HYLOW
End of Project

PUBLISHABLE SUMMARY

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Editors:	Dr. Gerald Müller
	Dr. William Batten

TABLE OF CONTENTS

SECTION 1.EXECUTIVE SUMMARY

The exploitation of renewable energy is today an environmental requirement as well as a political objective. Hydropower with very low head differences below 2.5 m is a significant potential source of renewable energy. However, due to the lack of an economic and ecologically effective hydropower converter, this resource is so far mostly unused. Recent theoretical developments in the field of hydropower machinery opened the possibility to exploit this field. Within the project Hylow, these concepts were employed to develop novel hydropower converters for three different applications:

1. Run-of-river, with head differences between 1 and 3 m
2. Exploitation of river currents
3. Energy in water supply systems / pipelines

The Hydrostatic Pressure Machine (HPM) for river applications with head differences between 1 and 3 m was developed using theoretical work, physical and numerical modelling. The results of this work were then used for the design of two field installations of 5 kW and 10 kW power rating and 1.20 m head difference. Both field installations were built and tested, whereby the 5 kW machine (River Lohr, Germany) was connected to the grid, the 10 kW was a stand-alone installation at a river weir (River Iskar, Bulgaria). Mechanical efficiencies ranged from 0.5 to 0.82 for a flow range of 0.4 to 1.0 Q/Q_{Desin} (River Iskar installation), and electrical efficiencies from 0.5 to 0.65 (River Lohr). In both installations the downstream, water level was low, leading to reduced efficiencies – a fact which was only later demonstrated in laboratory experiments. The ecological characteristics of the machines were found to be very favourable. A run-of-river HPM deflects the main sediment flow around the installation, avoiding accretion problems. Sediment which enters the HPM can pass it easily. Fish passage studies indicated that only 25% of the downstream migrating fish choose the HPM for passage. Mortality for fish with lengths less than 160 mm was only 1.4%, injury rates were 5%, significantly less than comparable low head turbine types. The simplicity of the HPM indicates good cost-effectiveness.

The floating or Free Stream Energy Converter (FSEC) was also initially assessed in model tests. A 7 m long, 2.4 m wide prototype was built and tow-tested in a harbour. With 32%, efficiencies were good for a kinetic energy converter at only 1.5 m flow velocity. Further fundamental tests indicated that a stationary converter in a current would have an increased efficiency compared with towed tests so that overall efficiencies of 40 to 48% could be expected for a river situation. Further tests in a narrow river focussed on the ecological compatibility, which was found to be very good. Micro-turbines for energy generation from pressure drops in drinking water pipelines were developed. Initially, turbines and positive displacement (PD) concepts were investigated. It was found that PD converters led to unfavourable pressure surges and turbines were therefore investigated further. Based on tests and CFD models, a 5 blade turbine was designed and tested in a real water supply system. With efficiencies of 40 to 80%, and comparatively low costs, such turbines were found to be economically very attractive (Return-on-investment less than four years).

With the completion of the Hylow project, three new types of hydropower converters for very low head differences have been developed and demonstrated up to electricity production for the grid. Concepts have been shown to be effective, economical and ecologically compatible.Environmental Concerns / Water Framework Directive

SECTION 2.SUMMARY DESCRIPTION OF PROJECT CONTEXT AND OBJECTIVES

1. INTRODUCTION

In Europe, there exists an unused (i.e. 50 to 1000 kW) hydropower resource in rivers of approximately 5 GW. In the UK, this potential with head differences below 2.5 m is estimated as 600 – 1000 MW, in Germany as 500 MW. Most of the available hydropower is available at existing weirs. Commercial turbine technology is considered not cost effective for these very low head differences. Kaplan turbines e.g. have very high efficiencies reaching 92%, but require large diameters and significant civil engineering structures in order to cope with the high flow volumes at low head differences. In addition, these turbines are considered ecologically not effective since they can cause physical damage to fish by either blade strike or low pressure. Other converter technologies offer some cost and ecological advantages over turbines, but have still not led to a wider application.

Low head hydropower schemes can have significant environmental impact at the local scale. In light of the EU Water Framework Directive, which requires that member states ensure aquatic environments meet "good ecological status", or "good ecological potential" if heavily modified, and the economic value of these ecosystems, continued development of hydropower must be environmentally sustainable. New hydropower developments must ensure river continuity. This can however not be done with existing technology and therefore requires innovative technological progress, i.e. the development of an economically and ecologically effective turbine or other type of energy converter.

2. PROJECT CONTEXT

2.1 HISTORIC CONTEXT

Hydropower with very low head differences below 2.5 m has been utilised for centuries; for several reasons:

- The construction of dams and weirs for low head differences is simpler and less costly than larger dams.
- Mechanical power was very valuable, and even small head drops or fast currents were therefore economical.
- Small natural falls in low land river reaches can be exploited.

A number of different hydropower converters established themselves for this hydropower segment; the type of machine built depended on head difference and, more importantly, the flow volume. Water wheels were employed for small, turbines for larger volumes. Technologies with increasing efficiencies evolved with the development of hydraulic engineering as a scientific subject. The interest in the subject disappeared in the 1950's to 1970's, with centralised large power stations becoming the prevailing solution. In recent years, with growing interest in all renewable energy sources, very low head hydropower has become attractive again and some new developments have appeared, whereby the increasing ecological awareness has meant that design criteria focus not just on power output and cost-effectiveness but also on ecological performance.

2.2 EXISTING TECHNOLOGIES

There are several turbine or hydropower converter technologies which are currently employed in the ultra low-head segment (H < 5m) as well as a number of experimental and proposed machines. The most frequently built turbine type are the Kaplan turbine, the Zuppinger water wheel and, a development of recent years, the Archimedes screw working in reverse as power generator.

Kaplan turbine: The Kaplan turbine is a propeller turbine which, in order to achieve good efficiencies for varying flow rates and pressure differences, has adjustable inflow vanes and variable pitch blades. The low-head Kaplan turbine is employed for head differences between 1.8 and 5 m, and power ratings from 10 to 1000 kW. The construction effort is comparatively high, since the turbine itself is complex, large diameters are required for low head / high flow situations and since complex civil engineering works are required. Costs range from 15 to 25,000 Euros per kW installed capacity. The ecological characteristics of the Kaplan turbine are a matter of discussion. Sediment cannot pass, and fish passing through the turbine suffer from mechanical damage (blade strike) as well as damage caused by low pressure in the turbine’s suction tube.

Archimedes screw: these machines are built for head differences from 1.2 to 10 m and power ratings from 5 to 300 kW. They have mechanical efficiencies of up to 80%. Fish passage downstream is possible and due to the low mortality and moderate injury rate they are considered as fish friendly. Sediment however cannot pass through the Archimedes screw. Costs range from 4,000 to 10,000 Euros per kW installed capacity (the lower price is for the higher capacity). Zuppinger water wheel: these wheels were developed in the 1850’s and have diameters from 4 to 7.5 m, Peak efficiency is 70 to 74%, and power ratings range from 3 to 100 kW. With 3 to 6 rpm the wheels have a slow speed, which means that expensive gearing is required. Costs range from 10 to 12,000 Euros per kW installed capacity. Sediment cannot pass through the Zuppinger wheel. No recent study of fish compatibility is available although old studies suggest that fish damage is significantly less that with turbines.

Despite the available market potential, none of the existing technologies has so far succeeded in establishing a larger market – very probably because of the costs involved combined with the ecological disadvantages of the individual technologies.

2.3 ENVIRONMENTAL CONCERNS /WATER FRAMEWORK DIRECTIVE

In order to improve the ecological status of rivers and lakes, the European Water Framework Directive has been introduced over the last decade. This legislation, and the resulting implementation guidelines requires e.g. the re-introduction of continuity in rivers. Most hydropower sites require a weir which with a head difference. The potential energy created by the head difference is then employed to generate power. Weir structures however interrupt the continuity of the river, with severe consequences:

- The sediment transport is interrupted, leading to accretion up- and erosion downstream of the weir.
- Fish migration up-and downstream is interrupted. This interferes with the river’s ecosystem and with the procreation cycles of migrating species such as salmon and eel.

Conventional turbines can damage a significant percentage of the fish passing through them, leading to increased mortality. All currently available hydropower converters do not allow for the passage of sediment so that the ecological effects of hydropower on rivers can be negative. This contradicts the requirements from the WFD, making the development (planning application) of the low-head resource very difficult.

2.4 ECONOMIC ASPECTS

The costs for currently available low-head hydropower converters lead to return-on-investment (ROI) periods of 11 to 24 years, making an investment in hydropower marginally or not economical. In particular the lower power ratings between 5 and 100 kW, which applies for the majority of sites, suffer from high unit costs and long ROI periods. Maintenance costs in particular for Kaplan turbines can affect the overall economy of an investment negatively.

2.5 NEW DEVELOPMENTS

Based on theoretical work, the concept of a novel low-head hydropower converter which employs hydrostatic pressure differences as driving force was developed recently. The machine – in its simplest form a type of water wheel with radial blades which runs in a slight curvature on the river bed – generates power and also acts as a weir, maintaining the water level difference between up and downstream. The concept leads to high efficiencies for low, and medium efficiencies for high flow rate. This makes the exploitation of highly variable flows which are typical for low-head sites more economical. The slow speed and large cells of the machines indicate that fish passage with low mortality and injury rates may be possible. The river bed remains continuous, so that sediment can pass the machine. Finally, the concept led to very simple machine geometries which indicate cost-effectiveness.

Currently, there is also a strong interest in the exploitation of the kinetic energy of river currents. Unfortunately, kinetic energy converters (and in particular the simple resistance-type machines) have very low efficiencies of 30% or less. Combined with the low energy density of typical flow velocities in rivers of 1.5 to 1.8 m/s (1.7 to 2.9 kW/m^2), this leads to great difficulties in the effective utilisation of this resource. The principle of the utilisation of hydrostatic pressure differences in combination with an artificially induced pressure drop in a free current situation could also allow for a more efficient energy conversion in river currents. Since river continuity is not affected by kinetic energy converters, their ecological characteristics are generally considered to be favourable. The transition of such a concept into real machines, involving not just engineers but also fish biologists and environmental engineers during all stages of the development has the potential to create a cost-effective and ecologically compatible hydropower converter for very low head differences.

3. PROJECT OBJECTIVES

The proposed project has the aim to develop and optimise a novel type of turbine for small hydropower (< 1000 kW) and very low head differences below 2.5 m, which is significantly more cost-effective than current technology, and minimises adverse ecological effects. It will therefore be compatible with the water Framework Directive. This novel turbine utilises hydrostatic pressure differences in free surface flows. It will be developed for three specific applications, namely the application in rivers (and in particular at existing weir locations), the deployment in free stream situations and the exploitation of very small head differences in water supply and distribution networks. In order to widen the potential area of application, the technology will be adapted for developing countries.

In order to achieve this aim, the following objectives have been defined:

- Investigation of generic configurations of energy converters using theoretical and physical models.
- Development of energy converters for three different applications using theoretical and numerical modelling and 2/3D physical model tests.
- Concurrent assessment of / design for minimised environmental impact in order to develop a design with minimum ecological impact.
- Optimisation using numerical modelling.
- Design and deployment of large scale models in nature to assess scale effects and environmental effects in a real environment.
- Development of designs with appropriate technology (developing countries).
- Design recommendations and design handbook.

4. CONCLUSIONS

In Europe there exists a significant but mostly unused resource of renewable energy in the small hydropower range with very low head differences, only part of which is even charted. One of the principal obstacles for the exploitation of this resource is the lack of an economically and ecologically effective turbine or other type of energy converter. Recent developments of novel concepts for energy conversion using hydrostatic pressure differences opens the possibility to develop cost-effective and ecologically efficient hydropower converters for head differences between 0 and 2.5 m. The project Hylow aims at the development of such converter technology based on novel theoretical concepts, and the demonstration of technical and ecological characteristics in the field.

SECTION 3. DESCRIPTION OF MAIN S & T RESULTS/FOREGROUNDS

PREAMBLE

The following document summarizes the main scientific and technological developments achieved within the project 'HYLOW'. For simplicity, it is organized alongside the work package structure. Work packages 1, 4, 6, and 15 are not listed since these work packages had managerial or construction tasks without S/T aspects. The figures and tables mentioned in the text are available in two separate attached documents

WP 2: CONVERTER TECHNOLOGY AND DEVELOPENT

2.1 WORK PACKAGE AIMS AND OBJECTIVES

Work package 2 has the aim to develop the theoretical and practical information required for the design and performance prediction of the Hydrostatic Pressure Converter for very low head differences in river application. Objectives:

- Development of more accurate theory, including turbulent losses
- Generic model tests to improve fundamental understanding
- Verification of generic model test at increased scale to assess scaling effects
- Determination of optimum geometry for HPM (economic / environmental efficiency)
- Assessment of HPM performance in a river situation (flooding, fish compatibility, sediment - transport)
- Identification of geometry for WP3
- Design, installation and monitoring of MSM
- Validation of optimised geometry

Therefore a more accurate theory was developed and a wide range of model tests with different scales in the laboratory and in the field were conducted. To assess environmental aspects like the fish compatibility, the possibility for sediment passage and flooding additional investigations took place. Based on all tests performance curves were determined and design parameters for the Hydrostatic Pressure Machine and its application were developed.

2.2 MAIN SCIENTIFIC AND TECHNOLOGICAL RESULTS

Two novel hydropower converters for very low-head differences were developed under WP2: The Hydrostatic Pressure Wheel (HPW) and the Hydrostatic Pressure Machine (HPM). Both machines employ the hydrostatic pressure difference between up- and downstream of a head drop as the driving force. The HPW is a simple wheel type machine with radial blades and is useful for sites with a head difference of 0.2 to 1.0 m (see Fig. 2.1a). The HPM has a hub at which radial blades are fixed that close the machine against the upstream water pressure (see Fig. 2.1b). This machine was developed for head differences between 1.0 and 2.5 m. The theory for both machines was developed further and loss effects like leakage and turbulence losses were included in the theory (see Senior et al., 2011). Using the theoretical framework, other hydropower converters for which no theory exists as yet were investigated as well. Theories could be developed for the Zuppinger and Sagebien-type water wheels as well as for the Archimedean screw (see Schneider et al., 2009; Müller and Senior, 2009).

a. HPW with a diameter of 800 mm

b. HPM with a diameter of 1200 mm

Fig. 2.1: Hydrostatic Pressure Converters

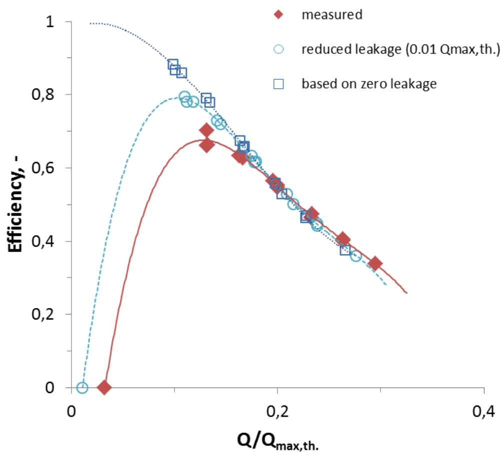


Fig. 2.2: Performance curves of HPM in flume (D = 1200 mm)

A wide range of test in different scales to assess the performance characteristics of these machines were conducted at the University of Southampton, the Technische Universität Darmstadt and in the field (MSM Partenstein). Experiments with three HPWs with diameters of D = 840, 1000 and 1800 mm confirmed the theoretical predictions and suggested cost-effectiveness of the wheel. Initial tests with a small scale HPM at the University of Southampton showed quite promising mechanical efficiencies of up to 81 %. Since the scale was quite small. the HPM was then built in a larger scale (D = 1200 mm) at TUD and tested in a 1 m wide channel to assess the effect of different blade geometries and of different wheel width to channel ratios under varying flow conditions and water levels. The model had a hub diameter of 0.40 m and blade depth of 0.40 m. Straight, curved and diagonal fixed blades were installed and tested. A HPM configuration with straight blades that are mounted diagonally with an angle of 20 degrees on the hub was found to give best performance. This installation has the advantage that the blades dip relatively steep into the upstream water surface and therefore cause the smallest turbulences on the upstream side. In addition water lifting on the downstream side of the HPM was prevented. A ratio of 1:2 between the HPM and the channel width was found to be ideal. This constellation allows water to fill the cell volumes not only frontally but also laterally. Therewith higher maximum flow rates can be processed and over a wider range of flow rates higher efficiencies are present. Further details can be found in Schneider et al.

(2011). The described optimum characteristics for the HPM were also determined with the numerical model that was set up in WP9.

With the described configurations and with a realistic reduction of gap losses to 1 % of the maximum theoretical flow rate mechanical efficiencies of up to 78 % could be reached (see Fig. 2.2). Leakage losses only played an important role in the lower flow rate range (< 0.15 • Qmax,th.) and lose their influence for higher flow rates respectively higher rotational speeds. Then, other losses like turbulence losses are dominant. The results from physical model tests agree reasonably well with the theory.

For a further improvement of the performance curves the effect of the downstream water level elevation and the effect of any installations in the direct downstream area of the HPM were investigated in detail. Different diffusors were installed in the downstream flume (see Fig. 2.3). Tests were run with an upstream water level at the top of the hub and two different downstream water levels (at full blade depth T and at half blade depth T/2).

In contrast to the importance of the downstream water level the upstream water level does not seem to influence the efficiency at all in the model scale (see Fig. 2.4). Since that finding was not observed in the field tests, it needs to be treated carefully. An explanation might be that certain losses don’t cause any measurable effect in a laboratory scale but have significant effects in large scale, e.g. losses due to entrapped air might increase disproportionally.

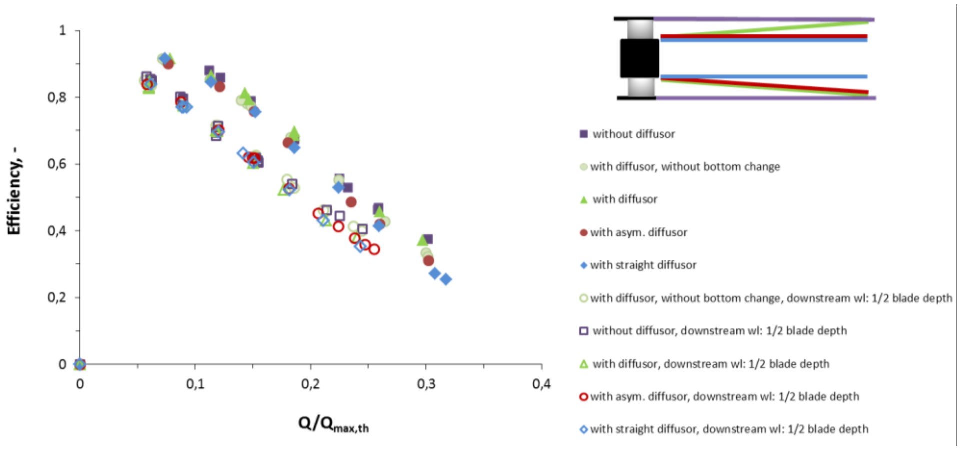


Fig. 2.3: Performance curves for different downstream water levels and different diffusors

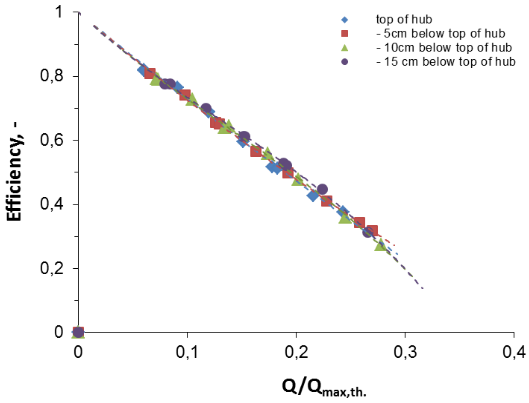


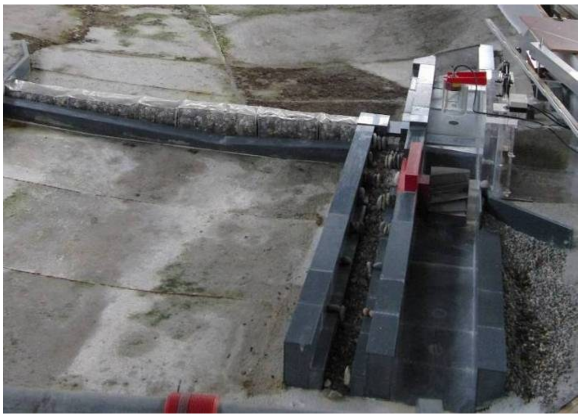
Fig. 2.4: Performance curved for different upstream water levels

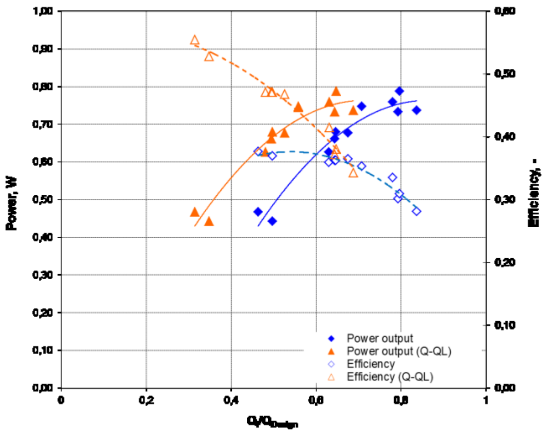
Based on a preliminary design derived from the model tests at TUD a HPM for the field installation in Partenstein was developed. The machine had a diameter of 2.45 m, a width of 0.82 m and a design flow rate of 0.635 m³/s was selected occurring at a rotational speed of 10 rpm. It was installed in an existing mill race where a head difference of 1.2 m was present. A full planning, permission and construction process was gone through in which all environmentally relevant issues like the residual flow rate and necessary measures to improve the river continuity were addressed. The MSM was grid connected and monitored for 10 months. Rubber flap-seals, approximately 10cm wide, supported by adjustable stainless steel back plates, are fixed to the edges of each blade. Further details can be found in Müller et al. (2012). During most tests current and voltage readings were taken directly from the output of the generator rectifier. The mechanical power output was derived from those readings with the help of characteristic values for generator and gearing of the manufactures. First tests started in June 2011. Unfortunately only a limited time could be used due to low flow conditions (lack of flow due to residual flow regulations) and interruptions due to necessary repair works (e.g. tooth belt replacement).

Electrical efficiencies of up to 68 % and mechanical efficiencies of 70 to 89 % for flow rates up to 0.81 Q_{Design} (low turbulences), in particular good for higher downstream water levels, were reached. For higher flow rates, efficiencies dropped rapidly. Up to a rotational speed of 7.1 rpm the wheels' movement was smooth. Higher speeds led to splashing at water entry and strong turbulences what was not anticipated from the model tests. Scale effects seem to be represented; air entrainment appears to be higher at full scale. Due to that effect an improvement of the inflow situation in terms of minimization of turbulences while the blades are entering the water is necessary. Due to the natural variation of the downstream water levels in Partenstein its importance was demonstrated very clearly. Like already observed during model tests higher downstream water levels significantly increase the efficiency. It appears during the field tests that the upstream water level affects efficiencies, with efficiencies increasing with lower water levels. That is an effect that was not visible in model scale. During the whole testing period gap losses could be kept relatively small (0.018 to 0.02 Q_{Design}) due to good sealings.

A 1:15 scale 3D physical model of the prototype installation at the River Iskar / Bulgaria was built in order to assess the stability of the gabion weir structure, the performance of the wheel in its real geometry including the optimization of the in- and outlet structure and the effect of the wheel installation on the sediment transport regime. Fig. 2.5a shows a view of the model. The HPM model had a diameter of 160 mm and a width of 133 mm. The design flow was defined as Q_{Design} = 2.0 m³/s.

The performance curves of the model show quite low efficiencies which are due to the downstream water levels close to zero (see Fig. 2.5b). That effect was also observed during the flume model tests and the field tests at river Iskar. There a mechanical efficiency of 0.41 for a flow rate of Qi = 0.6*Q_{Design} was determined. In the 3D physical model for a flow rate of Qi = 0.6 Q_{Design} a mechanical power output of 0.37 based on the measured flow rate and 0.41 for flow rates with reduced leakage were determined.





a. HPM installation (view from downstream) b. Performance curves

Fig. 2.5: HPM in 3D physical model (1:15)

The stability of the gabion weir structure could be shown in the model. Even for high floods the position and elevation of the gabions remained stable. The optimized inlet structure was determined with the help of the Particle Image Velocity (PIV)-method (see Hecht et al., 2011). A bell mouth shaped inlet was found to be optimal for the performance of the HPM. The effect of the installation on the sediment transport regime was determined within WP2a.

In addition to the hydraulic observations tests were conducted to determine fish behaviour in the proximity of the wheel, and the potential for sediment passage. Sediment and debris passage was investigated also in a flume at TUD. Sediment of different size and floating material were inserted upstream of the HPM with a diameter of 1.2 m for different blade configurations. The effect of the HPM on the movable particles was determined. Sediment that was getting into the influence area of the HPM was entrained and processed into the downstream water. Particles that were not getting into that area were pushed backwards and settled upstream of the HPM in zones of low to zero velocity. In order to force sediments through the machine zones with velocities close to zero should be prevented. Sediments that are passing the machine and are small enough don't jam the machine. Floating debris can enter the machine relatively easy.

In total three series of fish observations were done in the flume at TUD. The first test series was run with an HPM with simple straight blades. During the second test series curved blades and straight blades with rubber bands at the tip of the blades were installed. Finally the last test series was run with an HPM with reduced width. All test series showed the same trend. After a certain period of time all fish arrived directly upstream of the HPM and were only hindered by a safety screen to swim into the HPM. The arrival time was mainly depending on the fish species and the actual flow velocity in the flume. Fish were not banished by the noise, turbulences or waves created by the blades while entering the water body. Some fish were even searching for a passage way at the safety gutter. Since no living fish were allowed to pass the HPM, several fish dummies were used to demonstrate what might happen in that case. The highest injury risks seem to be that a fish might get hit by a blade or get caught between a blade and the bottom section. It seems that the shape of the blade did not have any influence on the approaching behaviour of the fish nor on the potential injury risk. The actual injury risk at a real hydropower site couldn't be estimated with the ethohydraulic tests in the flume at TUD.

This can only be determined with field tests (see WP3 and WP13). The following main results with respect to the machines performance were achieved:

1. An optimum geometry including curves for performance prediction was determined. In the model tests mechanical efficiencies of up to 78 and in the field test of up to 70 to 89 % were achieved.

2. A HPM configuration with 10 – 12 straight blades that are mounted diagonally with an angle of 20 degrees on the hub in combination with a HPM to channel width ratio larger than 1:2 to that side filling and ventilation is possible was found to give best performance.

3. Minimizing the gap between the tip of the blade and the curved bottom section with a flexible rubber band increase the available power output and efficiency significantly and reduces the risk of jamming of the machine due to sediments or debris.

4. The downstream water level should be as close as possible to the hub since lower downstream water levels lead to a decrease in efficiency.

5. The upstream water level should not exceed the level of the top of the hub. It is advisable to keep the water level lower and thereby reduce losses due to turbulences while the blade is entering the water surface especially for higher rotational speeds (based on results from field observations).

2.3 POTENTIAL IMPACT, THE MAIN DISSEMINATION ACTIVITIES AND EXPLOITATION

Two public workshops were held: One in November 2011 in Southampton (UK) and another one in January 2012 in Braunschweig (Germany). During both workshops the main focus with respect to WP2 was on the presentation of the field installation in Partenstein and the design of the HPM. At the deployment site in Partenstein an official initiation of the HPM was held in July 2011. About 50 local people as well as mill owners looking for new concepts to reactivate their site were present. In August 2010 a TV team from the Bayrisches Fernsehen in Germany visited the laboratory at TUD and filmed the model tests in the flume and in the 3D physical model (BF, 2010). After the broadcast of the TV show a wide spread audience - from mill owners to companies - contacted partner 2. In addition the results of the model tests were presented at several conferences.

It is planned to utilise the foreground developed under WP's 2, 3 and 4 to design low head hydropower plants. The coordinator has set up an engineering consultancy which is currently engaged in two feasibility studies. If further market opportunities arise, it is envisaged to form a consortium to exploit the HPM technology further. This is however difficult to assess at present.

WP 2A: MORPHODYNAMIC REGIME NEAR HYDROPOWER STATIONS

2A.1 WORK PACKAGE AIMS AND OBJECTIVES

Contrary to all other low head hydropower converters currently in use, the HPM/HPW will allow sediment to pass through the machine as bed load and suspended load. This may lead to as yet unknown effects such as the mobilisation of hitherto trapped sediment and possibly sediment deposition downstream. In such complex environments, which involve hydraulic machinery, physical model testing is the only realistic design tool. The aim of his WP is to assess the effect of the HPM run-of-river installation on the sediment transport path and to provide recommendations to minimise the impact of sediment on HPM operation.

Objectives of WP 2a:

• Literature / field study of sediment deposition / erosion at small hydropower installations

• Assessment of effect of HPM on morphodynamic regime

• Development of sediment guidance structures

• Design recommendations morphology near HPM/HPW installations

2A.2 MAIN SCIENTIFIC AND TECHNOLOGICAL RESULTS

The HPM is designed to allow the passage of small debris flow, suspended load, and bed load with small grain sizes. However, if coarse gravel is transported into the HPM, it can damage the blades and block the machine. The installation of a HPM can lead to morphodynamic changes such as mobilisation of hitherto trapped sediment and sediment deposition downstream. The morphodynamic regime near small run-of-river installations was investigated in generic model tests. The cases “new weir” and “existing weir” were distinguished to consider the different morphological boundary conditions upstream of the weir. Two distinct effects were observed:

• Scouring at the inflow wing wall of the HPM installation

• Redirection of sediment around the HPM installation and over the weir

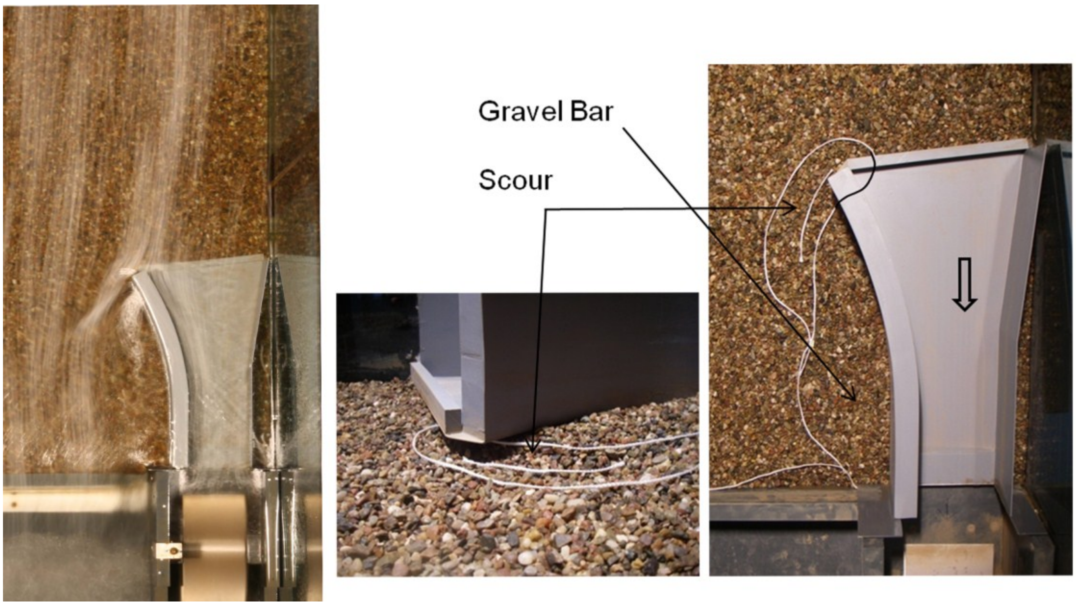
In case of a new weir the backwater area upstream of the weir is not filled with deposited sediment. Bed load which enters the section of interest from upstream settles down at the beginning of the backwater area and a dune like sediment body develops, which grows towards the weir if bed load input continues. During siltation of the backwater area, the bed at the inlet to the HPM is scoured. If the depth of the scour is not limited, e.g. by riprap, it can reach dimensions large enough to compromise the stability of the construction. With further flood events which are high enough to cause bed load transport the front finally reaches the weir and pass it. The scour dimensions decrease but the scour itself remains. Upstream of the scour and downstream of the HPM gravel bars develop. An effect on the operation of the HPM, such as an increase of the downstream water level at low flow conditions, could not be determined in the flume experiments.

The final stage of the bed morphology of the “new weir” situation is comparable to the morphology which develops if the HPM is installed into an existing weir, i.e., the backwater area is already filled with sediment. The position (at a bank or in the middle of the river) and the width of the HPM affect the scour dimensions. However, at this state of knowledge concluding relations cannot be given.

The installation of an intake channel structure has revealed the need for a hydraulically optimised design of the structure. Otherwise the flow can be separated at the side wall causing deep scours and, thus, instability of the construction (see Figure 2a.1).

The flow in front of the turning wheel is strongly decelerated. Sediment which enters this area from upstream or is mobilized in front of the HPM is redirected and passes the weir. The bed load path has to be considered, especially, when planning the location of a fish pass. The straight blades of the HPM, induced turbulences that pushed incoming grains back into the scour. No sediment was transported through the HPM. However, a different design of the HPM or changed hydraulic conditions may change this result. Thus, sediment transport into or near the intake as well as uncontrolled scouring should be prevented.

Sediment guidance structures with a shape of submerged groynes were used to investigate the possibility of controlling the transport path. The results confirm the potential of the structures to guide sediment towards the weir and to decrease the scour in front of the HPM (see Figure 2a.2).



(a) (b) (c)

Figure 2a.1: Streamline visualization and bed topography due to an inlet structure.

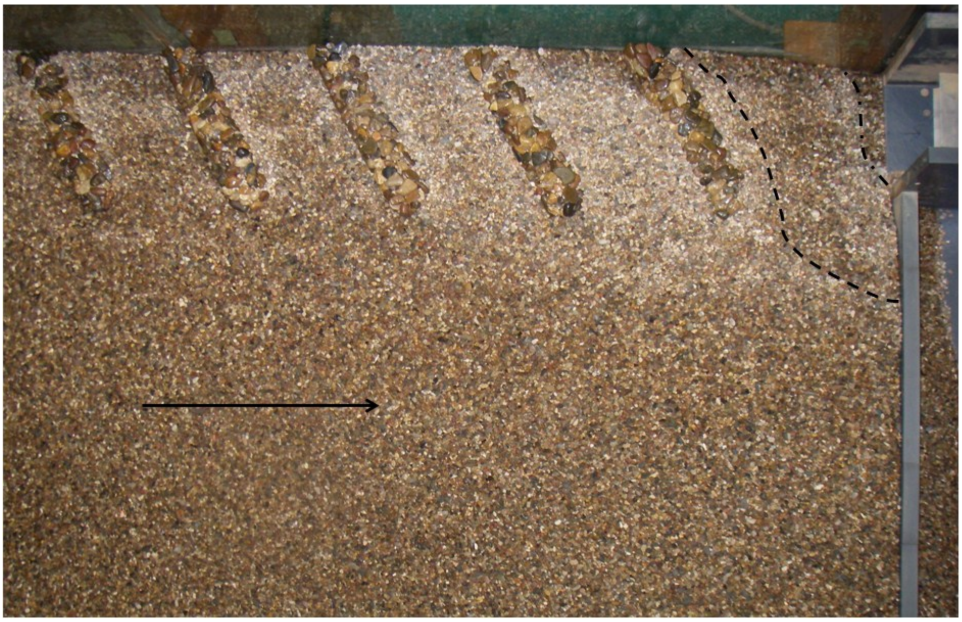


Figure 2a.2: Contour lines of the scour upstream of the HPM in case of sediment guidance structures.

WP 3: LARGE SCALE MODEL, DESIGN AND MONITORING - HPM

3.1 WORK PACKAGE AIMS AND OBJECTIVES

Work package 3 has the aims to design, install and monitor the performance at full scale the newly developed hydropower convert for very low head differences. The aim of this experimental application of the Hydrostatic Pressure Machine (HPM) is to test the technology in natural environmental conditions at full prototype scale in order to study and analyze the whole range of its technical and environmental performance. Performance curves to be established based on the test results from the performed experiments.

Objectives of WP 3:

- Determination of design flow and water levels
- Hydraulic design of LSM for chosen site including flood risk analysis,
- Obtain planning permits
- Monitoring of HPM performance and environmental aspects (fish passage, sediment regime)
- Analysis of data, comparison with design information (WP 2.4, 2.5, 2.6)

3.2 MAIN SCIENTIFIC AND TECHNOLOGICAL RESULTS

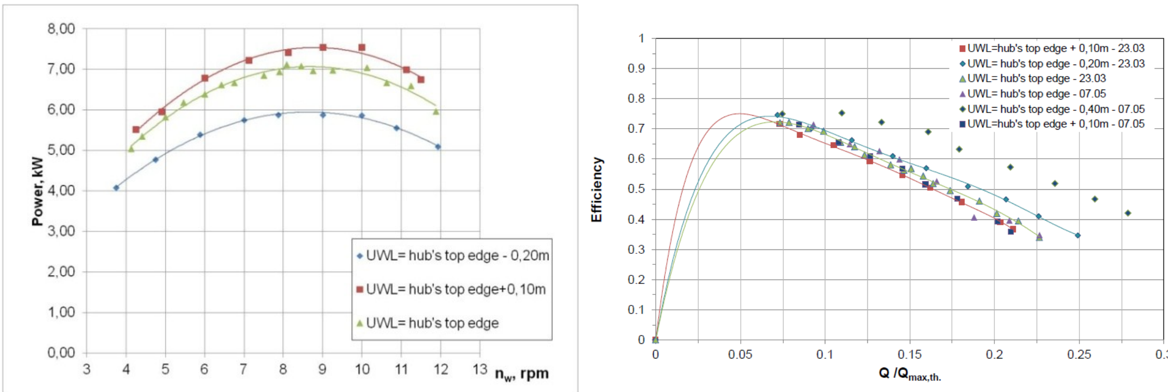
The full scale prototype of the HPM was installed in a small research hydro power plant on the river Iskar in Bulgaria. The HPM was designed and built, based on the results of numerous experiments on a row of small-scale models of such machine (in a few different versions), conducted in the hydraulic laboratories at TU Darmstadt and University of Southampton in the frame of WP2.

The Large Scale Model of the HPM has a diameter of 2.4 m and width of 2.0 m with 10 blades inclined at 15 degrees. The chosen installation site is a weir which was reconstructed in order to ensure the necessary conditions for the HPM operation. All required permissions for construction of the experimental SHPP and HPM installation from different authorities (Environmental authority, River basin directorate, Municipality etc.) have been obtained.

Assessment of the efficiency of the machine was carried out under isolated operation of the generator without connection to the common grid. The HPM shaft was connected with the generator via gear box for multiplying the speed of rotation. The two-stage cylindrical gear box has a transmission ratio of 8. A special device for measurement of the mechanical torque at the machine shaft (torque sensor) was placed between the gear-box and the generator. These measurements were of crucial importance for investigation of the machine efficiency under different load conditions. The generator is a permanent magnet type with rated output power of 20 kW and rated rotation speed of 100 rpm. The generator loading is carried out by a resistor bank. Real time changes of the load on the generator were possible with the power electronics converter that allows the controllable load variation. It permits the load current to vary between 0 and 48 A (DC). A control and monitoring system was specially developed to measure and follow the main parameters that give an account for the HPM efficiency. Monitoring of the HPM performance was performed under different conditions that allowed assessing the optimal performance of the machine.

a) Upstream view of the HPM b) Downstream view of the HPM

Fig. 3.1 HPM in operation



a) Power output of the HPM b) Mech. efficiency of the HPM

Fig. 3.2 HPM performance curves for different UWL

The following conclusions for the HPM performance could be made:

- The optimal performance of the machine is achieved when the speed of rotation of the HPM wheel is in the range 7, 5 – 10 rpm.
- For the conditions of optimal performance the achieved power output is in the range of 6.0 – 7.5 kW for different upstream water levels and the mechanical efficiency is in the range of 55 – 65%.
- Higher efficiency of the HPM is achieved when the UWL is lower than the top edge of the hub but higher power output is achieved when the UWL is higher than the top edge of the hub.
- For fish passage through the weir in both directions, a fish pass was built with parameters developed at the TU Darmstadt (Germany). It proved to work well although the observations were performed mainly outside the time of active migration.
- Statistically representative mortality and injury tests were carried out with typical species both local and common for Europe (e.g. trouts).
- The mortality through the HPM is almost 0, injuries were observed mainly at the larger fishes which can easily not be allowed into the HPM with simple measures (e.g. appropriate trash-rack bar distance).
- The following conclusions can be drawn from the research operation of the HPM:

- A complete Energy Convertor solution for very low head differences has been developed and successfully implemented as a full-scale prototype application;
- The developed engineering know-how covers the whole process from site location via energy production up to dealing with extraordinary situations;
- In this head range (1 – 2 m), the developed and implemented in full scale Hydraulic Pressure Machine successfully proves so far to be a quite competitive alternative to the usual energy producing technologies;

3.3 POTENTIAL IMPACT, THE MAIN DISSEMINATION ACTIVITIES AND EXPLOITATION

The experimental application of the HPM tested the newly technology in natural environmental conditions at full prototype scale in order to study and analyze the whole range of its technical and environmental performance. The development and results from monitoring of the performance of the HPM were presented at several conferences and workshops.

WP 5: LARGE SCALE MODEL DESIGN AND MONITORING – FSEC

5.1 WORK PACKAGE AIMS AND OBJECTIVES

Within this work package a large scale model has to be developed and designed. Other activities result from the aim of testing the large scale model. To the latter belong the choice of measurement equipment and the suitable programme. An important objective is the identification of two deployment sites. This includes also boundary, transport and monitoring conditions.

Objectives;

- Determination of large scale model geometry including stability and station keeping
- Design of large scale model including power take-off
- >Measurement equipment and programme
- Identification of two suitable deployment sites (low flow velocity for initial large scale testing (inland) and one site with higher flow velocities and coastal conditions for large scale testing of FSEC-model)
- Design and construction of mooring
- Transport, deployment and monitoring
- Monitoring
- Validation

5.2 MAIN SCIENTIFIC AND TECHNOLOGICAL RESULTS

Within the HYLOW project a floating energy converter, the -so called- Free Stream Energy Converter (FSEC) was developed, designed and tested. For the determination of FSEC design are used many experimental tests. These were beginning with simple and special parts of future FSEC design.

Pre tests in the wind tunnel:

- closed or perforated paddle sheets,
- parallel or divergent or convergent side walls,
- position of paddle sheet in the length of model,
- width of gap between paddle edge and bottom plate of model,
- Pre tests in the small flume:

- closed sheet or perforated paddle sheets,
- inflow edges at side walls and bottom plate convex or concave - equally for the outflow edges,
- position of paddle sheet in the length of model,
- width of gap between paddle sheet and bottom plate of model,
- relation between draught of model and gap,
- After that are used model tests with fixed and floating small scaled models based on pre test results for validation and new findings with the aim to maximise the power output.
- Small Scale Model (SSM) tests with three types of model in four different flumes and tank:
- relation between floating bodies breadth and perfusion breadth also inflow and outflow angle,
- floating bodies convex or concave,
- position of wheel axis in the length of model,
- width of gap between wheel paddle edge and bottom plate of model,
- relation between draught of model and gap,
- influence of flow velocity for buoyancy, stability and trim,
- influence of appendages in front and stern of models – scoop and separator types,

The next step was a Medium Scale Model (MSM) for validation SSM test results. It was tested in naturally water and towing tank:

- position of wheel axis in the length of model,
- width of gap between wheel paddle edge and bottom plate of model,
- relation between draught of model and gap,
- flow velocity influence for buoyancy, stability and trim,
- influence of four separator types at model stern,
- floating stability

On basis of the small and medium scale model tests, a large scale model (LSM) of the FSEC (length = 7.6 m and width = 2.4 m) was designed and constructed for field tests under nearly natural conditions.

Based on the results of model tests, the optimised design of the FSEC created. The design of the FSEC with its main components is shown in Fig. 5.1. It is modelled in the CAD programme CATIA V5. The main assemblies are the pontoon with two hulls connected via a base plate and the waterwheel with 12 straight blades. This variation of the LSM is designed as bidirectional model with a buoyancy chamber in the inlet area.

The base plate has a u-profile, and has metal plates below for more stiffness. Two hulls are arranged on the left and on the right, and completely welded on the base. Inside the hulls are bulkheads which generate single sections. These sections are planned for trimming with sandbags and water bags, and for carrying technical equipment. More stiffness can be reached with diagonal stiffeners in each section. All sections are equipped with tops. This design shows two k-frames in in- and outlet area. The buoyancy chamber in front of the model is installed above the waterline, and gives the last safety, before the LSM could tip forwards.

In preparation of the large scale model tests, two suitable deployment sites (Naval base at Warnemuende and natural Warnow River) were determined and analysed and all necessary permissions for field tests with the FSEC at the deployment sites were applied and obtained. Before the FSEC was installed at the deployment sites, the mooring system was designed and the transports were organised, respectively.

For the field tests in the natural Warnow River, a mooring system with two heavy weight anchors (one at bug and one at stern) was chosen. The dimensions of anchors as well as ropes and additional components were determined based on potential hydrodynamic at the deployment site. All transports from the construction company (Partner 6 - RUSTA) to the deployment sites and return as well as installation and de-installation of the FSEC were executed by external transport companies (subcontract).

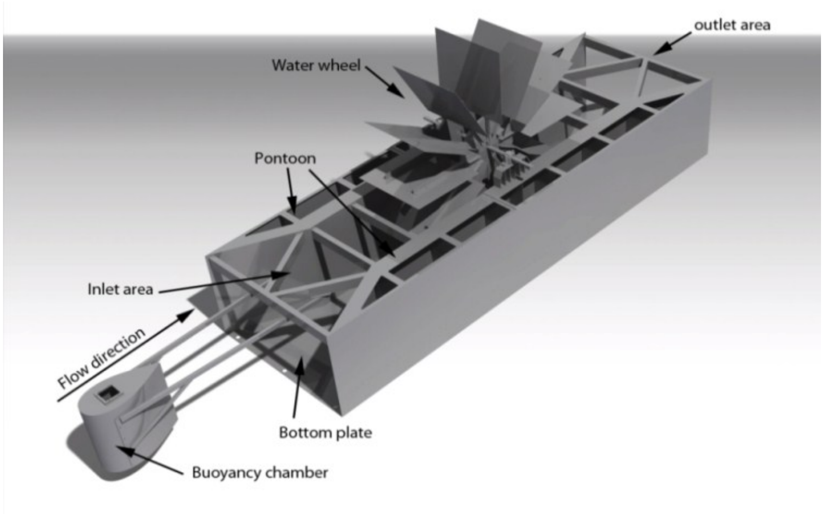


Fig. 5.1: The modelled LSM in CATIA V5

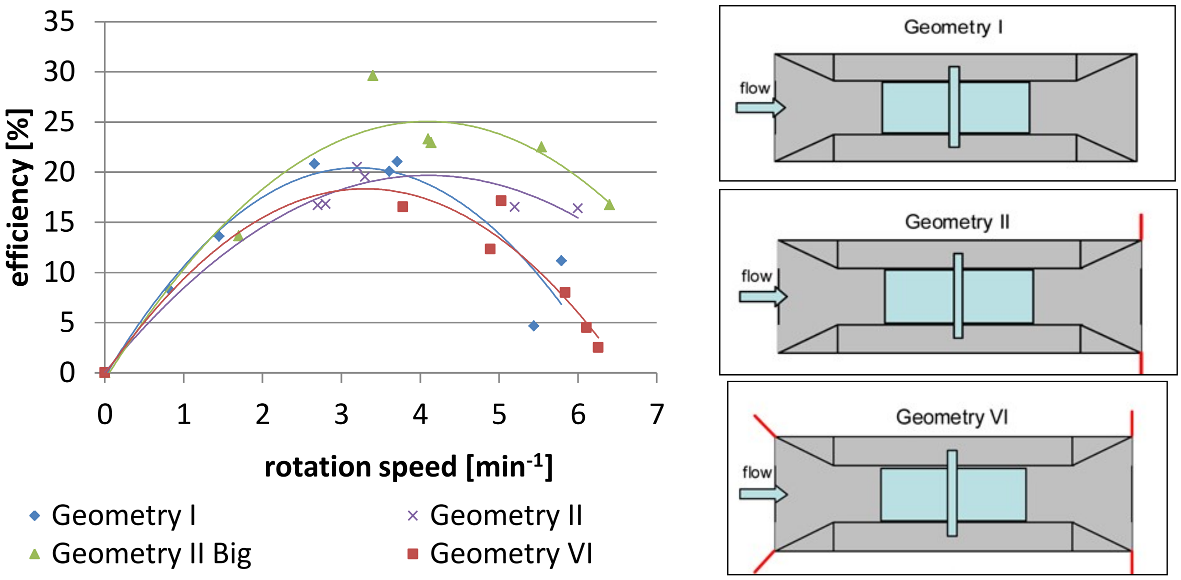


Fig. 5.2: Power output of selected geometries for towing velocity of 1 m/s

In the period from June 2010 to November 2010, the FSEC was tested at the naval base of Warnemuende (northern Germany) as towing tests. This method offered the possibility to test the FSEC with different and defined tow velocities and different geometries (different separators at bow and stern). The main focus during the first field tests were, to determine the:

- influence of different separator sizes /geometries
- influence of different tow velocities
- influence of different draughts
- influence of different rotation speed
- stability and trim

In total, 170 tests according previous compiled measurement programme were executed. The determined power outputs and efficiencies depend on the towing velocity, floating position, geometry and rotation speed of the water wheel as to be expected. Fig. 5.2 shows the efficiencies (related to the whole width of FSEC (2.4 m)) of the main sufficient geometries for a towing velocity of 1 m/s.

The highest power output of about 600 W was measured with a towing velocity of 1.5 m/s. As expected, the power output is higher with bigger separator. Highest power output and efficiency were measured in case of low rotation speed (3 to 5 min^{-1}).

As further results of the field tests in the naval base, the need of a buoyancy element at the bow of the FSEC was clearly determined. A buoyancy chamber was designed and constructed for the test at the second deployment site.

In the period between February, 21st 2012 and April, 1st 2012, the optimised FSEC LSM was tested in the second deployment site, the Warnow River (northern Germany), see Fig. 5.3 . During the test time, the Warnow River had a flow velocity of approximately 1m/s and a water depth of 1.5 m.

Investigations of performance were executed with different draughts, inclinations, fish racks and brake systems. Further, the flow conditions and the influence of the buoyancy chamber on the performance were investigated. The measured power output for different draughts is displayed in Fig. 5.3. The maximum power output of almost 350 W with a peak efficiency of 30 % related to the whole width was measured. As already noticed in the first field test (naval base), the highest power out was measured in case of low ration speed (3 min^{-1} to 4 min^{-1}).

In addition to the investigation on performance of the FSEC-LSM under near natural conditions, investigations for the assessment of possible environmental impacts were the main focus of the second deployment.

The investigation on the environmental impact included measurements around the FSEC-LSM, regarding changes of flow direction and velocities. The changes of the river bed were assessed and the sound level on different distances to the FSEC-LSM was recorded.

The flow velocities and the flow directions were measured around the FSEC-LSM. No significant increases of current velocities were determined. For the assessment of change of the riverbed, the bathymetry (river bed morphology) was surveyed. In individual case the river depth was change up to 40 cm, based on local scours or accumulation. Direct under the FSEC-LSM a maximum change of the river depth of 20 cm (accumulation) was surveyed. These riverbed changes are also based on the natural seasonal dynamics (without FSEC). The increase of the local noise emission is negligible.

Fig. 5.3: Free Stream Energy Converter in the Warnow River

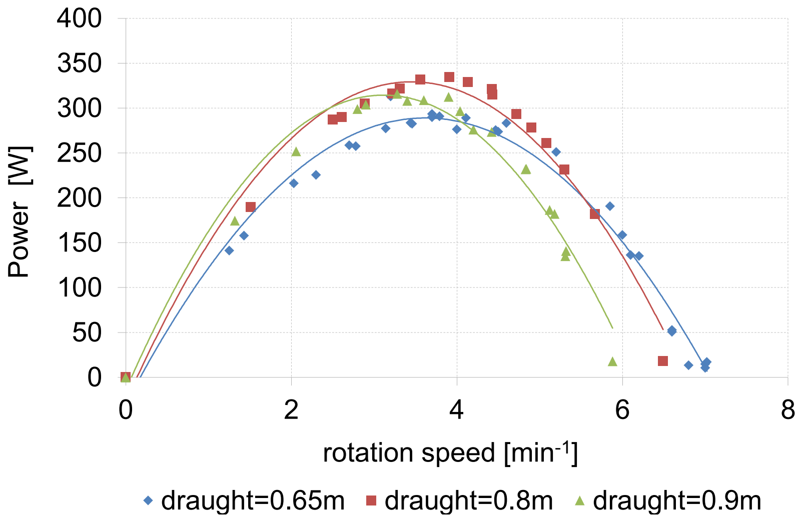


Fig. 5.4 Performance tests in the River Warnow / Northern Germany, measured power output for different draughts

Furthermore, investigations to the fish behaviour were executed during the field test in the Warnow River. The results of these investigations are described in WP 13.

In addition to the physical model tests, several numerical investigations were conducted with the models FLOW 3D and ANSYS. The main focuses of numerical investigation were on:

- investigations regarding power output and efficiency with different types of cross sections, different bed roughness and water different levels,
- investigations regarding environmental influences e.g. change of surface elevation, change of flow velocities and change of morphology,
- development of numerical model about influence of fluid effects to the approaching flow below inlet of FSEC-model

- numerical analysis of the approaching flow for previous test conditions in flumes, towing tank, small rivers

For validation of flowing influences was developed a numerical model. This model described the relations of flow velocities inside and outside the FSEC with the possibility of different geometric design specifications for floating pontoons (side bodies) and other main dimensions for design and

As results of data analysis, design and operation criteria for the FSEC were compiled with the aim to maximise the power output:

A further scientific result is the development of a possibility to the forecast calculation for power output FSEC. Fig. 5.5 demonstrate the good accordance of the measured values with the forecasted values.

WP 7: DEVELOPMENT AND MONITORING OF MICRO-TURBINE AND VOLUMETRIC/SPIN-TYPE HPE

7.1 WORK PACKAGE AIMS AND OBJECTIVES

The work comprises the concept development for the best turbine configuration for water distribution system extending traditional turbine technology into a new range, and assessing a novel positive displacement (volumetric) and rotor-dynamic turbines' type.

It was developed models for a PD, a pump as turbine (PAT) and a novel tubular propeller (TP) turbine configuration. Analysis based on CFD simulations and model tests for the final geometry and an intensive test programme (for variables, geometry variation, design outcomes and range of application) are performed; performance curves (power output and efficiency) are also determined.

The work presents new energy converters applied in water distribution systems, extending the traditional turbine technology into a new range, and assessing a novel piston-type technology.

Turbine Propeller of Five Blades (TP5B)

The laboratorial system was tested under different flow conditions. 250W and 500 W DC permanent-magnet machines were tested (Figure 7.1). A variable rheostat, ranging from 0 Ω (short-circuit) to 6 Ω load, was included to simulate different levels of electric load.

The tested DC electric converters and electric loads showed that the best results (Figures 7.2 and 7.3) were obtained with the 500 W converter with a 3 Ω load. The 500 W DC converter had a better adaptation to the used range of rotational speeds (values lower than 250 W).

Figure 7.1 - DC permanent-magnet machines

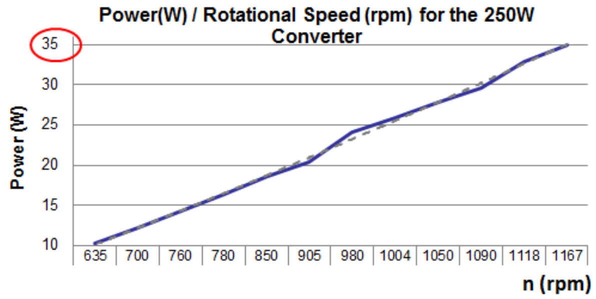


Figure 7.2 - Power (W)/Rotational speed (rpm)
for the 250 W converter

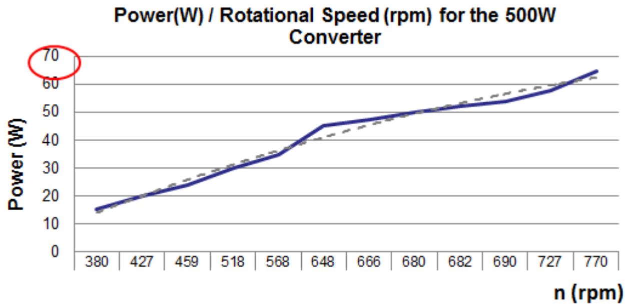


Figure 7.3 - Power/Rotational speed (rpm)
for the 500 W converter

TP5B Outdoors

An authorization was obtained for the assembly and testing of the TP5B system in the real Mafra system (Figure 7.4). The TP5B system was adapted at the Reservoir of Encarnação, inside the valve's chamber, with the support of the Mafra WSS staff.

Different tests and records were made to study the hydrodynamic behaviour of the system under different flow conditions and discharge variations (Figure 7.5) for periods of 24 h, depending on the water consumption. Power variation and torque values were measured too (Figures 7.5 and 7.6).

The use of theTP5B in water supply systems demonstrates performances. The generator used is the DC converter with 500 W. During laboratory tests (H=1m; Q=12 L/s), 65 W were generated. When applied to water supply systems the simulations show with the optimization with AG the value of the investment was fully recovered after the 1st year of operation with a discount rate of 6% improving the whole system efficiency.

Figure 7.4 - Mafra Water Supply System

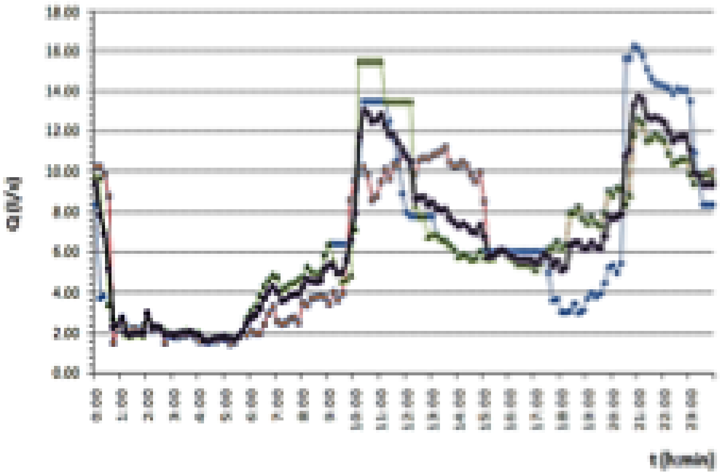


Figure 7.5 – Discharge variation

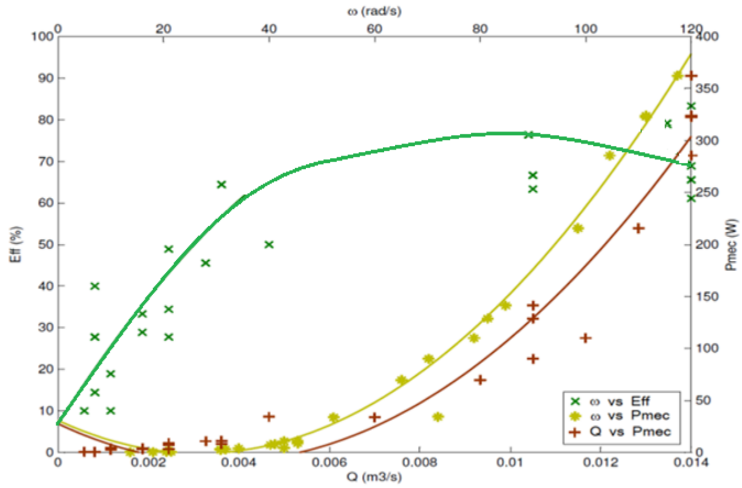


Figure 7.6 – Power variation

Positive Displacement Turbine (PDT)

During the laboratory tests it was verified that the PDT system has a low rotational speed and a high torque. The application of a gearbox linked to the PDT system might lead to higher rotation speed, and then the 500W DC generator can be used for electricity power generation

Hence simulations were made in the optimal operating point of the PDT system using a gearbox (x10 rpm) with speed-changing gears. This set-up was linked to a 500 W DC converter to generate electricity. In these conditions 51 W of electricity were attained (Figure 7.8).

PDT is a complex machine with significant frictions and leaks between the rotor and the casing. The results suggest that the turbine is suitable for high pressure and low flow, although definitely it is not adequate for low heads.

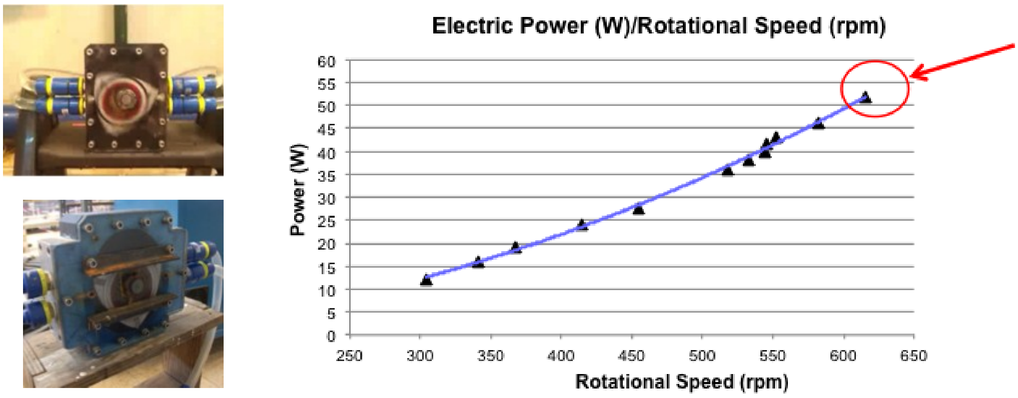


Figure 7.8 – PDT last iterations / Power

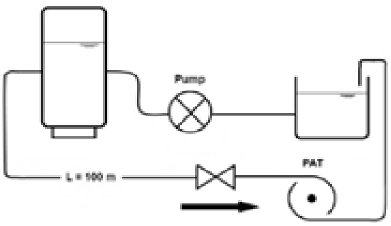
Pump as Turbine (PAT)

The overall characteristics of the used PAT system are presented in Figures 7.9 and 7.10. The PAT equipment has nspt (m, m^3/s)=21 and nspt (m, kW)=51 and the scheme of the laboratorial system that allowed for head and flow variations is presented in Figure 7.11. Two conditions were tested: for steady and for runaway conditions as presented in Figure 7.12. In runaway conditions, for the same flow rate value, pressure surges occur as described by an increase in the available head.

Figure 7. 9 - PAT system characteristics

Parameter	Value
Operation Frequency (Hz)	50
Nominal Voltage (V)	230/400
Rated Power(W)	550
Power Factor	0.74
Maximum current supported	2,8

Figure 7. 10 - Asynchronous generator characteristics



PAT Experimental setup

Figure 7. 11 - Laboratorial system

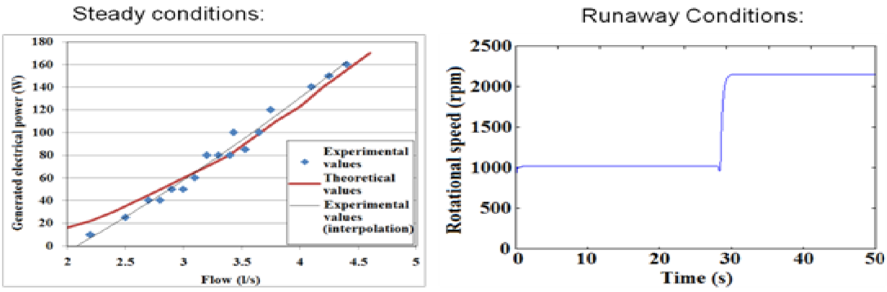


Figure 7. 12 - Tested steady and runaway conditions

PAT Outdoors

A PAT system was installed in a water distribution system (S. Martinho near Covilhã). The section of pipeline under study is managed by Waters of Covilhã (Figure 7.13).

It was established that AC machines with a shunted rotor need reactive power to work properly. A set of capacitors was installed to excite the asynchronous machine. The results obtained from a 1 hour feeding of electric common loads are presented in Table 7.1.

The main disadvantage of using a PAT is its operation, which is highly dependent on the flow rate. Better results were obtained for high pressures and flows, which correspond to higher rotational speeds and generated power. The PAT characteristics curves obtained outdoors are presented in Figure 7.14. About 4500 W of electric power was generated in a real context and the achieved efficiency was 50%.

Table 7.1 - PAT Results for one hour feeding electric common loads

Hour	Rotation [rpm]	Tension [V]	Current [A]	Pressure [bar]	Flow [m^3/h]	Power [W]
9:12	1868	231	0	2,1	19	0
9:15	1958	240	2,1	3	22	504
9:22	2056	235	4,6	3,9	24	1081
9:23	2325	240	6,6	4,9	27	1584
9:28	2543	238	8,9	5,7	31	2118,2
9:32	2678	243	11	6,3	35	2673
9:37	2749	235	12,9	6,7	37	3031,5
9:41	2994	239	15,2	7,5	38,5	3632,8
9:45	3041	233	17,2	8	40	4007,6
9:47	3100	246	18,2	8,5	41,4	4477,2

Figure 7.13 - PAT testing outside

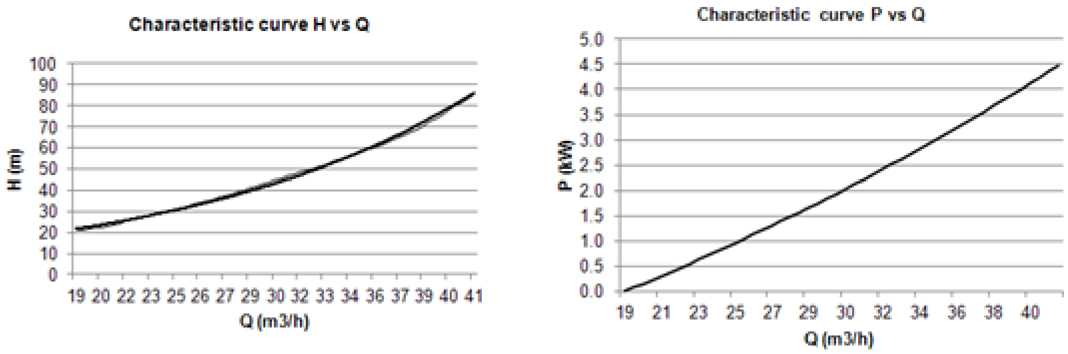


Figure 7.14- PAT characteristic curves obtained Outdoor

7.3 POTENTIAL IMPACT, THE MAIN DISSEMINATION ACTIVITIES AND EXPLOITATION

Reducing environmental impact

Hydro-energy sources have the potential to provide urban and rural/isolated areas with a reliable, efficient, safe and economic source of energy, and in this, to improve the overall system effectiveness of the decentralised areas and industries. The use of these novel types of hydropower converters can allow for best performances and efficiency of the whole system. They are relatively simple machines and do not require a significant installation/maintenance effort.

The use of water to produce energy directly impacts the minimization of carbon dioxide, sulphur dioxide and nitrous oxides, and no solid or liquid wastes products are released. Therefore, this type of converters could contribute to a substantial global reduction of CO_2 emissions responsible for the formation of greenhouse effects.

This type of converters do not involve drastic infrastructure changes, they can use economic equipment. This means that no environmental and social disruptions will be caused. In fact, presently, the water flow, which is available 24-hours per day in any water system, is not utilized for electricity production, and it is most of times effectively wasted.

Based on different types of analysis, including the optimization of WSSs operation, it was found that the implementation of micro-hydro turbines would allow for more than a 60% cost reduction during the exploitation life of the turbines. Additionally, the investment return comes as early as in the 3rd year of exploitation.

The impact can therefore be expected to be significant on a number of levels:

1. Novel concepts and technologies were developed and demonstrated, expanding the area of hydropower application;

2. Reductions in carbon dioxide emissions can be realized;

3. These converters could lead to a more decentralised energy production, reducing the reliance on large central power stations and improving the degree of energy security;

4. It could be expected that these converters could be exported to countries with significant numbers of small, medium and low head hydropower sites. These converters could also harvest energy resources in developing countries, reducing the amount of fossil fuel and greatly increasing the quality of life.

WP 8 VIABILITY ANALYSIS FOR POTENTIAL HYDROPOWER SITES IN WATER SUPPLY SYSTEMS – HPE AND MICRO-TURBINE

8.1 WORK PACKAGE AIMS AND OBJECTIVES

The objective of the Work package 8 is to analyse Water Distributions Systems located in Portugal in order to install a micro turbine in a specific selected site which allows producing electricity that will be delivered to the national grid or consumed near by the site of production.

8.2 MAIN SCIENTIFIC AND TECHNOLOGICAL RESULTS

> Several Water Distribution Systems located in different regions of Portugal were analysed and in all of them was possible to identify locations that permitted to install a micro turbine, the prototype developed in work package 7 or a PAT, Pump As Turbine.

> Some of the locations that were identified technically allowed some production but economic viability was not guaranteed.

> Most cases that were identified and analysed allowed both technically and economically the installation of micro-turbine prototype.

> In some cases, if there´s enough space, it´s only needed to clear the manoeuvre chamber of part of the conduits, which will be replaced, and install the by-pass with PAT. Fig. 8.2 shows an example of PAT installation.

> Some difficulties appeared when dealing with Owners and Managers of the systems. They start to be very interested in producing some renewable energy that can be delivered to the grid, and generate an income revenue, but in some cases collecting and gathering all the needed information can get really slow.

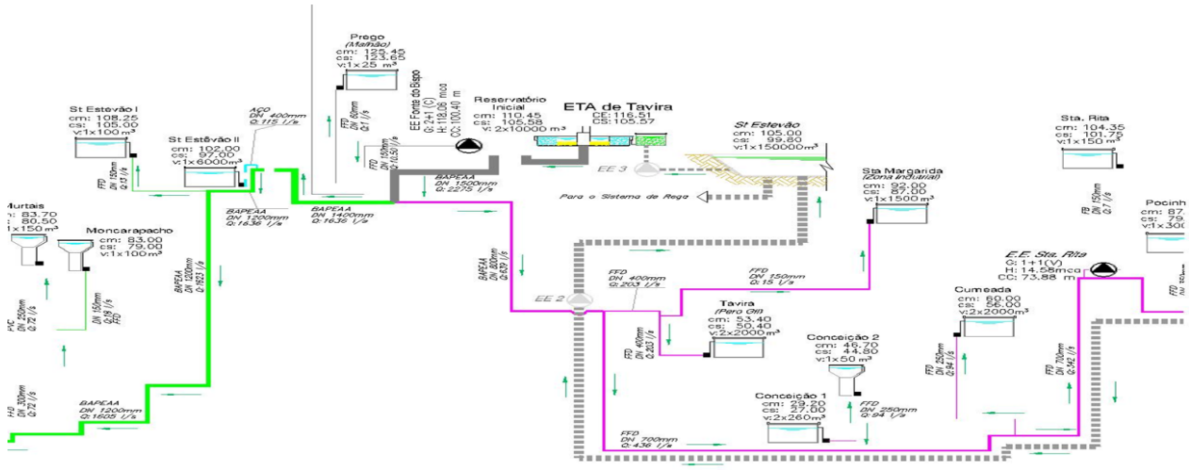


Fig 8.1- Water Distribution System in the South of Portugal – Altimetric scheme

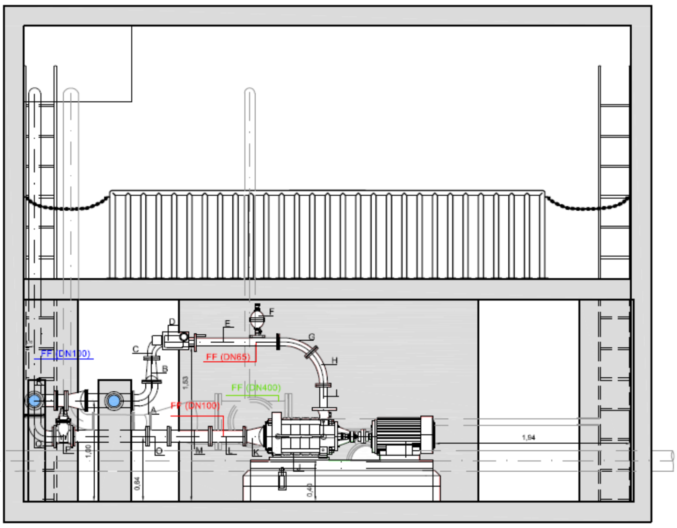


Fig. 8.2 – Installation of PAT (Pump As Turbine) in a reservoir manoeuver chamber

8.3 POTENTIAL IMPACT, THE MAIN DISSEMINATION ACTIVITIES AND EXPLOITATION

This type of micro hydro production has the possibility of being installed in most of existing Water Distribution Systems and like this produce locally some energy that in most cases will be possible to consume locally, besides the opportunity of selling it to the grid.

Other institutions, like EDP INOVAÇÃO and PCT, Pole for Competitiveness and Technology, in Portugal considered the project is eligible and want to support its dissemination.

WP 9 CONVERTER OPTIMISATION – HPM AND FSEC

9.1 WORK PACKAGE AIMS AND OBJECTIVES

This work package has the aim to initially develop and validate numerical models of the HPM and FSEC, which are them employed to optimise their geometries.

9.2 MAIN SCIENTIFIC AND TECHNOLOGICAL RESULTS

The numerical model of the HPM is generated using commercial CFD software and the model is validated with data from WP2.4. The optimisation of the HPM blade geometry is done in order to maximise performance. This will include different blade angles, blade curvature as well as moveable blades thereby enabling performance prediction for the optimised geometry.

The modelling of the machine is done in two steps. The initial step consists of setting up a 2D model for the HPM with straight blades. In a further step, the complete 3D HPM and the channel will be modelled to enable the implementation of curved blades. This model will be considerably larger that the 2D model. High computational time can be expected.

The aim of the numerical models in this project is to understand better the physical processes involving free surfaces in rotating machines such as the HPM using computational fluid dynamics (CFD) simulation software. This includes implementing direct simulations using Volume-of-Fluid (VoF) methods for the case of free surfaces.

The model was verified using the results from WP2. A typical set-up with pressures and velocities is shown in Fig. 9.1.

Main results HPM:

• Effect of blade angle: Three variations in blade angle show that machine efficiency increases with an increase in the angle of the blade to the machine axis (Fig. 9.2a). Blades with an angle of 0° to the axis show the least efficiency, blades with a 20 degree angle the best.

• Influence of relative wheel/channel dimensions on machine performance: Three cases with varying machine width were investigated with the fixed channel width. The reduction of blade width in the channel shows that efficiency drops in reaching the maximum width of the channel. Figure Fig. 9.2b shows a drop in efficiency as the wheel width approaches channel width. This indicates that the recirculation in the flow caused by the asymmetry of the blade geometry has a high influence on the performance. A small wheel width would reduce the influence of recirculation at the inflow region of the machine blades allowing for vortices and other local losses to dissipate between wheel and channel.

• Influence of end-plates: Experiments were carried out on a HPM model at the University of Southampton laboratory and these were replicated in CFD to enable further optimisation as it was thought that end-plates might influence efficiency. This model consisted of a HPM, the sides of which consisted of an extension of the walls adjacent to the wheel. The removal of the end plates at the sides of the wheel (upstream and downstream sides) shows a marginal change in the machine efficiency from 0.688 to 0.681. From these results it was concluded that the end-plates have little effect on efficiency.

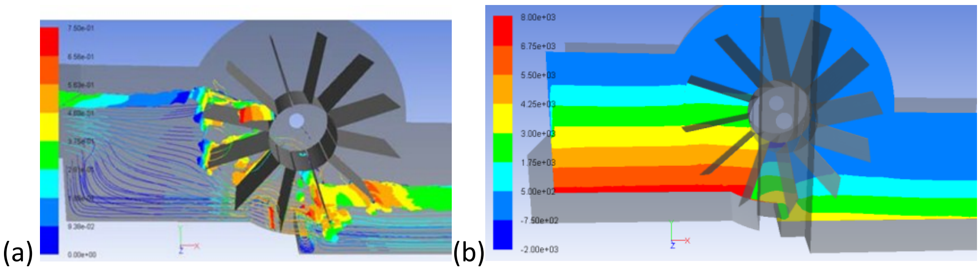
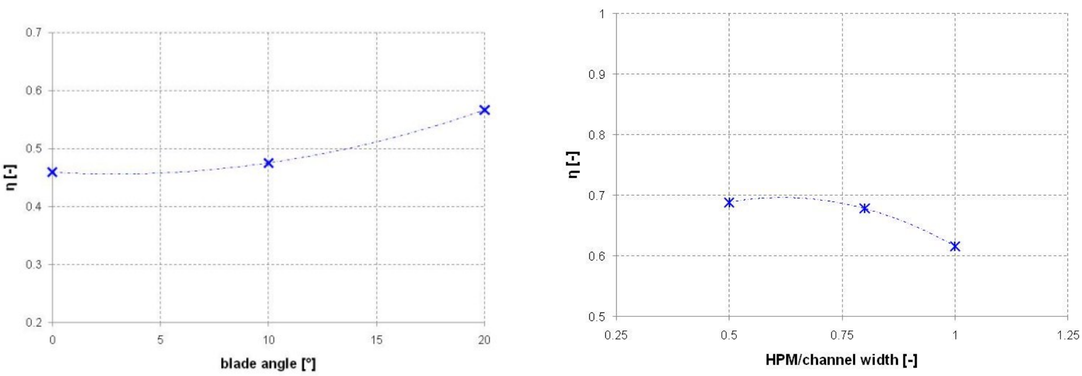


Fig. 9.1: Velocity contour (a) and pressure distribution



a. Variation of blade angle

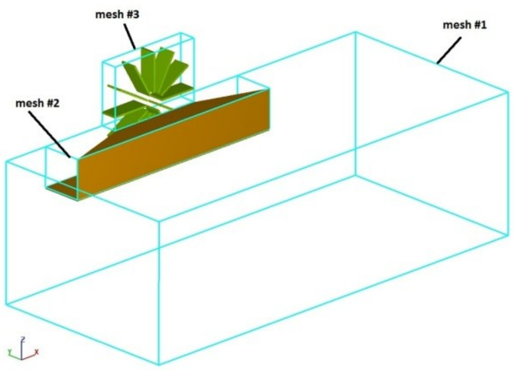
b. Efficiency as function of channel width ratio

Fig. 9.2: Effect of geometry on HPM efficiency

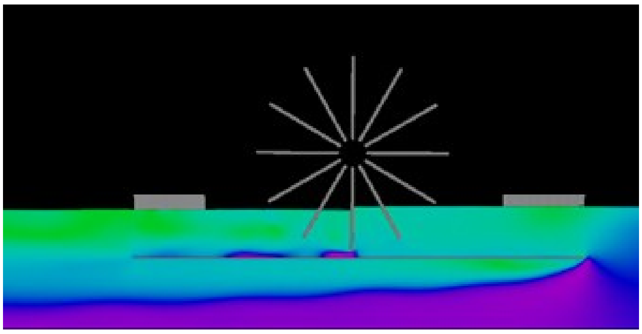
Main results free stream energy converter (FSEC):

• A verified numerical model was setup in FLOW 3D was compared with the experiments performed in WP 5. Figure 9.3 shows the typical domain and example flow conditions. The image shows the flow acceleration between the base plate and the wheel and a small head difference across the blade. Several parameters were investigated to understand the flow around the machine and a parametric study was developed in order to optimise the design.

• Figure 9.4 shows the influence of model draft on performance and comparison with experimental model results. The following parameters were studied including; internal draft, blade thickness, number of blades, and size of the clearance gap. The results indicated the effect of flow blockage is the most important effect which can govern the optimum design. The shape of the blockage and bed roughness has also shown to have an effect. It is therefore important to optimise the design for a given river site.



(a) Model Domain



(b) Typical flow field

Figure 9.3: Flow 3D setup and a result

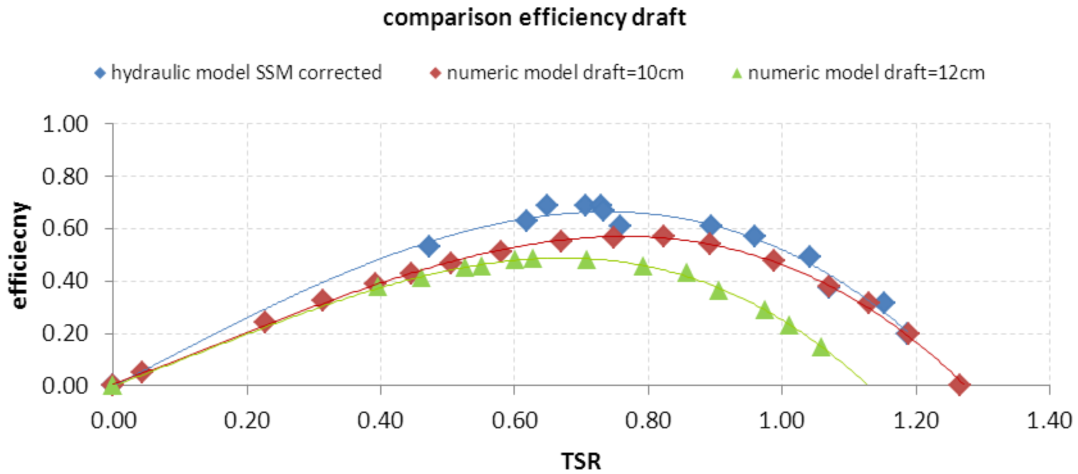


Figure 9.4: Comparison of efficiencies with different drafts and experimental results

WP 10: DEVELOPMENT OF APPROPRIATE TECHNOLOGY

10.1 WORK PACKAGE AIMS AND OBJECTIVES

This WP aims at creating an outreach where the technology developed in the project is transferred into and adapted for other interested countries, in particular developing countries. The WP runs as a background activity, complementing WP 9.The objectives are defined as:

- Analysis of target country requirements / resources / technological base
- Technology analysis
- Development of direct energy conversion
- Island generation
- Report

10.2 MAIN SCIENTIFIC AND TECHNOLOGICAL RESULTS

The technology developed under WPs 2 and 5 was assessed with regard to their suitability for / adaptation to developing countries. This included the available resource, materials employed and power ratings required. The analysis of the resource in developing countries indicated that irrigation canals, which have drop structures with head differences between 0.3 and 3.5 m, can constitute a major source of hydropower. Detailed data on five irrigation systems indicated that in Pakistan a potential of 5 GW or more exists which is currently unused, and where the technology developed in Hylow could be of great advantage.

WP 2.5 showed that the gearing is a major cost item, amounting to 40 – 50% of the total cost of an installation and requiring high-tech products (high-torque / low speed gearing with very high efficiencies). Low-cost solutions for gearing as well as for direct energy conversion systems where no gearing is required were therefore assessed.

• Direct energy conversion: Several possibilities of direct energy conversion were investigated both theoretically and experimentally. Pumping e.g. for irrigation or water supply purposes was found to be a very interesting usage since the pump / pressure vessel system smoothened the wheel's power output. Experiments indicated that even locally built single-cylinder pumps have an acceptable efficiency and acceptable pressure variations of +/- 6% . Using high-pressure pumps, desalination or water filtering is also possible with high efficiencies. Cooling using air expansion was also assessed based on theory; the results indicate that efficiencies increase with increasing temperature difference, and this is a possible mechanism for direct energy conversion if a local requirement exists.

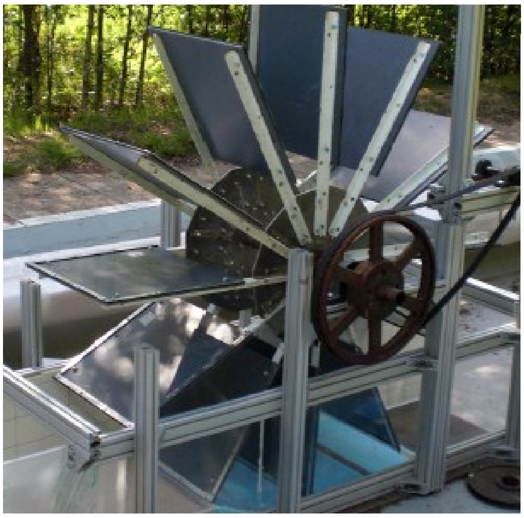
• Power requirements: The initial analysis of power requirements indicated that only a small power production of 0.1 to 5 kW is needed for individual houses, workshops or small settlements. Power can be required as mechanical, hydraulic or electric power. In the same time, simplicity of construction for energy converters and power take-off /electricity production are of prime importance from the points of view of construction, maintenance and economics.

• Hydropower converters: With the demand structure in mind, the technology developed in Hylow was assessed. The HPE/microturbine was considered not suitable for developing countries because of its complexity, the pipe system required (which may not exist) and interference with drinking water supply. The HPM was found to be too complex for the power requirements, in addition it is not really suited for very low head differences.

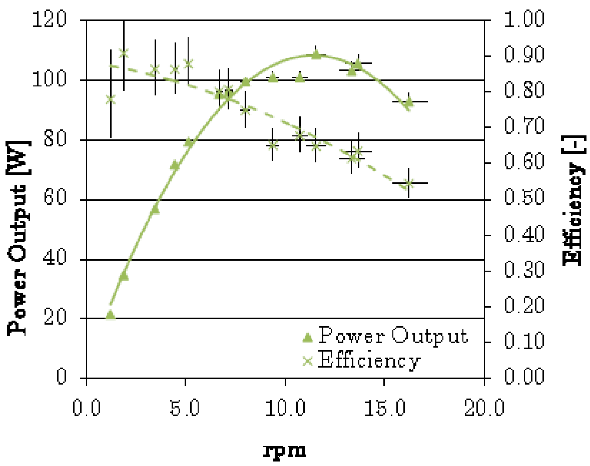
The technology developed under WPs 2 and 5 was therefore adapted by e.g. developing a simplified version of the HPM for very low head differences and low power outputs. Detailed tests with a near full scale model (1.80 m diameter, 0.25 m head difference, 0.5 kW/m width) demonstrated the potential of the Hydrostatic Pressure Wheel (HPW). Fig. 10.1 shows a 1.8 m diameter model and some test results. Efficiencies reached 90% for slow speed, and then gradually reduced giving very favourable working conditions for a wide speed range. The simplicity of construction lends itself for small installations e.g. in developing countries.

Table 10.1: Demand structure and distribution distances

	Electricity [kW]	Mech. Power [kW]	Hydr. Power [kW]	Distribution distance [m]
Single household	0.1-0.5	-	-	< 100
Small settlement	1-5			< 100
Agriculture	-	1 - 2	-	<100
Workshops / businesses	0.2 - 2 (lighting, recharging)	1 - 2	-	< 5 (mech. power) < 100 (El. Power)
Water purification	-	-	1 - 5	< 30 - 50
Irrigation / water supply	-	-	1 - 5	10 - 1000



a. HPW, model D = 1.80 m



b. power and efficiency as function of speed

Fig. 10.1: Hydrostatic Pressure Wheel

Conclusions:

• During the assessment of the technology developed in Hylow it soon became clear that the HPM is not really suitable for an adaptation to appropriate technology for developing countries, and that the HPE/microturbines do not have a significant market potential. The Free Stream Energy Converter on the other hand is well suited for decentralized energy production on the larger rovers with power ratings from 1 to 3 kW.

• In order to produce energy from low head hydropower, which is available both in streams and in irrigation systems, a simplified version of the HPM was developed theoretically and tested with physical models in different scales up to a scale suitable to supply individual houses, small settlements or small businesses.

• This very simple Hydrostatic Pressure Wheel (HPW) appears to be a promising technology for very small head differences between 0.2 and 1m, in particular since it can be built with very simple means, and without specialized tools.

10.3 POTENTIAL IMPACT, THE MAIN DISSEMINATION ACTIVITIES AND EXPLOITATION

Impact:

The main potential impact of the work conducted in WP10 is the possible application of the Hydrostatic Pressure Wheel for hydropower with head differences of 0.2 to 1m. Further impact is foreseen for the hydraulic power take-off, which offers the possibility of a low-cost PTO system with the possibility to pump water (e.g. for irrigation), to store energy and to generate electricity.

Main dissemination activities:

The HPW was described in an article in a scientific journal, and the results from experiments on the hydraulic power take-off were presented at a conference.

Exploitation:

The results from the experiments on the HPW led to two feasibility studies commissioned by owners of ultra low-head sites with head differences of 0.45 to 0.9 m (Cuddington Mill/Suffolk, Lovington House/Hampshire).

The hydraulic PTO experiments demonstrated the feasibility and advantages of the concept. As a result, a £14,000 grant was won to develop the concept further (SEDF grant).

WP 11: INTERNET BASED INFORMATION EXCHANGE AND DISSEMINATION

The regional distribution of site visits is shown in Fig. 11.1.

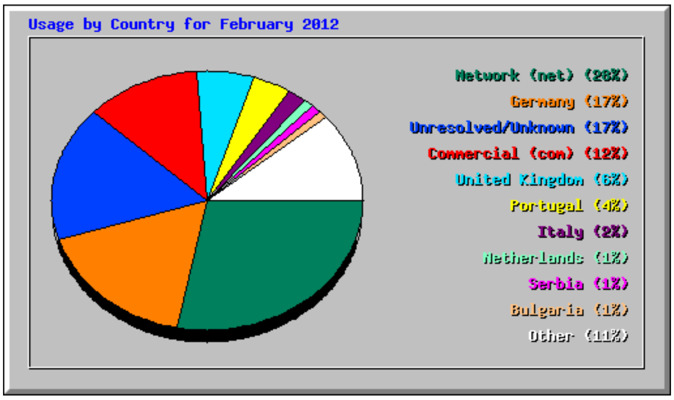


Fig. 11.1: Diverse global activity on the HYLOW website

WP12: KNOWLEDGE MINING

12.1 WORK PACKAGE AIMS AND OBJECTIVES

Small hydropower was very important as primary power source before the advent of electricity grids and electric motors. A substantial amount of development and research was done, mostly in continental Europe, to harness this source. Therefore, this work package had the aim to review and analyse German, French, English and Eastern European engineering literature on low head hydropower from 1850 on in order to establish whether or not useful principles and other information can be extracted which were forgotten or not accessible for a longer period of time (especially in Eastern Europe). Principles and concepts should also be analysed in terms of not being feasible in the past but today due to better control and design methods, improved theoretical knowledge, new available materials or different requirements on technology caused by ecological restrictions.

The following objectives were achieved: (1) Reports on English, French and German literature (1850-1950) and on pre-1990 Eastern European literature, (2) Analysis of finding with respect to project aims and achievements as well as use for further development and research.

12.2 MAIN SCIENTIFIC AND TECHNOLOGICAL RESULTS

The review and analysis of historic and contemporary engineering literature brought up interesting concept, some of which have as yet not been assessed regarding their performance potential (e.g. Chinese Chain Pump or Buoyancy machines). The Eastern European literature revealed some interesting free stream concepts which could be used within the development process of the Free Stream Energy Converter (WP 5). Regarding the usefulness of some of the other machines and ideas for low head hydropower it appeared that the concepts proposed are useful not for the area they were proposed in, but mostly in neighbouring newly developed areas (e.g. buoyancy devices for wave energy conversion). The original idea that new developed materials and better design methods may allow to bring old concepts forward was not necessarily valid. As results of the literature study a significant amount of original and novel theoretical work was conducted in order to establish the performance characteristics and limits of several machines (e.g. Archimedes Screw or Zuppinger wheel. This led to further insights about these machines.

The following main results were achieved:

A number of machines with unusual working principles or geometries were discovered. For many older machines, neither theory nor experimental performance data exists. Therefore, theories were developed which showed that the Archimedean screw, the Chinese chain pump, the AUR Water Engine and the Zuppinger wheel from 1848 are hydrostatic pressure converters whose efficiency is a function of the geometry. This led to a further substantial widening of the theoretical base of hydropower converters and subsequent publications.

Zuppinger's second wheel from 1848 provided the concept of curved horizontally fixed blades with lateral inflow. It may be able to process larger flow volumes than the known conventional Zuppinger water wheel from 1890. The comments on the importance of lateral inflow into the wheel confirmed assumptions made during development of the HPM and led to a series of tests to assess the optimum ratio of inflow and wheel width. Tests that allow lateral inflow could increase the efficiency of the machine significantly and allow for larger flow rates that can be processed. An efficiency increase of up to 15 % during model tests was the effect.

The Russian literature on floating converters gave interesting information about the trim angle required for maximum performance; this information was integrated into the WP 5.1 test program and found to give a performance increase of 10 - 15 %.

Some concepts, notably the Under-Water Motor and the AUR Water Engine, appear to be better suited to areas other than run-of-river hydropower, namely the utilisation of pressure differences in pipelines and in energy generation from waves.

The analysis of some converters indicated a connection with wave energy, which of course can be interpreted as a low head hydropower resource. The concept of buoyancy converters was developed further theoretically. Experiments on wave energy conversion were conducted; results agreed well with theoretical predictions of efficiencies of up to 40% indicating interesting development potential. In addition, technology developed under WP 2 was found to make the exploitation of potential energy created by wave overtopping possible.

Effects of hydropower converters on fish were already studied in the late 19th Century; here it was determined that standard water wheels do not have negative effects whilst Poncelet wheels and the 'modern' turbines do.

12.3 POTENTIAL IMPACT, THE MAIN DISSEMINATION ACTIVITIES AND EXPLOITATION

All results of the research on German, English, French and Eastern European literature were assessed for their relevance for the project itself and further exploitation.

Information on the stern-down trim angle for a floating energy converter could be included in the test programme for the Free Stream Energy Converter (WP 5) and information on the advantages of lateral inflow to a water wheel could be used during the optimization process of the Hydrostatic Pressure Machine (WP 2).

Theories were developed for different workings principles and machines found in the studied literature to assess their potential. For most of the found machines applications were not found in the area of low head hydropower but in other fields such as wave energy. A publication on the use of technology developed in work package 2 for the exploitation of potential energy created by wave overtopping is available.

The findings during the literature research were compiled in a literature review paper on low head hydropower machines. This has been submitted to the peer reviewed journal "ICE Proceedings Water Management" in August 2011. A further publication on the theory of Zuppinger and Sagebien type water wheel is planned.

A literature list was compiled as a 'living document' on the website (www.hylow.eu). A related archive was also set up on the website, so that references or copies of all relevant articles are available to the project members and selected articles also for the public.

WP 13: ENVIRONMENTAL DESIGN INPUT AND IMPACT STUDY

13.1 ASSESSMENT OF FISH RESPONSE TO LOW-HEAD ENERGY CONVERTERS

The development of Europe's potential for low-head hydropower is likely to play an important role in meeting Renewable Energy Obligations. This must be achieved within the constraints of stringent environmental legislation, including European commitments to preserve biodiversity (Convention on Biological Diversity), the EU Habitats Directive (92/43/EEC), the EU Water Framework Directive (WFD) (2000/60/EC), and EU Eel Regulations (1100/2007). The WFD requires that water courses and water bodies in all EU member states meet definitions of either "good ecological status" or, where heavily modified, "good ecological potential". To reach these targets there are two general obligations; first, that any deterioration in ecological quality is prohibited, and second, that any alterations should lead to the protection, enhancement or restoration of the water body (Water Framework Directive 2000/60/EC). The EU Eel Regulations requires member states to implement a number of short- and long-term measures to achieve a target of ensuring that at least 40% of potential production of adult eels return to the sea to spawn on an annual basis. It is therefore essential that new hydropower technology is robustly tested to ensure it fulfils strict environmental standards.

The aim of work package 13 was to assess the potential impact of novel energy converters, referred to as Hydrostatic Pressure Converters (HPCs), developed under HYLOW may have on populations of fish. To meet this aim the following objectives were set:

- Assessment of local environmental impact of free-stream energy converter (FSEC).
- Development of a numerical model for blade strike.
- Investigation of converter impact (flow velocity / turbulence, acoustics) on fish under laboratory conditions.
- Investigation of converter impact on fish under natural field conditions.
- Develop an Environmental Impact Statement.

Fish (brown trout, Salmo trutta) response to a model FSEC was investigated under laboratory conditions at the University of Southampton, and the impact of a full scale prototype was assessed using a combination of trapping and radio telemetry on the River Warnow, Germany. In the laboratory, fish exhibited a low level avoidance response (hesitation) when the model was present, but this did not cause any significant delay relative to the control (model absent). In the field trials, approximately 65% of fish (multiple species) released upstream moved downstream past the device within 1.5 hours. There was no difference in the percentage of fish that moved past the energy converter in the first 30 minutes after release or in the total number caught between the treatment (FSEC present) and control (FSEC absent) conditions. Of the 186 fish that passed through the FSEC, only 3 fish had potential blade strike related injuries. Thus maximum injury rate due to blade strike was 1.6%, which is comparable to values obtained for the Archimedes screw turbine (e.g. 1.4% of juvenile salmon suffered scale loss and 0.64% of eels were damaged). Under both laboratory and field conditions the FSEC did not obviously delay downstream movement of fish. For fish released downstream, no fish moved upstream past the device within 30 minutes. There was no difference in time taken to pass the study reach between treatment and control, with fish passing within 6 hours. A single fish (n=16) exhibited hesitative behaviour on encountering the FSEC and then failed to pass upstream. Overall, the presence of the FSEC did not delay upstream movement of fish.

A numerical blade strike model was developed. In addition to blade striking and grinding between moving parts, traditional turbines (e.g. Kaplan or Francis) can injure or kill fish that pass through them due to rapid pressure fluctuations, cavitation, shear stress and turbulence. As HPCs have a relatively slow rotational speed compared to other turbines, and operate at near atmospheric pressures, the primary cause for concern relates to injury that occurs as a fish is trapped between the blade tip and the shroud of the device. Probability of mechanical blade strike and grinding damage is lower for small fish, travelling faster than the current, and when blades are rotating slowly. Damage is also likely to be lower for the FSEC compared to other HPCs as a gap is left between the blade tip and the infrastructure, which is generally greater than the body depth of the fish. The blade strike model provides a useful first step in understanding potential impacts and mitigation options but is a simplification of reality as fish are assumed to act passively and exhibit limited behaviours.

In a blade strike validation study, freshly euthanized hatchery reared brown trout were recorded as they passively drifted through a model HPC. The frequency of blade strike was recorded, and fish were photographed before and after passage to determine the nature of injury sustained. Forty-eight percent of fish made contact with the blades, and 28% showed signs of physical injury. Note that while validating the blade strike model, these results do no represent those expected in the field as the model was not a full scale prototype and hence blade strike was predicted to be higher. However, the test does replicate the type of injury that would be expected, and this ranged from abrasive scale loss, to lacerations, internal haemorrhaging and skeletal damage.

Under laboratory conditions, using an internal flume, the response of fish (grayling, Thymallus thymallus; rainbow trout, Oncorhynchus mykiss; European eel, Anguilla anguilla) to the hydraulic conditions created by and visual presence of a model HPC was assessed. Using a larger external flume, fish (chub, Leuciscus cephalus, and eel) response relative to the acoustic environment created by a model of a HPC was investigated. Approximately 85% of fish that moved downstream within the internal flume and first encountered the HPC made contact with a screen at the intake, suggesting that if a screen was absent fish would likely pass through the device rather than actively avoid it. Similarly, in the external flume fish moving downstream did not appear to avoid the acoustic environment created, and would have likely passed through the device if a screen had been absent. The experimental studies indicate that physical screens are required to prevent fish entering HPCs, and potentially to divert them to more benign routes such as fish bypasses.

The impact of a full-scale prototype HPC installed on the River Iskar, Bulgaria, (Fig 13.1) and the effectiveness of an associated pool and weir fish pass for multiple species was investigated using a combination of netting and Passive Integrated Transponder (PITs) telemetry. As predicted by the blade strike model, mortality rates associated with passage through the HPC increased with fish length, and for fish shorter than 220 mm was generally less than 2%. However, for fish longer than 220mm, mortality was approximately 26%. Interestingly, damage to euthanized fish of the same size category passed through the converter was between 8 and 9%, indicating that the high rates of mortality observed for live fish was largely as a result of the behaviour exhibited. For several species, downstream moving fish exhibit a switch in rheotactic orientation to positive rheotaxis (face into the current) on encountering velocity gradients, such as at the intake to a HPC, and subsequently move downstream tail first at a rate slower than the water velocity. As a result, probability of blade strike is increased.

Fig. 13.1: Assessment of fish pass effectiveness River Iskar/Bulgaria

Upstream movement through the fish pass was recorded for 1 species (Romanian barbel, Barbus petenyi) only. This is likely, partially at least, to be a result of the time of year (late autumn) during which the study was conducted, when fish were expected to be less active. However, a recent meta-analysis has demonstrated that fish pass efficiency of these traditional fishway designs tend to be relatively low, particularly for non-salmonid species. Approximately half of fish that moved downstream did so through the fish ladder (8 species) when the HPC was inoperative. When the HPC was operating, 50% used the fish pass, with the remainder either passing over the weir or through the energy converter.

The FSEC was found to be relatively environmentally benign when compared with traditional hydropower technology, largely because it does not require an impoundment to generate a hydraulic head (i.e. based on the principles of hydrokinematics), and operates on the river surface. It was not found to induce delay, and even for those fish that entered the intakes, probability of blade strike is likely to be reduced as a gap is often provided between the blade tip and the converter. Nevertheless, screening may still be required depending on local legislation. The HPCs that require an impoundment to provide a head difference can impact fish moving upstream or downstream by inducing delay which can result in energetic expense and predation risk. To mitigate for this, a fish pass should be provided that can be demonstrated to work efficiently for both up- and downstream moving fish. Considering the low head nature of the technology described, nature-like fishways or rock ramps would provide optimal fish passage efficiency. However, attraction remains problematic and hence the entrance (for upstream moving fish) should be located close to the bulk flow of water, i.e. the energy converter tail race. Further, due to the high risk of injury and mortality associated with passage through the HPC, especially for long bodied fish such as eels that are afforded considerable legislative protection, physical screens of appropriate dimension (bar spacing) should be installed. This should be done in a manner that reduces risk of entrainment (and suffocation of fish) against the screen face under high flows, while directing the fish towards an appropriately located bypass.

WP14: RESOURCE ANALYSIS AND WATER FRAMEWORK DIRECTIVE (WFD):

14.1 WORK PACKAGE AIMS AND OBJECTIVES

The objectives of this work package are related to the influence of the implementation of the Water Framework Directive (WFD) on small hydropower as well as the compliance of small hydropower converters with the aims of this directive. The main objectives are defined as follows:

- Compliance of technology development with the WFD,
- Determination of WFD requirements for hydropower converters,
- Design input based on WFD requirements,
- Effect of WFD requirements on hydropower development,
- Contact with regulatory bodies to assess technology acceptance,
- Analysis and assessment of free stream resource on the coastal zone and estuaries,
- Analysis and assessment of low head resource in selected countries.

14.2 MAIN SCIENTIFIC AND TECHNOLOGICAL RESULTS

Water Framework Directive (WFD)

The Water Framework Directive (WFD), established in year the 2000, is probably the most important directive for protection of water bodies in the European Union. Central parts in the WFD are to improve the state of a water body quality as well as to prohibit deterioration of the state of a water body. The aim of the Water Framework Directive (WFD) is to achieve a good status/good potential of all or at least most water bodies. This results in the fact that only a “low level of distortion of the water body” is allowed.

For the assessment of the water body status, quality elements are defined in the WFD regarding the environmental quality (biological, hydromorphological and chemical as well as physico-chemical elements) and the chemical status. The assessment of the chemical status is based on existing emission limit values and environmental quality standards described by directives. The evaluation of an ecological status is based on a comparison of the present status of a water body with a reference status representing a good status. A good ecological status is assured, if the deviations from the reference status are of minor degree and show therefore minor levels of distortions resulting from human activities.

Hydropower is one of the so called green energies or renewable energies. Anyhow, hydropower plants have negative impacts on the environment. Typical impacts of hydropower on the environment are for example i) disruption in river continuity, ii) disruption of sediment transport, iii) low/reduced water flow, iv) direct mechanical damage to fauna/flora and v) artificialized discharge regime.

With the aim to fulfil the requirements of the WFD, possible impacts of hydropower plants need to be counterbalanced. The possible impacts itself indicates, where and what mitigation measures need to use to fulfil the requirements of the WFD. Consequently, measures or adjustment of hydropower plants are needed, which promote/ensure for example:

• Safety migration of fish fauna and benthic invertebrate fauna as well as aquatic flora to ensure natural abundance and composition of them.

• Flow regime upstream and downstream of the hydropower plant with natural fluctuation of water discharge and water level to ensure the biodiversity of river.

• Sediment dynamic with natural level to ensure the sediment continuity.

• Natural structure and condition of river bed, banks and riparian.

• Several mitigation measures or adjustments of the construction of hydropower converters, e.g. fish pass or fish rack, have an influence on the flow rate, the head difference, the flow velocity or the efficiency and finally on the hydropower potential.

The in the HYLOW Project developed and optimized energy converters “Free Stream Energy Converter” (FSEC) and “Hydrostatic Pressure Machine” (HPM) were investigated regarding the performance and also the impact on the environment. In addition to a theoretical assessment and environmental assessment based on field tests of the mentioned converters, regulatory bodies were contacted for getting information about potential problems that may arise during a permission process.

Hydrostatic Pressure Machine (HPM)

In general, the installation of the HPM in an existing weir can be an improvement of a weir site. The installation of an HPM will require the installation of a working fish pass (permission process). Hence, the continuity for fish and benthic invertebrate fauna migration will be restored with that measure. In addition, the HPM itself has only a minor impact on fish and sediment continuity. Smaller fish can pass the HPM without high injury risk and small to medium fine sediments can pass the machine directly without causing any damages. For protection of larger fish, a fish rack is necessary.

Free Stream Energy Converter (FSEC)

A Free Stream Energy Converter has in general no or minor negative influence on the ecologic system of a river. Due to the mooring and operation of the FSEC the changes of the environment are only minor, especially in comparison with conventional hydropower plants (which completely obstruct the river and/or discharge high amount of water). No parameters of the WFD quality elements (see above) are changed more than in a minor level. A fish protection system is recommended, anyhow.

Consequently, the FSEC and HPM (incl. fish pass) are - from the author's point of view - compatible with the requirements of the WFD.

Resource Analyses

In addition to the environmental compliance, the resource in case of a deployment of the mentioned energy converters was a main point of interest.

The hydropower potential for floating energy converters in general and especially the potential of floating energy converters with low draught are not studied in detail up to now. In the HYLOW project, the free stream resources were assessed for the northern part of the River Ems, for the southern part of Netherlands, for the UK continental shelf and for irrigation canals in Pakistan.

In general, suitable sites are sites with flow velocity between u=1.0 m/s and u=2.5 m/s, with adequate water depth (depend on the dimension of FSEC) and with no or compatible existing uses.

The Ems Estuary offers good condition for deployments of FSEC. Anyhow, the environmentally compatible potential is strongly reduced, due to wide areas which are reserved for nature protection areas.

On the UK continental shelf, different sites have comparatively high flow velocities and are well suitable for a deployment of FSEC.

The Irrigation canals of Pakistan are not appropriate for the deployment of converter types like FSEC, because most of the irrigation canals are small and show only low flow velocities (below u=0.7 m/s).

The potential deployment sites for the HPM are existing weirs with head difference up to 2.5 m. Low head resources were assessed for the selected countries Netherlands, Northern part of Germany, Bulgaria and for irrigation canals in Pakistan.

In spite of bad data situation, 9 suitable cross structures in the regional Water Authority "Brabantse Delta (South Netherlands) were found. In the sum, the cumulative theoretically power is 200 kW for all sites.

In Germany, from total 100,000 considered cross structures, for approx. 17,000 cross structures the information of head differences are available. 6440 cross structure are available in the range of head difference from 0.6 m to 2.5 m, which is appropriate for deployment of the HPM. Exemplarily for the Hunte River (Lower Saxony), estimated discharge values of an external study were used for the analyses of hydropower potential. The cumulative technical potential of the 30 considered structures is in the range from 1.7 MW to 7.5 MW.

For Bulgaria 89 appropriate weirs and sills were explored of old maps. In the data base only the structure heights (no head differences) and the average annual water discharge are given. The discharges in the range of 0.02 m^3/s and 53 m^3/s. At more than the half (55%) site, the mean annual discharges are less than 3 m^3/s.

For the six considered districts of the Province Khyber Pakhtunkhwa, 1108 suitable cross structure were indicated. The cumulative technical power of all 1108 site is about 28,225 kW (based on fully discharge supply). In opposition to FSEC, deployments of HPM in irrigation canals are quite advisable.

Results of the resource analyse in Lower Saxony (North Germany) can be used for assumption of resources in other low lying areas with gentle slopes. Also in other countries with flat land, many of existing head differences will be lower than 0.5 m and therefore are not suitable for the installation of HPMs. Furthermore, the most of the suitable cross structures would be located in small rivers. Large rivers are often used for navigation and must not be obstructed.

SECTION 4. POTENTIAL IMPACT AND MAIN DISSEMINATION ACTIVITIES AND EXPLOITATION RESULTS

1. POTENTIAL IMPACT

1.1 TECHNOLOGY DEVELOPMENT

The Hydrostatic Pressure Machine (HPM)

The project has demonstrated the feasibility of a novel type of turbine or rotary hydropower converter for a section of low head hydropower which can currently not be exploited in an economically and ecologically effective way. The '*increase in efficiency*' therefore should be redefined as the '*increase in area of application*' of hydropower with an acceptable efficiency / cost-effectiveness.

- It can be expected that in the near future at least a part of the as yet unused low head hydropower resource will be developed to generate electricity, creating a manufacturing market, reducing fossil fuel or nuclear power with decentralised generation capability and providing site owners with an independent supply.
- The development and in particular the demonstration in the field of the novel technology will increase its acceptance, leading to a further implementation.
- Ultra low-head hydropower installations will have average capacities of 50 to 70 kW, and will be distributed fairly evenly over the country. This means that energy generation happens close to the consumer, and long transport paths are avoided, contributing to an increase in efficiency.
- The theoretical framework developed within this project was modified, and theories for two hydropower converters which so far could not be analysed theoretically, were developed and validated (Archimedes screw, Zuppinger wheel).
- The high profile of both the topic and the project itself supported the development of other technology development / research activities in the field of low head hydropower.
- As a consequence, the EC is now internationally recognized as the leading centre for research and technology development in this area of activity.

Free Stream Energy Converter (FSEC)

The development of the FSEC has demonstrated that it is possible to generate electricity in this environment with reasonable efficiencies of 40% for with typical flow velocities of 1.5 to 1.8 m/s.

The comparatively low energy density of river currents combined with the existence of other intensive uses of rivers such as ship transport however means that the implementation of such schemes in Central Europe will be difficult.

Several queries from Brazil, Alaska and Zambia showed that this technology is of great interest to countries where the power supply in remote areas is difficult. Most settlements are located at the larger rivers, which also serve as transport paths so that power generation with the FSEC there is possible and economical (the diesel fuel in more than 250 settlements in Alaska e.g. has to be flown in or brought once a year by ship). The potential impact for the ecologically acceptable and economic supply of remote settlements worldwide is therefore large.

Micro Turbines

The development and demonstration of micro turbines for application in drinking water distribution systems has a series of potential impacts:

1. Novel concepts and technologies were developed and demonstrated, expanding the area of hydropower application;

2. Reductions in carbon dioxide emissions can be realized;

3. These converters could lead to a more decentralised energy production, reducing the reliance on large central power stations and improving the degree of energy security;

4. It could be expected that these converters could be exported to countries with significant numbers of small, medium and low head hydropower sites. These converters could also harvest energy resources in developing countries, reducing the amount of fossil fuel and greatly increasing the quality of life.

1.2 ENVIRONMENTAL IMPACT:

The development of hydropower with low head differences is impeded by environmental concerns, and by the requirements stated in the WFD, where the desire for an increase in the ecological quality of our water bodies is given its legal expression. The development of slow moving energy converters with continuous bed lead to significant improvements in environmental effects of hydropower installations when compared with standard technology. These in turn will allow for a much more widespread possible application of the novel technology (planning permission made easier to obtain):

- Contrary to Kaplan turbines, no local acceleration of the flow is required. The slow motion of the proposed energy converters, and in particular the fact that blades move with the velocity of the water, means that the potential for mechanical damages to fish is minimal.
- The energy converters operate under atmospheric pressure, so that damages to the fish's bladder (in particular for juvenile fish which cannot swim against the current) are not probable. The continuity of the flow means that the juvenile fish will not fall over weirs; it should be noted that from drops of 1.5m onwards such a fall can lead to physical damage to juveniles.
- The outflow velocities of the converters are very near to the velocity of the free stream. This means that guiding currents from fish passes for upstream migration will not be masked by fast outflows, as it can happen with Kaplan- or Ossberger installations.
- The converters create a continuous river bed, so that sediment can pass through unhindered.
- With a potential capacity of 0.6 GW (el.) in the UK alone, carbon dioxide emissions of 1.8m metric tons annually could be avoided.
- The new technology therefore offers a significant improvement in environmental impact when compared with existing technology, and will reduce adverse environmental effects on one side, and also improve or widen the potential area of application / number of sites open for development.

1.3 ECONOMIC IMPACT

HPM

The development of ecologically acceptable and cost-effective hydropower converters for very low head differences (HPM) which have been demonstrated in real field applications, has the potential to open up a new market. This will allow to exploit this hitherto unused source of renewable energy. The economic impact can be summarized as follows:

- Assuming average costs of €4,500 per kW installed capacity, and assuming that 50% of the existing potential can be developed, the market value in the UK and Germany is estimated as 2.2 bn€. This market would predominantly be served by consultancies and small manufacturing businesses, leading to local employment, added value and tax generation. The annual production in the UK, with a feed-in tariff of 19.7 p/kWh can be valued at 638m€, providing additional income for a large number of site owners rather than large conglomerates..
- Extrapolating the estimate of unused low head potential from the UK to the Northern / Western and central European Countries with a similar climate, a hydropower potential of (very approximately) 3 GW could be made available for exploitation. With an estimated average power plant capacity of 100 kW, this would mean a potential market for 30,000 sites. Since the technology must be competitive, costs of 4,500 € pre kW installed capacity would lead to a market value of 750 bn €.
- Hydropower will lead to a more decentralised energy production, reducing the reliance on large central power stations and improving the degree of energy autarky.
- Export: it can be expected that the technology will be exported to countries with significant
- numbers of small, low head hydropower sites such as Canada or the US. The development of appropriate technology will mean that energy resources in developing countries can be exploited, reducing the amount of fossil fuel and / or the length of electricity required, or indeed bringing electricity for the first time, thus greatly increasing the quality of life. In particular the large irrigation systems, where very large numbers of head drops between 0.5 and 3-4m exist are a potential market. In Pakistan alone, the available hydropower with head differences below 3m is estimated as 19 GW.

Micro turbines:

Hydro-energy sources have the potential to provide urban and rural/isolated areas with a reliable, efficient, safe and economic source of energy, and in this, to improve the overall system effectiveness of the decentralised areas and industries. The use of these novel types of hydropower converters can allow for best performances and efficiency of the whole system. They are relatively simple machines and do not require a significant installation/maintenance effort.

This type of converters do not involve drastic infrastructure changes, they can use economic equipment with ROI periods of less than four years This means that no environmental and social disruptions will be caused. In fact, presently, the water flow, which is available 24-hours per day in any water system, is not utilized for electricity production, and it is most of times effectively wasted.

Based on different types of analysis, including the optimization of WSSs operation, it was found that the implementation of micro-hydro turbines would allow for more than a 60% cost reduction during the exploitation life of the turbines. Additionally, the investment return comes as early as in the 3rd year of exploitation.

1.4 END USERS AND END USER IMPACT

The development of a novel technology up to the testing of technology demonstrators will conclusively show that this technology is feasible, ecologically and economically effective and therefore close to the market. The beneficiaries can be seen as:

(a). Owners of hydropower sites with very low head differences, who get the possibility to utilise this hydropower in combination with convincing evidence or performance characteristics without the acceptance problems often connected with small scale model tests.

(b). Hydraulic engineers will be provided with detailed design information about the low head

hydropower converters and will thus be able to offer solutions to potential projects which were so far not feasible.

(c). The introduction of a new type of hydraulic machine may lead its adaptation in other related fields, such as tidal energy.

2. SOCIO-ECONOMIC IMPLICATIONS OF PROJECT TO DATE

The socio-economic impact of the project is difficult to measure, since the project's main effects in these areas cannot be assessed with numbers – at least at this point. So far however five different project effects could be observed:

(a) Discussion: the publication of results and further dissemination through seminars and media coverage led to the development of a strong interest in the utilisation of ultra-low head hydropower, giving rise to often quite controversial public discussions between the stakeholders.

(b) Further technical development: the increased awareness of the topic also led to the uptake of the topic in other research institutions and areas (University of Technology Nuremberg started to develop inverter and generator systems for very low/variable speed applications, Hochschule Darmstadt is now evaluating Zuppinger water wheels and will take up some of the concepts from WP12).

(b) Involvement of industry: several companies are now becoming involved with the manufacture of HPMs and HPW's (Peter Elektronik Berg/Germany, www.peter-electronic.com, Burger Wasserkraftanlagen in Engetried/Germany, www.wasserkraft.biz.)

(d) Site development: in general there is a very pronounced reluctance of potential owners of hydropower sites to invest in experimental technology. Despite this, two projects are currently entering the stage where planning permission is applied for. The successful completion of these projects would open up the market further, allowing to commercialise the developments.

(e) The operation of a significant number of small hydropower installations with different owners will lead to a more diverse ownership of power generation. This will bring responsibility as well as information to a wider community, this increasing the number of stakeholders.

3. MAIN DISSEMINATION ACTIVITIES

3.1 SEMINARS

Three seminars / workshops addressed at engineers and site owners were organised during the lifetime of the project.

> Workshop 1 (01.10.2011); Title: Hydropower from water distribution networks; Location: Instituto Superior Tecnico, Lisbon/Portugal; Nr of attendees: 30.

> Workshop 2 (04.11.2011); Title: HYLOW Workshop: Development of hydro power converters for low head differences; Location: University of Southampton/UKl; Nr of attendees: 8.

> Workshop 2 (30.01.2012); Title: Neue Entwicklungen im Bereich Kleinwasserkraft (New developments in the field of small hydropower); Location: TU Braunschweig/Germany,; Nr of attendees: 47.

At the two last workshops, the HPM and FSEC technology was presented.

During both workshops, the main focus with respect to WP2 was on the presentation of the field installation in Partenstein and the design of the HPM. At the deployment site in Partenstein an official initiation of the HPM was held in July 2011.

3.2 PUBLICATIONS

In all, 58 articles were published in peer reviewed journals or conferences. Publications in journals include scientific as well as institution journals. Four articles are currently submitted, and one is accepted for publication. 8 more articles are planned (see list of publications)

The further dissemination of foreground will predominantly take place through publications in conference proceedings and journals (scientific and professional institutions) and through the website, which will remain active for at least two years. The coordinator will update the website and look after contacts.

Future presentations are planned, e.g. an invited presentation on low-head hydropower at the DWA annual meeting on 15.10.2012 in Wiesbaden/Germany.

3.3 TV AND RADIO COVERAGE

In August 2010 a TV team from the *Bayrisches Fernsehen* in Germany visited the laboratory at TUD and filmed the model tests in the flume and in the 3D physical model (BF, 2010). After the broadcast of the TV show a wide spread audience - from mill owners to companies - contacted partner 2.

The field deployment of the FSEC in Sagsdorf / River Warnow (Northern Germany) February 2011 led to a very widespread TV coverage, with German national channels ZDF and SAT 1 running 15 minute specials on the technology. The project was also featured in several national newspapers (e.g. Die Welt, 07.03.2011, daily circulation 250,087 prints) and weekly magazines (Focus, 06.03.2011, weekly circulation 137,537).

3.4 WEB PRESENCE

Web page coverage is reported in detail in WP11. The external usage of the site increased with time and in particular the downloads (historic engineering literature without copyright issues) proved to be very popular.

Feedback came mostly through queries about potential projects, from people active in low-head hydropower R/D looking for potential cooperation and from inventors, who either wanted an independent assessment of their developments or looked for funding.

The feedback from site owners led to three feasibility studies being commissioned so far. A cooperation with the Univ. of Applied Science Nürnberg/Germany and Peter Elektronik (also Nürnberg) was established to look at power take-off and grid connection for variable speed hydropower machines.

3.5 OTHER ACTIVITIES

A design manual has been compiled and will be published in the University of Southampton Sustainable Energy series as volume 6, 7 and 8 (ISSN 1747-0544).

One patent (flexible blades for HPM) has been applied for (Patent application reference number: GB1007134.8)

4. EXPLOITATION OF RESULTS

4.1 COMMERCIAL

HPM

It is planned to utilise the foreground developed under WP's 2, 3 and 4 to design low head hydropower plants. The coordinator has set up an engineering consultancy, which is currently engaged in two feasibility studies. If further market opportunities arise, it is envisaged to form a consortium to exploit the HPM technology further. This is however difficult to assess at present.

Micro turbines

This type of micro hydro production has the possibility of being installed in most of existing Water Distribution Systems and like this produce locally some energy that in most cases will be possible to consume locally, besides the opportunity of selling it to the grid.

Other institutions, like EDP INOVAÇÃO and PCT, Pole for Competitiveness and Technology, in Portugal considered the project is eligible and want to support its dissemination.

4.2 FURTHER RESEARCH

Based on the foreground developed under WP2 and the identified further necessary development work a new R/D project was applied for by partners that have been involved in the development work of the HPM (German Fed. Ministry for the Env., €850k). The idea of the project is to extend the monitoring time for the field installations in Partenstein and at river Iskar as well as to allow for further investigation of the morphological and environmental impacts. In addition a guideline to apply for water legal permission should be developed.

> Within WP 12 (knowledge mining) a promising technology for head differences between 2 and 5 m was found (Zuppinger's water wheel from 1848). This technology was apparently tested but never applied, possibly because of cost disadvantages due to the all-iron construction. For today's hydropower environment it could offer the potential for a cost effective and ecologically acceptable machine. A stage 1 grant application (48,000 €) will be submitted to the Deutsche Bundesstiftung Umwelt (German foundation for the environment, DBU) within May 2012.