REVIEW OF CURRENT DEVELOPMENTS IN LOW HEAD, SMALL HYDROPOWER

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ABSTRACT

In Europe, the development of hydropower with installed capacities of more than 1 MW and head differences of more than 2 – 3 m is nearly completed. A promising corner of the future hydropower market remains the economical and ecologically acceptable exploitation of smaller hydropower from 100 – 1000 kW with very low head differences of 0.80 up to 2.00 m, where conventional turbines are neither economical nor ecologically undisputed. In response to this situation, a number of novel energy converters, some of which reliant on rather unusual principles, have been proposed and developed. The high efficiencies stated by the inventors are however often neither confirmed by theoretical considerations nor by measurements. Often a positive view of the innovator will valuate the efficiency too high, as well as the specific investment costs as too low, leaving potential investors with a large margin of risk. The most important new technologies were analysed from the view of underlying technical principles and possible efficiency, economy and ecological impact. It was found that most proposed technologies suffer from low efficiencies as well as high investment costs. Only the *Rotary Hydraulic Pressure Machine* appears to have development potential. The article aims to give an overview over an emerging market in order to give engineers a background for the rational assessment of a variety of new technologies.

Keywords: low head hydropower, micro-hydropower, small hydro, low head

1 INTRODUCTION

The European Commission has set a target of 12% renewable energy as percentage of the total electricity production by 2010. This gives the current interest in renewable energy sources an increased impetus. One significant but so far mostly untouched reservoir of green energy is hydropower with very low head differences of less than 2 m. The economical and ecologically acceptable use of this section of small hydropower, with power ratings mostly between 100 and 1000 kW and very low heads of 0.8 to 2.0 m, still represents an unresolved problem. The reasons for this are to be found in the inefficiency of smaller turbine plants as well as their reported negative ecological effects, *e.g.* Bunge (2001). As a result, the area of low head hydropower has attracted the attention of many researchers and inventors. With significant numbers of potential sites available, the perceived (or expected) economic potential often dominates the available information both in terms of positive attitude with respect to the (perceived) technical advantages, performance and availability of factual information, and regarding costs and environmental impact. At the same time, owners and operators of hydropower sites ideally require objective information about the potential of proposed energy converters; information which is more likely than not forthcoming only selectively. Academic research has recently shown only little interest in this topic, so that no overview of the current situation is available. In addition, many developments are limited to the German or French language zones, without coverage in English. The aim of this report is to give a review of new developments of micro-hydropower plants, particularly in the section of small head differences. For this purpose, new technologies are presented, which are nearly market-ready or only exist as a concept.

2 LOW HEAD, SMALL HYDROPOWER POTENTIAL

In Europe, already more than 70 % of the output of the theoretically available hydropower capabilities are fully developed (Giesecke & Mosonyi, 2005). The development of hydropower with more than 1 MW installed capacity in Europe is as far as possible completed. A promising niche for the future use however comes out of the economical and ecologically acceptable use of small-scale hydropower from 100 up to 1000 kW with very low head differences from 0.80 m up to 2.00 m. This bracket of hydropower is generally considered to be not exploitable and therefore not even included in many resource surveys, e.g. ETSU (1982). In order to get an idea of the number of possible sites, a count of the weir structures in rivers in a German *Land* (Federal State) of 1,000 km² area resulted in 1,304 locations with head differences between 0.20 and 1.00 m, which are considered as possible potential NRW (2005). Projecting this result to Europe, there should be several 10,000 locations as theoretical potential.

3 OVERVIEW OF NEW TECHNOLOGIES

3.1 GENERAL

Conventional hydropower converters such as turbines, waterwheels or Archimedian screws, cannot be used for low head hydropower because they are either not cost-effective (turbines) or limited in capacity (water wheels, Archimedian Screws). Subsequently, new technologies of micro-hydropower plant for low head differences have been emerging, most of which are still in the various stages of development. These converters will be analysed and presented in more detail in the following subchapters. The oldest energy converter for this hydropower bracket, the stream wheel, will be addressed only briefly since its capacity is – similar to ordinary water wheels – limited to less than 100 kW. Fig. 1 gives an overview over the areas of application as a function of head differences and flow rates for the various energy converters.

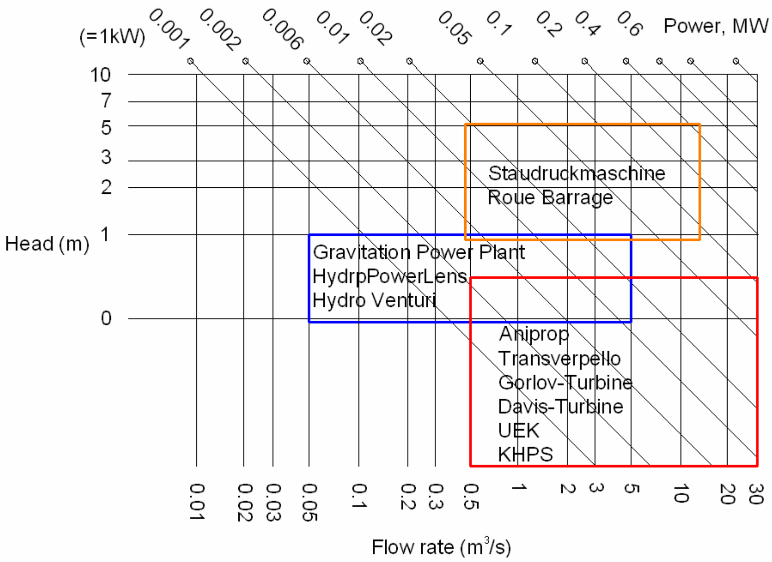

Fig. 1: Application areas of new hydropower technologies

3.2 TECHNOLOGIES CURRENTLY UNDER DEVELOPMENT

The technologies *Gorlov-Turbine*, *HydroVenturi*, *Davis-Turbine, KHPS*-turbine and the *UEK*-turbine are developments coming from the field of tidal power research. To what extent derivations of these ideas can be employed for hydropower remains to be seen within the next years. Except for the *HydroVenturi*, all energy converters utilise the kinetic energy of the flowing water.

The *Gorlov-Turbine* generates energy from the hydro kinetic energy in a watercourse without head difference. The turbine is a direct flow turbine with wing-shaped rotor blades and a diameter of 1.5 m as well as a length of 2.5 m. The power generation starts at 1.5 m/s flow velocity with a nominal output of 1.5 kW. The overall efficiency factor is at 33 %, Bedard (2005). The *Gorlov-Turbine* combines a solid, simple design with a simple technology which manages with comparatively few component parts. In a river deployment however, problems can be expected due to natural growth – which would destroy the hydrodynamic profiles, combined with low efficiency as well as the maintenance effort of the bearing, which is permanently exposed to the water.

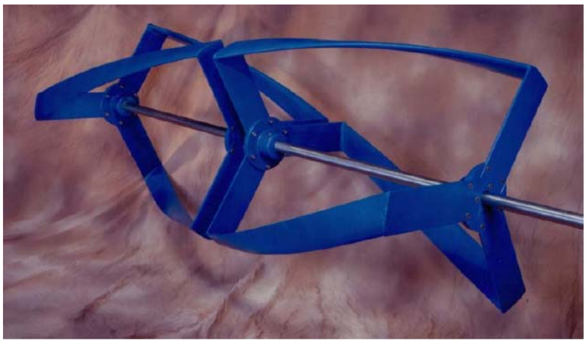

Fig. 2: *Gorlov-Turbine* as computer model, Bedard (2005)

The *Davis-Turbine* employs the concept of the *Darrieus* turbine. It has a vertical axis and has been developed for a long-life under water application. The four blades of the *Davis-Turbine*, similar to hydrofoils, are connected to a rotor, which in turn actuates a drive and a generator, Blue-Energy (2006). Up to now six prototypes have been built to assess feasibility under the supervision of the National Research Council of Canada and independent institutions. Unfortunately there are actually no binding statements about the achieved degrees of efficiency available, Bedard (2005). Comparison with the *Darrieus* turbine suggests an efficiency of 30%.

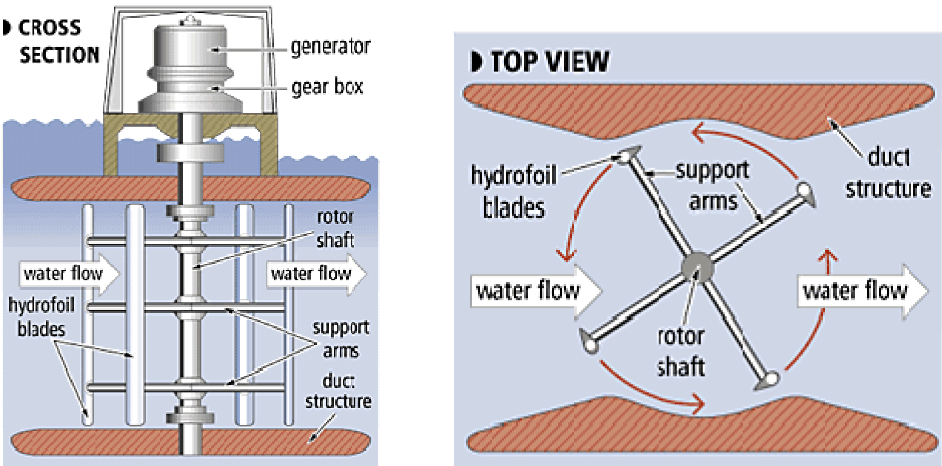

Fig. 3: *Davis-Turbine*, (a) side elevation, (b) Plan view, Blue Energy (2006),

The *Underwater Electric Kite* (UEK) is a horizontal axis propeller type turbine with a so-called augmenter ring. The ring is part of the enclosure which protects the turbines and adjusts the water flow in such a manner that behind the turbine a low pressure zone emerges in order to achieve higher degrees of efficiency, Bedard (2005). In Switzerland possible locations are currently being identified for a pilot project within the scope of a feasibility study. The possibilities of use in rivers have to be viewed critically in regard to the expected considerable dimensions of the system, Randall (2006). The manufacturers claim a 57% hydraulic to electrical efficiency.

Fig. 4: *UEK* prototype, Bedard (2005)

The *Kinetic Hydro Power System*, (KHPS) is a 3-blade propeller turbine with a high efficiency designed for a wide flow velocity range. The current turbine which was constructed for the well-known RITE-project on the East River in New York, has a diameter of 5 m with a nominal output of 35.9 kW for a flow velocity of 2.2 m/s. Depending on the flow velocity, the efficiency of the turbine is approximately 30 %, Bedard (2005). The cost estimates, which were at that time too optimistic, resulted in power production costs of 0.10 US$/kWh. Until today, this technology could not be commercialised. The main obstacle appears to be the requirement for (for rivers) very large water depths in combination with high flow velocities, which limit the number of possible installation sites substantially.

Fig. 5: *KHSP-turbine* (a) computer image, Bedard (2005) and (b) photo of prototype *KHPS*-turbine, Verdantpower (2006)

The technology of the Company *HydroVenturi* employs a combination of a pull-push mechanism. The river is guided through the so-called “shaper“ which accelerates the flow, inducing a pressure drop, which is used to suck air in from the atmosphere through an air-driven turbine which generates power. Based on manufacturer’s statements, the efficiency at low head differences is between 20 and 25 %, Hydroventuri (2006). Within the scope of a study from the American research centre EPRI, an independent expert determined a possible efficiency of only 3%, Bedard (2005). Furthermore the vacuum generated by the shaper is expected to lead to problems such as cavitation – which will limit the possible power output - and to have a negative impact on the fish population.

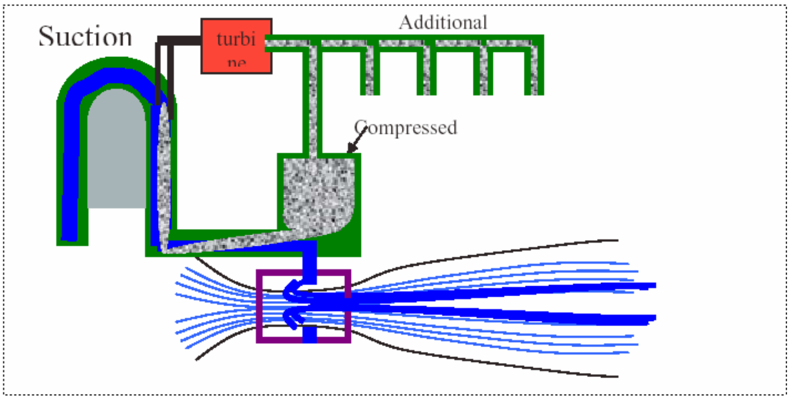

Fig 6: Principle *HydroVenturi*, Bedard (2005)

3.3 TECHNOLOGIES AT LABORATORY STAGE

The *Transverpello*-Technology and the *HydroPowerLens* have not yet reached prototype status. The concept of *HydroPowerLens* is presently being tested in detail at the University of Eindhoven in the Netherlands. The working principle of the *Transverpello* is based on the horizontal hydrodynamic forces developing on a vertical hydrofoil. A vertical axis to which a floating pontoon-formed blade is attached is anchored in the river. As the water flows by, the hydrodynamic force will push the hydrofoil to one side. At the maximum angle of deflection, where hydrodynamic 'uplift' and counteracting impulse balance, the blade reverses automatically and thus moves into the opposite direction. This oscillating movement, is then employed for power generation. The Federal Army's Technical University at Munich / Germany conducted physical model tests and found that the efficiency - determined as the ratio of actual and maximum theoretical power output based on airfoil theory - was a function of the pendulum frequency and varied between 44 % and 81 %, Transverpello (2006). A careful analysis of the data given in the model test report however revealed that the actual efficiency was only 4.6 % of the total available energy since an airfil would only have a maximum efficiency of 5%. An application of the *Transverpello*-technology is not expected within the next years. In regard to environmental impact the *Transverpello* is expected to creat an upstream increase of water level, and significant wave and turbulence propagation downstream with impact on the sediment transport, and shore erosion.

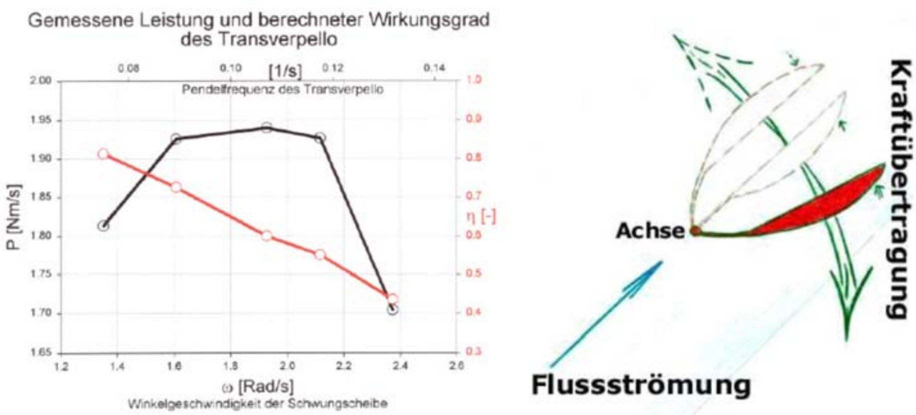

Fig. 7: *Transverpello* (a) efficiency as function of frequency, and (b) functional principle, Transverpello (2006)

The *HydroPowerLens* is based on the transformation of wave energy. Using a wave oscillator, waves are generated from a head difference in a river. Since the waves are generated by a concave weir, their direction of propagation focuses in one point. The waves become constantly higher from the outside to the centre, because the energy of the wave has to stay constant. The waves then spill over onto an elevated basin; the potential energy gained is then converted into electricity using a standard turbine The expected efficiency for a 0.5 m head is conservatively estimated at 25 %, Berkel (2006). The developers give a cost of. 4,200 Euro/kW installed power, this however appears very low in particular when considering the fact that a special concave weir needs to be built.

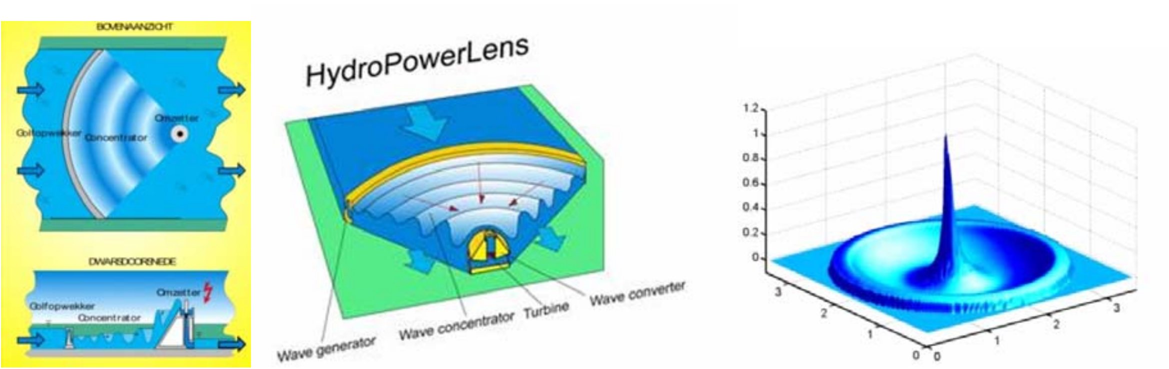

Fig. 8: Principle *HydroPowerLens*, Entry Technology (2006)

The *stream wheel* or impulse wheel is a water wheel which employs the kinetic energy of a free surface flow. Stream wheels for river applications had capacities ranging from 1.0 to 40 kW, with efficiencies of 30-40%, and are therefore not subject of this article. Only the stream wheel in deep water, mounted on a floating platform with a *Venturi* – type channel to increase the flow rate appears to have potential for further development. For this type of energy converters, model tests and theoretical analysis indicated that power ratings of up to 1 MW seem possible. Further information is given in Müller et al. (2006).

3.4 TECHNOLOGIES – PROTOTYPE STAGE

For these technologies, prototypes have been constructed, which are presently in trial. If these tests are successful commercialisation would be the next step.

Fig. 9: (a) *Gravitational Vortex Converter*, side view of vortex, Zotlöterer (2006) and (b) photo of *Aniprop*, a stroke wing power generator, Aniprop (2006)

The *Gravitational Vortex Converter* is a novel hydroelectric power plant, which uses the concentrated rotational energy from the centre of a whirlpool with help of an automatic flow controlled, vertical axis turbine which is located inside the vortex for energy production. The efficiency figure given by the inventor for head differences larger than 0.7 m is 80 %, Zotlöterer (2006). The use of this technology in terms of so-called multi-purpose projects for ventilation of waters and for energy production is in conflict with the necessary civil work which represents a considerable interference with nature. A theoretical evaluation conducted by the authors, based on the Bernoulli formula with an additional term for centrifugal forces resulted in maximum efficiencies of 28-35 %.

The *Aniprop*, a vertical stroke kinetic energy converter is based on the up- or downward acting forces on an inclined plate in horizontal flow. This vertical stroke motion is then converted into electrical energy. In June 2006, a two-year test run with a 1 kW-machine was finished (v = 2 m/s, Q = 3 m^3/s). The efficiency was measured as 12.5 %. The innovator had expected a maximum theoretical efficiency of 59.3 %, Aniprop (2006). A close inspection of the theoretical basis for this assumption showed that the theory was derived from airfoil theory, and the effect of the fee surface had been neglected. If the distance from the machine to the water surface is too low, this causes surface waves, which probably will reduce the efficiency considerably. At the downstream, water waves can be expected, which in turn will have negative impact on river bed and banks. The conversion of the vertical into a rotational movement for connection to a generator unit constitutes a further cause of energy loss.

The *Roue Barrage* developed by the French engineer Michel Fonfrede is a dam effect wheel for head differences from 0.50 to 5.00 m, and a power output of 20 to 1000 kW. The wheel hub acts as dam and as support of a gearwheel for power transmission. Theoretical considerations resulted in a maximum efficiency at 95 %. More detailed results of model measurements are not known; in the year 2006 a company was founded and the commissioning of a 50 kW prototype is pending, (Fonfrede, 2006). The use of the support structure for power collection enables a prevention of high torsional stress at the axis. In actual operation, maximum average efficiencies of 67 % are expected, Fig. 10a.

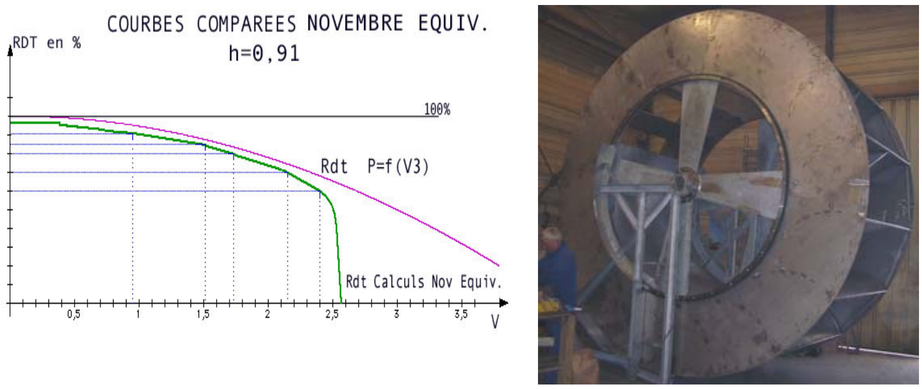

Fig. 10: *Roue Barrage* according to Fonfrede (a) theoretical efficiency, and (b) 50 kW prototype Fonfrede (2004, 2006)

The *Rotary Hydraulic Pressure Machine* (RHPM) (German: "*Staudruckmaschine*") looks similar to the *Roue Barrage*, but actually works on a different principle. A channel is locked by means of buckets and hub of a wheel, Fig. 11a. If power is extracted from the shaft, a dam gauge arises and leads to a gauge pressure. The water pressure interacts with the diagonal located blades and actuates the wheel. The innovator indicates an efficiency of more than 90 % for all flow rates, Brinnich (2001). This machine allows for the passage of sediment and fish, creating continuity along the river bed. Three prototypes have been built so far, but neither measurements or performance figures nor a plausible theory of the working principles were published, Fig. 11b. The direct energy conversion (as opposed to most other proposed technologies, where phase changes, multiple energy conversion or complex control mechanisms were required) in combination with the ecological advantages made this energy converter interesting, A simple theory – based on the assumption of a free surface rotary hydraulic pressure machine - was initially developed at the University of Southampton in order to assess the theoretical potential of this energy converter, Müller (2006).

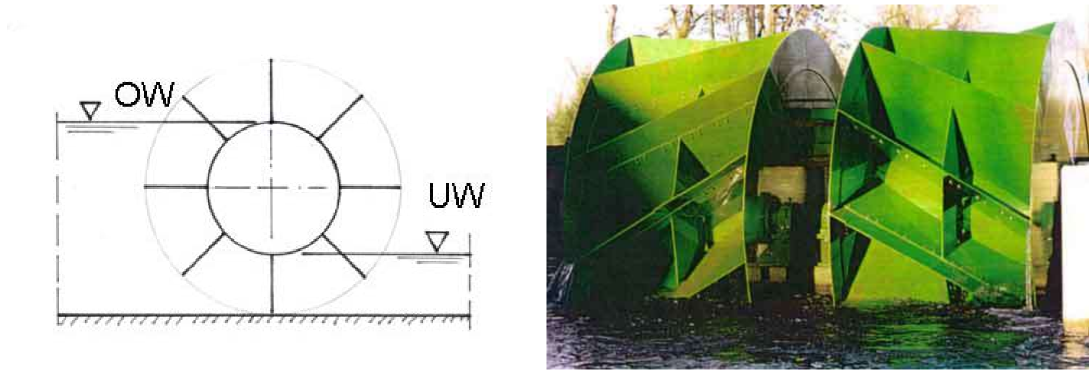

Fig. 11: Hydraulic Pressure Machine – (a) cross section, and (b) Frontal view of 4m diameter prototype

Fig. 12 shows performance (power out) and efficiency; it can be seen that – theoretically – approximately 70% efficiency are possible. The figure also indicates that fluid flow related losses dominate the performance; initial model tests showed that the inventor's geometry only had an efficiency of 40%. Current research efforts are therefore directed to minimize losses.

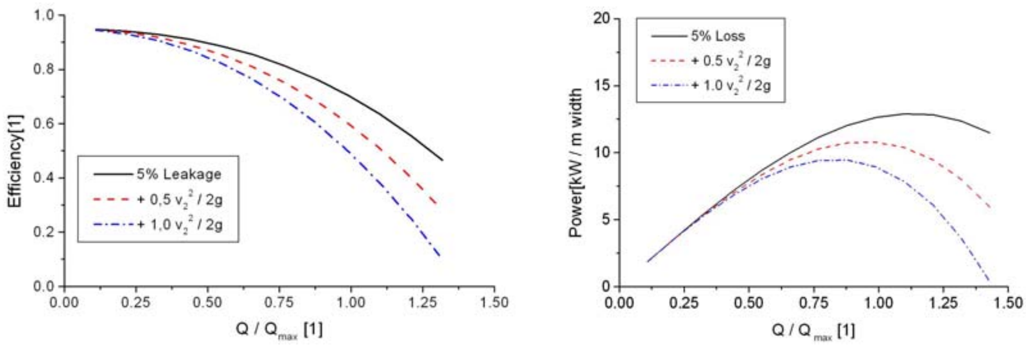

Fig 12: Characteristic curves for the RHPM (a) Power out, and (b) Efficiency as function of Q / Q_{max} Müller (2006)

4 DISCUSSION

Owners of low head hydropower sites as well as engineers have a strong interest in the utilization of the energy potential; an interest which is also driven by legal requirements. In the literature, internet and press a large number of different new technologies and machines in different development stages have been published. Often, very high efficiencies (and comparatively low cost estimates) are claimed, inducing in particular non-engineers to invest in untried and unverified technologies. Since developers and inventors retain intellectual property rights and are in general not very forthcoming with more detailed technical and standardised information, it is often quite difficult even for the expert to assess the value of any one proposed technology. At the same time, many developers choose to market their hydropower converters through the media and non-engineering lobbies. A collection of information in combination with analysis and the development of theoretical models showed that in most cases, the efficiencies indicated by the inventors / manufacturers could not be confirmed, and it was found that potential negative effects – in particular ecological effects – were often simply ignored. Sometimes efficiency was given as the ratio between theoretical possible and actual power output, which can lead to strongly distorted values (*Transverpello* gives 81 % efficiency; the overall converted energy is however only 4.6 % of the total available energy). Strangely, there are not many universities active in this field of research to try to ‘level the field’ by providing neutral research and evaluation. Lastly, the large number of ‘failed’ prototypes whose performance did not match the (inflated) expectations has created the impression that ‘everything has been tried’ and ‘nothing works’, leading to a negative attitude of research funding bodies in this area. This discrepancy between manufacturers/innovators and potential customers led to the situation where promising new technologies can not or only with difficulties be implemented into the market. Fundamentally this “vicious circle” can only be broken, when innovators, universities and potential customers chose a realistic, critical course of action and try to support each other. Important research and development funds for the micro-hydropower can only be achieved, if all parties are acting in concert. This is of great importance because even the most promising product hardly has a chance for market launch without scientific evidence of efficiency etc. The new technologies can only be established, if the actual performance corresponds to the expectations.The following table is showing an overview of the most important characteristics of all examined machines within this report.

	Machinery Efficiency as quoted by manu-facturer	Total-Effi-ciency	Total-Effi-ciency based on experts' estimat-ions	Electrical power for Q=2,5 m³/s and H=1,5 m and v=5,4 m/s	Investment costs of machinery and electrical components	Investment costs of civil engineering	Specific investment cost per installed kW	Fish compatibility in comparison with turbines
values for the orientation				37.5 kW	112,500 EUR	112,500 EUR	6,000 EUR	0
Stream Wheels	40 %	34 %		13 kW	0	-	-	+
Staudruckmaschine	95 %	76 %	67 %	25 kW**	0	0	0	+
Roue Barrage	95 %	76 %	67 %	25 kW**	0	0	0	+
Aniprop*	59 %	50 %	12.5 %	1.9 kW**	0	0	0	+
Gravitation Vortex Converter	80 %	52 %	35 %	13 kW**	-	+	0	+
Transverpello*	44 %	37 %	5 %	0.8 kW**	0	0	0	+
HydroPowerLens	25 %	21 %		8 kW	0	+	+	+
Gorlov-turbine*	45 %	33 %		5 kW	+	-	0	+
Davis-turbine*	-	-	30 %	4.5 kW**	+	-	0	+
Hydro Venturi*	30 %	20 %	10 %	1.5 kW**	+	-	0	+
UEK*	57 %	37 %		5.5 kW	+	-	0	+
KHPS*	30 %	20 %		3 kW	+	-	0	+

Legend: + higher, - lower, 0 similar to value of orientation; *referred to the kinetic energy; all other referred to the potential energy,
**** Efficiency total is calculated with the experts estimation**

Fig. 13: summary of the most important characteristics of new low head energy converters

5 CONCLUSIONS

A large number of energy converters, some of which are based on rather unusual principles, have been proposed for the exploitation of the currently unused hydropower sites with head differences lower than 2 m, and power ratings of 100 – 1000 kW. The working principles range from kinetic energy conversion over the creation and utilization of vortex flow to siphon-action, wave energy conversion and re-conversion into higher head differences to ‘classic’ stream wheels and a rotary hydraulic pressure machine. In many cases, the developers/inventors give overly optimistic efficiency and cost estimates. At the same time, not much factual information is presented so that the potential developer of a low head hydro power site can not base decisions on a rational, factual basis. Collecting the given information, developing scientifically based theories of working principles and analyzing the results it could be shown that most proposed energy converters have limited actual efficiencies of 4.6 to approximately 35 %, whilst their ecological impact ranges from moderate to extreme. Although some energy converters such as the UEK may find niche applications, only the Rotary Hydraulic Pressure Machine appears to have development potential for large scale implementation. The area of low head hydropower is one where inventors – not always with an engineering or scientific background - scientific research, potential commercial interests and customer desires (and sometimes wishful thinking) all are active. This activity is however not necessarily mutually supportive; similar to other areas of renewable energy the area would benefit from a more collaborative, more open and more realistic approach of all parties concerned.

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