European Commission

HYLOW Report Summary

Project ID: 212423

Funded under: FP7-ENERGY

Country: United Kingdom

Final Report Summary - HYLOW (Hydropower converters with very low head differences)

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/QDes (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 computational fluid dynamics (CFD) models, a five 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.

Project context and objectives:

Introduction

In Europe, there exists an unused (i.e. 50 to 1 000 kW) hydropower resource in rivers of approximately 5 GW. Most of the available hydropower is available at existing weirs. Commercial turbine technology is considered not cost effective for these very low head differences. Low head hydropower schemes can have significant environmental impact at the local scale. In light of the European Union (EU) Water Framework Directive (WFD) 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.

Existing technologies

There are several turbine or hydropower converter technologies which are currently employed in the ultra low-head segment 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. 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.

Environmental concerns / WFD

In order to improve the ecological status of rivers and lakes, the European WFD has been introduced over the last decade. This legislation and the resulting implementation guidelines require, 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. 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.

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 can affect the overall economy of an investment negatively.

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 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 have very low efficiencies of 30 % or less. Combined with the low energy density of typical flow velocities in rivers, 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.

Project objectives

The proposed project has the aim to develop and optimise a novel type of turbine for small hydropower (less than 1 000 kW) and very low head differences below 2.5m which is significantly more cost-effective than current technology and minimises adverse ecological effects. It will therefore be compatible with the WFD. 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:

1. investigation of generic configurations of energy converters using theoretical and physical models
2. development of energy converters for three different applications using theoretical and numerical modelling and physical model tests
3. concurrent assessment of / design for minimised environmental impact
4. optimisation using numerical modelling
5. design and deployment of large scale models in nature
6. development of designs with appropriate technology
7. design recommendations and design handbook.

Project results:

Work package two (WP2): Converter technology and development

WP2 has the aim to develop the theoretical and practical information required for the design and performance prediction of the hydrostatic pressure converter (HPC) for very low head differences in river application. Objectives:

1. development of more accurate theory, including turbulent losses
2. generic model tests to improve fundamental understanding
3. verification of generic model test at increased scale to assess scaling effects
4. determination of optimum geometry for HPM
5. assessment of HPM performance in a river situation (flooding, fish compatibility, sediment transport)
6. identification of geometry for WP3
7. design, installation and monitoring of a medium scale model (MSM)
8. validation of optimised geometry.

Two novel hydropower converters for very low-head differences were developed, the hydrostatic pressure wheel (HPW) and the 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. The HPM has a hub at which radial blades are fixed that close the machine against the upstream water pressure. 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. 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.

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 (TUD) 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. Straight, curved and diagonal fixed blades were installed and tested. The optimum characteristics for the HPM were also determined with the numerical model that was set up in WP9. With a realistic reduction of gap losses to 1 % of the maximum theoretical flow rate mechanical efficiencies of up to 78 % could be reached. Leakage losses only played an important role in the lower flow rate range and lost 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. 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.

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. 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 0.7 QDesign (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 6 rpm the wheels' movement was smooths. 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 minimisation 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 (0.025 to 0.045 QDes) due to good sealings.

A 1:15 scale three-dimensional 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 optimisation of the in- and outlet structure and the effect of the wheel installation on the sediment transport regime. The HPM model had a diameter of 160 mm and a width of 133 mm. The design flow was defined as QDesign = 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. 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.

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 easily.

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. 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.

The following main results with respect to the machines performance were achieved:

1. an optimum geometry including curves for performance prediction was determined
2. a HPM configuration with 10 to 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. minimising 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.

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. 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 physical model. In addition the results of the model tests were presented at several conferences.

WP2A: Morphodynamic regime near hydropower stations

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. 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

WP2A:

1. literature / field study of sediment deposition / erosion at small hydropower installations
2. assessment of effect of HPM on morphodynamic regime
3. development of sediment guidance structures
4. design recommendations morphology near HPM/HPW installations.

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:

1. scouring at the inflow wing wall of the HPM installation
2. 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. 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.

WP3: Large scale model, design and monitoring - HPM

WP3 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 HPM is to test the technology in natural environmental conditions at full prototype scale in order to study and analyse 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 WP3:

1. determination of design flow and water levels
2. hydraulic design of large scale model (LSM) for chosen site including flood risk analysis
3. obtain planning permits
4. monitoring of HPM performance and environmental aspects (fish passage, sediment regime)
5. analysis of data, comparison with design information.

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 TUD and University of Southampton in the frame of WP2.

The LSM of the HPM has a diameter of 2.40 m and width of 2.00 m with 10 blades inclined on15 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 small hydroelectric power plant (SHPP) and HPM installation from different authorities 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. Real time changes of the load on the generator were possible with the power electronics converter that allows the controllable load variation. Monitoring of the HPM performance was performed under different conditions that allowed assessing the optimal performance of the machine.

The following conclusions for the HPM performance could be made:

1. the optimal performance of the machine is achieved when the speed of rotation of the HPM wheel is in the range of 7.5 to 10 rpm
2. for the conditions of optimal performance the achieved power output is in the range of 6.00 to 7.50 kW for different upstream water levels and the mechanical efficiency is in the range of 55 to 65 %.
3. higher efficiency of the HPM is achieved when the upstream water level is lower than the top edge of the hub but higher power output is achieved when the it is higher than the top edge of the hub
4. for fish passage through the weir in both directions, a fish pass was built with parameters developed at TUD. It proved to work well although the observations were performed mainly outside the time of active migration.
5. statistically representative mortality and injury tests were carried out with typical species both local and common for Europe
6. the mortality through the HPM is almost zero, injuries were observed mainly at the larger fishes which can easily not be allowed into the HPM with simple measures.

The following conclusions can be drawn from the research operation of the HPM:

1. a complete energy convertor solution for very low head differences has been developed and successfully implemented as a full-scale prototype application
2. the developed engineering know-how covers the whole process from site location via energy production up to dealing with extraordinary situations
3. in this head range (1 to 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.

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.

WP5: Large scale model design and monitoring, free stream energy converter (FSEC)

Within this WP 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:

1. determination of large scale model geometry including stability and station keeping
2. design of large scale model including power take-off
3. measurement equipment and programme
4. identification of two suitable deployment sites
5. design and construction of mooring

6. transport, deployment and monitoring
7. monitoring
8. Validation.

For the determination of FSEC design many experimental tests are used. These were beginning with simple and special parts of future FSEC design, and included pre-tests in the wind tunnel and pre-tests in the small flume. After that model tests with fixed and floating small scaled models (SSMs) based on pre test results were used for validation and new findings with the aim to maximise the power output. SSM tests were conducted with three types of model in four different flumes and tank. The next step was a MSL for validation of the SSM test results. It was tested in natural water and a towing tank. On basis of the SSM and MSM, a LSM of the FSEC (7.6 m length and 2.4 m width) was designed and constructed for field tests under nearly natural conditions.

Based on the results of model tests, the optimised design of the FSEC is created. It is modelled in the computer assisted design (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. In preparation of the LSM 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.

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). In total, 170 tests according to 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. 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 21 February 2012 and 1 April 2012 the optimised FSEC LSM was tested in the second deployment site, the Warnow River (northern Germany). 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. Furthermore, the flow conditions and the influence of the buoyancy chamber on the performance were investigated. 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. No significant increases of current velocities were determined. For the assessment of change of the riverbed, the bathymetry (river bed morphology) was surveyed. The increase of the local noise emission is negligible. Furthermore, investigations to the fish behaviour were executed during the field test in the Warnow River.

WP7: Development and monitoring of micro-turbine and volumetric / spin type hydropower equipment (HPE)

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 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.

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 minimisation of CO2, 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 carbon dioxide (CO2) 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 utilised for electricity production and it is most of times effectively wasted.

Based on different types of analysis, including the optimisation of water supply systems (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 CO2 emissions can be realised
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.

WP8: Viability analysis for potential hydropower sites in water supply systems - HPE and micro-turbine

The objective of WP8 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 nearby the site of production.

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 WP7 or a PAT. 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. 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.

This type of micro hydro production has the possibility of being installed in most of existing WSS 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. Several institutions in Portugal considered the project is eligible and want to support its dissemination.

WP9: Converter optimisation - HPM and FSEC

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

The numerical model of the HPM is generated using commercial CFD software and the model is validated with data from WP2. 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 two-dimensional (2D) model for the HPM with straight blades. In a further step, the complete three-dimensional (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 CFD simulation software. This includes implementing direct simulations using volume-of-fluid (VoF) methods for the case of free surfaces.

Main results HPM:

1. Three variations in blade angle show that machine efficiency increases with an increase in the angle of the blade to the machine axis.
2. 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.
3. 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.

Main results FSEC:

A verified numerical model was setup and compared with the experiments performed in WP 5. 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. 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.

WP10: Development of appropriate technology

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 WP9.

The technology developed under WP2 and WP5 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 to 50 % of the total cost of an installation and requiring high-tech products. Low-cost solutions for gearing as well as for direct energy conversion systems where no gearing is required were therefore assessed. Several possibilities of direct energy conversion were investigated both theoretically and experimentally. Moreover, 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. 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. The developed 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, while it is not really suited for very low head differences.

The proposed technology 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 demonstrated the potential of the HPW. The simplicity of construction lends itself for small installations e.g. in developing countries.

The main potential impact of the work conducted in WP10 is the possible application of the HPW 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 system with the possibility to pump water (e.g. for irrigation), to store energy and to generate electricity. 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.

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

WP11 was concerned with internet based information exchange and dissemination.

WP12: Knowledge mining

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 WP 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 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. The Eastern European literature revealed some interesting free stream concepts which could be used within the development process of the FSEC. 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. 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. As part of this WP, a number of machines with unusual working principles or geometries were discovered.

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. Theories were developed for different working 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. 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 Institute of Civil

Engineers (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 (see http://www.hylow.eu online). 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.

WP13: Environmental design input and impact study

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. 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. 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 returns 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 WP 13 was to assess the potential impact of novel energy converters, referred to as HPCs, developed under HYLOW may have on populations of fish. To meet this aim the following objectives were set:

1. assessment of local environmental impact of FSEC
2. development of a numerical model for blade strike
3. investigation of converter impact on fish under laboratory conditions
4. investigation of converter impact on fish under natural field conditions
5. develop an environmental impact statement.

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 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 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 should be installed. This should be done in a manner that reduces risk of entrainment against the screen face under high flows, while directing the fish towards an appropriately located bypass.

WP14: Resource analysis and WFD

The objectives of this WP are related to the influence of the implementation of the 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:

1. compliance of technology development with the WFD
2. determination of WFD requirements for hydropower converters
3. design input based on WFD requirements
4. effect of WFD requirements on hydropower development
5. contact with regulatory bodies to assess technology acceptance

6. analysis and assessment of free stream resource on the coastal zone and estuaries
7. analysis and assessment of low head resource in selected countries.

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 disruption in river continuity, disruption of sediment transport, low/reduced water flow, direct mechanical damage to fauna/flora and artificialised 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.

In the HYLOW project, 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.

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.

A FSEC 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 are changed more than in a minor level. A fish protection system is recommended, anyhow.

Consequently, the FSEC and HPM (including 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. 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.

Potential impact:

Technology development

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 following impacts in the area of the HPM technology development are expected:

1. 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
2. the development and in particular the demonstration in the field of the novel technology will increase its acceptance, leading to a further implementation

3. ultra low-head hydropower installations will have average capacities of 50 to 70 kW and will be distributed fairly evenly over the country
4. 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)
5. 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
6. as a consequence, the European Community (EC) is now internationally recognised as the leading centre for research and technology development in this area of activity.

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.

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 CO_2 emissions can be realised
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.

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:

1. no local acceleration of the flow is required, meaning that the potential for mechanical damages to fish is minimal
2. the energy converters operate under atmospheric pressure, so that damages to the fish's bladder are not probable
3. the outflow velocities of the converters are very near to the velocity of the free stream, meaning that guiding currents from fish passes for upstream migration will not be masked by fast outflows
4. the converters create a continuous river bed, so that sediment can pass through unhindered
5. with a potential capacity of 0.6 GW in the UK alone, CO_2 emissions of 1.8 million 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.

Economic impact

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 exploiting this hitherto unused source of renewable energy. The economic impact can be summarised as follows:

1. assuming average costs of around 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 billion
2. 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
3. hydropower will lead to a more decentralised energy production, reducing the reliance on large central power stations and improving the degree of energy autarky
4. 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 United States of America. The development of appropriate technology will mean that energy resources in developing countries can also be exploited.

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 utilised for electricity production and it is most of times effectively wasted. Based on different types of analysis, including the optimisation 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 third year of exploitation.

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 owners of hydropower sites with very low head differences, hydraulic engineers which will be provided with detailed design information and other beneficiaries of potentially related fields, such as tidal energy.

Socioeconomic implications of project so far

The socioeconomic 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:

1. 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.
2. Further technical development: the increased awareness of the topic also led to the uptake of the topic in other research institutions and areas.
3. Involvement of industry: several companies are now becoming involved with the manufacture of HPMs and HPWs
4. 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 commercialisation of the developments.
5. 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.

The main dissemination activities included:

1. Three seminars / workshops addressed at engineers and site owners in Portugal, UK and Germany. At the two last workshops, the HPM and FSEC technology was presented.
2. 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. Eight more articles are planned. 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. Future presentations are also planned.
3. Television (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 After the broadcast of the TV show a wide spread audience contacted the partner. The field deployment of the FSEC in Sagsdorf / River Warnow in February 2011 led to a very widespread TV coverage. The project was also featured in several national newspapers and weekly magazines.
4. Web presence. The external usage of the project's 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 research and development (R&D) looking for potential cooperation and from inventors. The feedback from site owners led to three feasibility studies being commissioned so far.

Other activities included the compilation of a design manual and the application for one patent (flexible blades for HPM).

Exploitation of results

Commercial

It is planned to utilise the foreground developed under WP2, WP3 and WP4 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.

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 in Portugal considered the project is eligible and want to support its dissemination.

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. 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 standardised guideline for application for planning permission should be developed.

Within WP12 (knowledge mining) a promising technology for head differences between 2 to 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 one grant application was therefore planned to be submitted to the Deutsche Bundesstiftung Umwelt (German foundation for the environment, DBU) within May 2012.

Project website: http://www.hylow.eu

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