by the collar structure and the operation of the rotor, and since it only measures the current at one point it does not show the change in velocity over depth or the turbulence in the flow. For this reason, a boat-mounted current meter (acoustic Doppler current profiler, or ADCP) was deployed up-stream of the turbine for two spring tides in the autumn of 2003, and it is planned to deploy a seabed-mounted current meter in the summer of 2004 to further the understanding of the performance of the turbine.

5.1 TEST RESULTS

5.1.1 ROTOR POWER OUTPUT

The turbine has achieved peak electrical power just under 300 kW. The rotor has been found to be more efficient than predicted, but the hub-height current is somewhat lower than expected, leading to peak power levels that are a little less than the rated 300 kW.



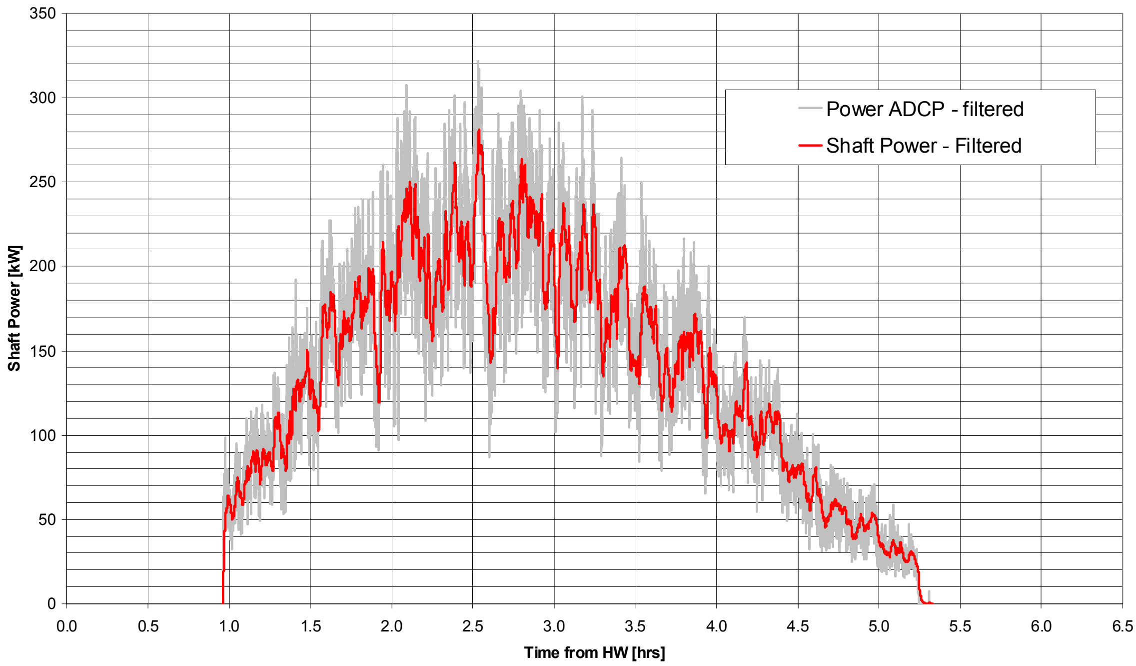


Figure 13: Typical test run results through and ebb cycle, rotor shaft power versus time after high water.

Typical test results are shown in Figure 13. These show the power output curves against time during two ebb tides. The upper curve shows one spring ebb tide in August 2003, the lower curve shows a larger spring ebb tide in October 2003. The graphs show both unfiltered data, which has a lot of spread, and filtered data, which gives a better indication of the average power; the fluctuation in power is discussed later. The power output is given as rotor mechanical shaft power.

5.1.2 TURBULENCE AND POWER FLUCTUATION

It is immediately obvious from Figure 13 that the power output of the turbine is not steady. There are variations of up to 30-50 kW, apparently randomly, with no particular period. The main reason for this is actual fluctuation in the power in the water flowing into the rotor. Figure 14 shows a typical curve for the energy flow into the rotor, from a 5-minute period of operation. This is calculated from the hub height current velocity as measured by an ADCP current meter. The variation appears to be due to turbulence in the water, similar to the power fluctuation found in wind turbines.

There are two other short period fluctuations that can be seen in the turbine output:

- Pile and current effects, related to the rotor speed. The pile slows down the water immediately ahead of it as it forces the current to go to either side around it. Also, each blade is passing from near the seabed up to the near the surface and back again. These effects introduce a periodic variation as each blade travels passes in front of the pile, roughly every 2 seconds.

- Control system oscillation. The rotor speed is controlled by the frequency converter, which works by adjusting the torque on the generator. This system has a certain stiffness, making the power output vary.

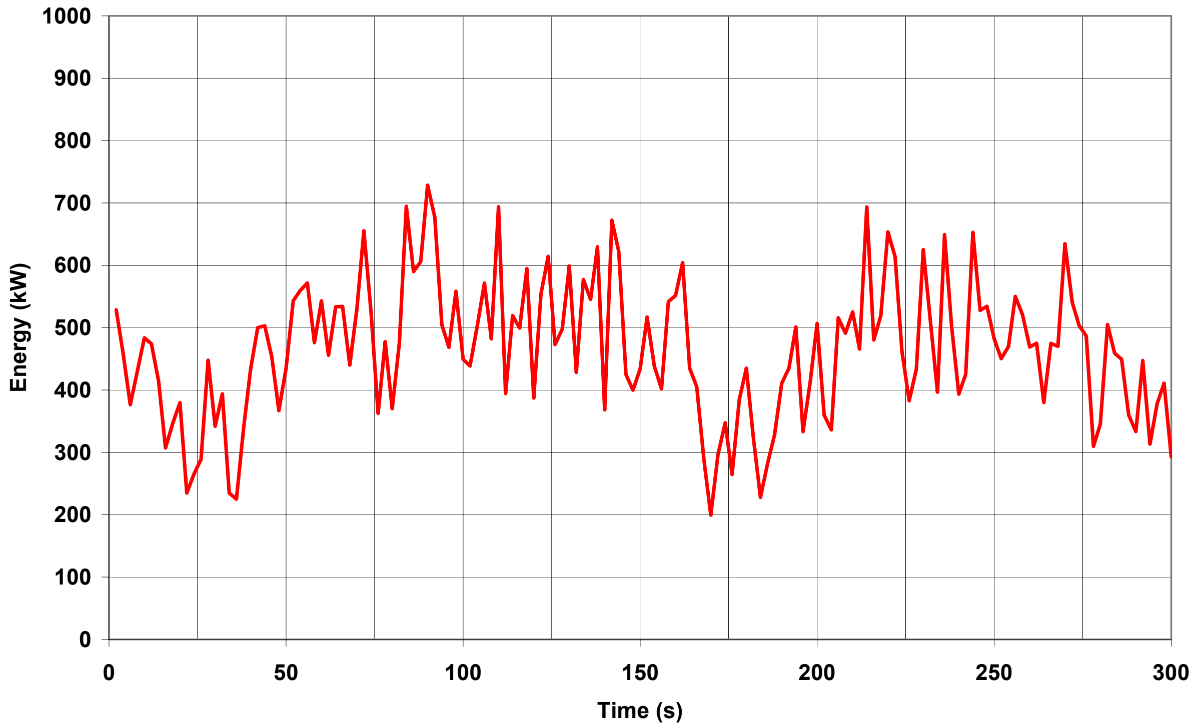


Figure 14: Typical time history of energy flow into the rotor.

Figure 15 shows a typical graph of the current at the turbine hub height. There are three curves:

- The black line, showing predicted current from tide tables, assuming a sinusoidal variation through half a tidal cycle, peak current proportional to tidal range.

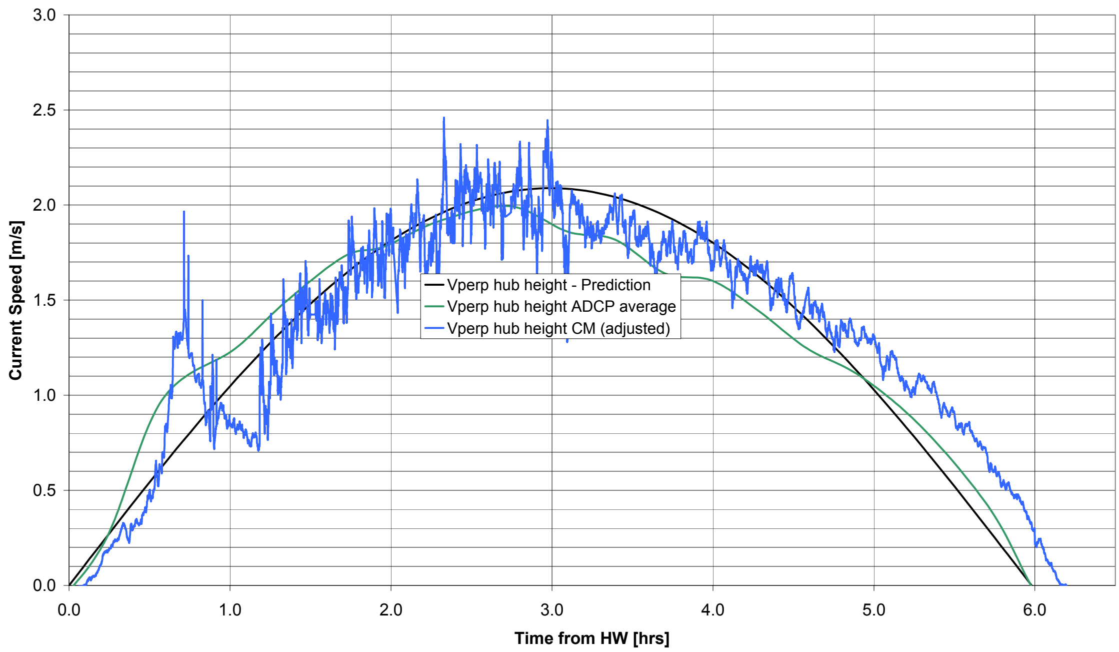


Figure 15: Current at hub height, ADCP, current meter and predicted.

- The green line, showing the averaged results from a boat mounted ADCP ahead of the turbine.
- The blue line, showing the output of the current meter on the collar, reduced to allow for velocity shear, and adjusted to allow for the reduction in velocity caused by the rotor when it is running. In this case, the turbine ran for only the first half of the cycle, up to the peak current.

From studying the graph a number of points can be deduced:

- There is a lot more fluctuation in the blue line during the first half of the cycle, which is to be expected as the rotor is running for this period, and the meter is downstream of the rotor.
- The predicted velocity is a reasonable estimate of the actual current, but not perfect.
- Both the current meter and, to a lesser extent, the ADCP, show a 'blip' at the start of the cycle, a period of raised current, which is not fully understood, but seems to be a peculiarity of this location.
- Both the ADCP and current meter readings show the peak predicted current to be slightly optimistic, around 0.1 m/s greater than the actual.

The SEAFLOW test results obviously only examine one location. It is not clear whether these flow characteristics are generic, or whether other sites may be different. It is possible that other sites may be more uniform, or they could be more turbulent. Clearly detailed survey work is required into the nature of current flow in a particular area before tidal turbines are installed.

5.1.3 ROTOR PERFORMANCE AND ENERGY CAPTURE

The rotor has been found to perform better than the computer model predicted. Considering the energy capture over an ebb tide on a mean spring cycle, the turbine has produced over 25% more power than the model predicts. This shows that further work is needed on the model, with a better understanding of the flow conditions derived from SEAFLOW.

It should also be noted that the SEAFLOW rotor is by no means optimised. Rather, the foil sections, the chords and the twist were chosen primarily for ease of manufacture. It is expected that future rotors will be able to show even higher efficiencies.

5.2 LESSONS LEARNED

SEAFLOW is a research project, and the aim of building a prototype marine current turbine was to learn both how such a machine would perform and how such an installation might best be achieved. While the fundamentals of the machine concept have not altered, many aspects of the design have changed during the course of the project, as the partners have learnt what is and what is not possible, and discovered better ways of achieving the end results. The sections below describe various lessons learned during the project.

5.2.1 TURBINE DESIGN

5.2.1.1 Site Conditions

It is not possible to tell yet how representative the Lynmouth site is of possible tidal turbine sites. It may be typical, but equally it may be that the flow conditions are different in different locations. It is clear that detailed site survey and modelling of currents will be required to determine flow regimes for commercial machines.

5.2.1.2 Visual Impact

Compared with a wind turbine, SEAFLOW stands very low in the water. Nevertheless, it is clearly visible even from 3-4 km away, and when seen from sea level it is quite noticeable, more so perhaps than photographs tend to indicate, as the eye is drawn towards it in an otherwise featureless sea. While the local people in and around Lynmouth have remained generally very supportive of the project, the only reservations expressed about developing from SEAFLOW to a farm of turbines on the site have been that the visual impact could be unacceptable.

The SEAFLOW turbine has two disadvantages in this respect. Firstly, not being grid connected it has considerably more equipment in the pod than would be required normally, making the pod disproportionally large. Secondly, the tidal range of around 10 m at that point in the Bristol Channel means that the turbine stand 15-20 m above the water at low tide, far more than would usually be the case. Nevertheless, it is clear that future machines must be made as unobtrusive as possible.

5.2.1.3 Pitch Control

Full blade pitch control was used successfully. This allows the turbine to respond to the change in current direction between ebb and flow by pitching 180°, and it provides a smooth, gentle way of braking the rotor. In addition, it allows the pitch to be adjusted for optimal performance over a range of current speeds, and can be used to accurately limit the load when the current exceeds the rated value.

5.2.1.4 Marine Growth

The rotor blades are protected with a proprietary antifouling paint that contains particles of copper in an epoxy base. The rotor hub has a different copper-based antifouling paint coating. Both have proved effective to date, with no signs of marine growth.

Small barnacles have begun to grow on the untreated paintwork of the collar, and seaweed is growing on the pile, access tube and ladder around the low water mark. Overall, there has been surprisingly little fouling of the turbine.

The structure is protected from corrosion by zinc anodes welded onto the pile. These sacrificial anodes have reduced noticeably in size, and so are obviously working to prevent corrosion on the steel.

5.2.1.5 Cables and Connectors

The cabling for SEAFLOW was both more expensive than expected, and has been a regular source of small problems. The high currents found around the turbine mean that any length of cable that is not securely fixed is liable to be moved by the currents and may chafe against the structure. Cable junctions, entry and exit points all are potential leak paths.

5.2.2 INSTALLATION

5.2.2.1 Site Investigation

The first attempt at installing the SEAFLOW pile failed because the ground conditions were much softer than expected. Information had been gathered from bores near the site, and published geological data, but this proved inadequate. It is advisable that a site investigation is carried out before the foundation is designed, even though such an investigation is expensive.

5.2.2.2 Installation Equipment

The jack up barge used to install SEAFLOW was at the limit of its operating capabilities, despite being one of the larger, most capable barges available at the time. The size of the SEAFLOW rotor and the depth in which it was installed were all limited by the capacity of Deep Diver. It is clear that larger equipment, able to work in higher currents and greater depths, will be required for future installations.

Such equipment is becoming available, as purpose-built vessels are made for offshore wind, and Seacore has a new barge, Excalibur, that extends its capabilities. However, offshore wind farms are not generally placed in areas of high currents, and further development work is needed to understand better how to work in a tidal site.

5.2.3 OPERATION AND MAINTENANCE

5.2.3.1 Access

Figure 16: Access, showing the access ladder on separate tube to the pile.

SEAFLOW is in a genuinely offshore site, experiencing the full brunt of ocean weather. While it is protected by land to the South, it is fully exposed to the prevailing westerly and south-westerly wind and waves, unlike other prototypes tested to date. This means that it can be used to test for real conditions, but it has also meant that access is not always possible. The basic approach adopted for SEAFLOW of using RIBs for access, and having a protected ladder to climb onto, has proved workable and safe.

5.2.3.2 Maintenance

An integral part of SEAFLOW is the lifting mechanism, which allows the collar and power train to be lifted out of the water for inspection and maintenance, without the need for additional equipment. The turbine also has an onboard crane that can handle any of the power train components individually. These features have proved invaluable, allowing some major maintenance to be done on the gearbox, and numerous minor jobs.

The difficulties of access to offshore machines mean that reliable remote operation, remote fault diagnosis, and condition monitoring will be essential.

6 CONCLUSION

The SEAFLOW turbine has been successfully installed and operated. It has proven the basic physics of power extraction from tidal flows, and shown that useful electrical power can be generated from horizontal-axis turbines. Furthermore, it has shown that there are considerable advantages in mounting the turbine on a fixed structure, and in being able to readily access the machine for maintenance without underwater operations.

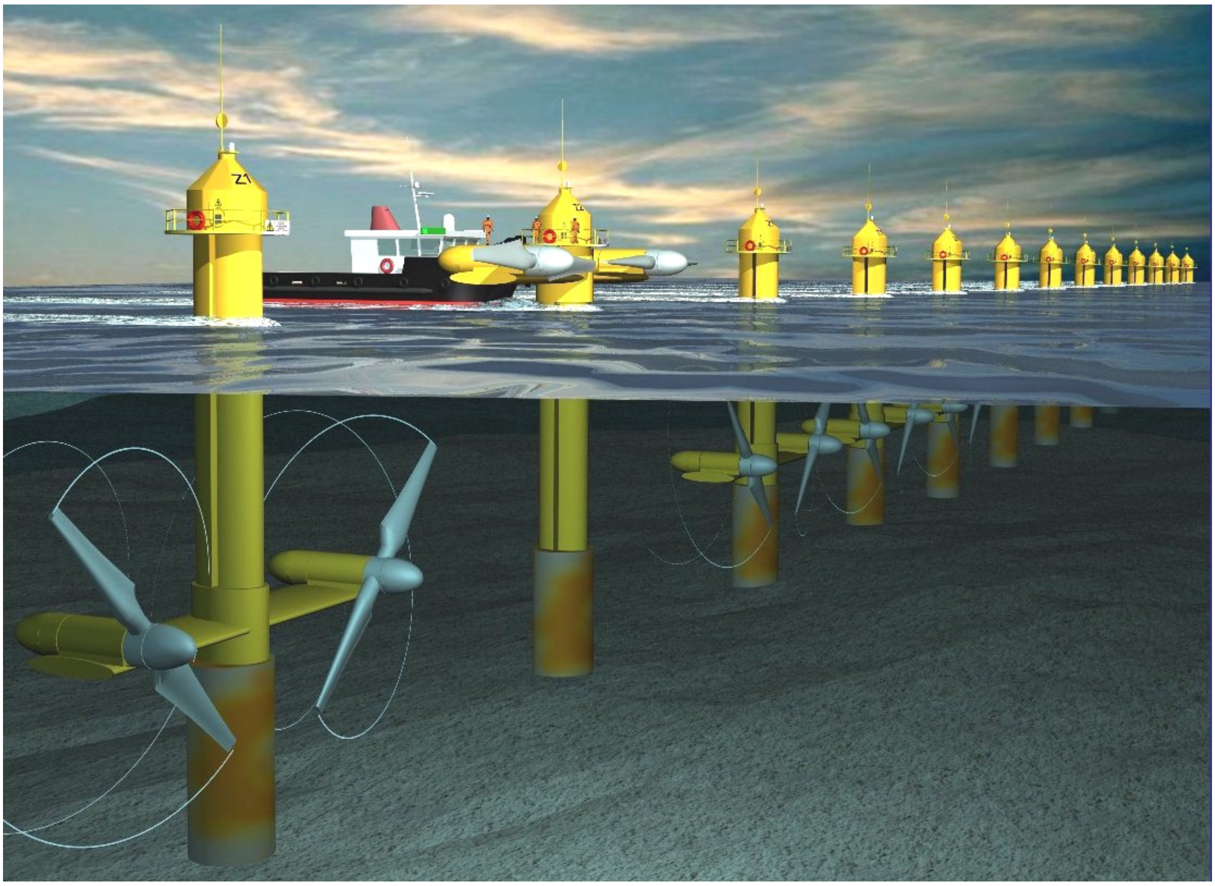


Figure 17: Artists impression of a future farm of twin-rotor marine current turbines.

The partners are now planning to design a larger, pre-commercial turbine. This will have two rotors, each generating at least 500 kW, to give a 1 MW rated output. The twin-rotor concept means that more power can be achieved from a single pile installation – reducing costs, and it also keeps the rotors away from the pile wake for regular bi-directional operation.

A dedicated company has been set up by the partners, Marine Current Turbines Ltd[3] to take forward the development of the technology. It will co-ordinate the work on the next turbine, and is progressing towards producing commercial machines. Figure 17 shows what a future farm of such turbines may look like, with one machine raised for servicing.

[3] www.marineturbines.com

ANNEXES

Annex I

LIST OF ABBREVIATIONS, GLOSSARY OF TERMS, ETC.

ADCP	Acoustic Doppler Current Profiler
Bathymetry	The topography of the seabed
BEM	Blade Element Method, simplified calculation technique for turbine rotors
Benthos	Seabed flora and fauna (cf. benthic)
BMU	Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety)
BMWi	Bundesministerium für Wirtschaft und Arbeit (Federal Ministry of Economics and Labour, replacing BM Wirtschaft und Technologie)
CCL	Climate Change Levy, UK tax on business use of fossil and nuclear energy
Cetaceans	Whales, dolphins and porpoises
CFD	Computational Fluid Dynamics
CPA	Coast Protection Act (CPA), UK, 1949: legislation covering environment and marine usage aspects of permission for construction at sea.
DEFRA	Department for Environment, Food and Rural Affairs, UK (replaced MAFF, Ministry of Agriculture, Fisheries and Food)
DfT	Department for Transport, UK (replaced DTLR, Department for Transport, Local Government and the Regions, which was DETR, Department for the Environment, Transport and the Regions)
DGPS	Differential or more accurate form of GPS
DTI	Department for Trade and Industry, UK
EC	European Commission
EIA	Environmental Impact Assessment
Elasmobranchs	Cartilaginous fishes, the group of which includes sharks, rays and skates.
EPSRC	Engineering and Physical Sciences Research Council, UK
FEPA	Food and Environment Protection Act, UK, 1985: legislation covering navigational aspects of permission for construction at sea.
GPS	Global Positioning System, position location system using signals from satellites
HAWT	Horizontal Axis Wind Turbine
IEE-RE	Institut für Elektrische Energietechnik - Rationelle Energiewandlung, University of Kassel, Partner in SEAFLOW Project
IPR	Intellectual Property Rights: patents, copyright, etc.
ISET	Institut für Solare Energieversorgungstechnik, affiliate of University of Kassel, working with IEE-RE on SEAFLOW Project
Isopachyte	With equal depth of sediment covering
ITP	IT Power, Co-ordinator of the SEAFLOW Project
Ja)(Ke	Jahnel-Kestermann, partner in the SEAFLOW Project
LAT	Lowest Astronomical Tide, usually approximately the same as Chart Datum
Littoral	Shore, more specifically the zone between high and low water exposed by the tides
MCT	Marine Current Turbine

MCT Ltd	Company established by IT Power for the commercial development of tidal turbine technology
Mean Neap	The average of all neap tides; half of all tides in a year are classified as neaps, the remainder are springs.
Mean Spring	The average of all spring tides
MHWN	Mean High Water, Neap
MHWS	Mean High Water, Spring
MLWN	Mean Low Water, Neap
MLWS	Mean Low Water, Spring
MSL	Mean Sea Level
NaREC	New and Renewable Energy Centre at Blyth, Northumberland, UK
Neap tides	Tides with minimum level change and speeds
NETA	New Electricity Trading Arrangements, introduced in Utilities Bill in UK, 2000
NFFO	Non-Fossil Fuel Obligation for the purchase of renewable energies at preferential rates in UK
Pinnipeds	Seals and sea-lions
REC	Regional Electricity Company
RET	Renewable Energy Technologies
RIB	Rigid Inflatable Boat
ROV	Remotely Operated Vehicle, un-manned submarine vessel
SHEFC	Scottish Higher Education Funding Council
Spring tides	Tides with maximum level change and speeds
Sublittoral	Shoreline below the level of low water
VAWT	Vertical Axis Wind Turbine
WAPTAP	UK DTI's Water Power Technology Advisory Panel
WEC	Wind Energy Converters, wind turbines
WTG	Wind Turbine Generator, alternative term for wind turbine

European Commission

EUR 21616 — SEAFLOW - *World's first pilot project for the exploitation of marine currents at a commercial scale*

Luxembourg: Office for Official Publications of the European Communities

2005 — 34 pp. — 21.0 x 29.7 cm

ISBN 92-894-4593-9

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KI-NA-21616-EN-C

This brochure is the final publishable report of the project SEAFLOW funded under the fourth RTD Framework programme (1995-1998). The project demonstrated the technical feasibility of converting energy from tidal current stream to electricity using conventional technologies in a rough under water environment. A 300 kWe prototype was installed near Lynmouth in North Devon (UK). The testing proved the validity of the concept and highlighted the research needed to bring it to the market place. The CENEX study, funded under the third RTD Framework Programme, showed that at least 48TWh could be exploited easily.

Publications Office
Publications.eu.int

ISBN 92-894-4593-9
9 789289 445931