Development of the cycloidal propeller StECon as a new small hydropower plant for kinetic energy

J Schmidt¹, J Jensen¹, J Wieland¹, W Lohr², J Metzger¹, H-L Stiller¹

¹ Research Institute for Water and Environment (fwu), University of Siegen, Paul-Bonatz-Str. 9-11, 57076 Siegen, Germany
² Institute for Engineering Design - CAD - Mechatronics (KCM), University of Siegen, Paul-Bonatz-Str. 9-11, 57076 Siegen, Germany

jessica.schmidt@uni-siegen.de

Abstract. The StECon (Stiller Energy Converter) is a promising new small hydropower plant for kinetic energy. It is an invention of Mr. Hans-Ludwig Stiller and has several advantages compared to the technologies for the use of hydropower known for millennia. It runs completely submerged forwards and backwards, with horizontal or vertical axis and has a compact design by using a single or a double-sided planetary gear with optimum alignment to the flow direction. The possible applications include mobile and stationary tide and current generators as well as hybrid solutions, either as a generator or as a propulsion system. The high expectations have to be confirmed in a research project StEwaKorad at the University of Siegen. Aim of this research project is to investigate the performance and characteristics of the StECon as an energy converter for producing renewable energy from hydropower with low fall heights including sea currents.

1. Functional principle of the StECon

| classic undershot waterwheel | StECon |
|------------------------------|--------|
| ![Classic Undershot Waterwheel](image1.png) | ![StECon](image2.png) |

Figure 1. Schematic illustration of the operation of an classical undershot water wheel (left) compared to the StECon (right).

The principle of the StECon is as follows: A classic undershot waterwheel with ten blades can be submerged maximum to the wheel axle, before it is slowed by counter-force effects. The idea of the StECon is based on rearranging the 5 lower blades around a new axis to reduce the opposing forces.
This construction has the advantage, in contrast to the undershot waterwheels, that the StECon works fully submerged. In this sense, it can be understood as an extensive technical optimization of the classic waterwheel. The movement sequence of the StECon is same as for the cycloidal propeller Kirsten-Boeing-Propeller (see also paragraph 3). Figure 1 shows the operation of an undershot waterwheel (left) compared to the StECon (right).

The StECon is a new small hydropower plant for kinetic energy (Figure 2) with two to five rotating blades. The functionality is guaranteed by a special planetary gear with 3 times tooth meshing, which ensures a uniform movement course forwards and backwards. By rotating the sun gear, the blades can be optimally aligned to the flow or be brought in an indifferent position to stop the rotational movement. The incident flow on the blades occurs in the first revolution from the front and in the second from the rear. While the blades in the lower half of the StECon are nearly perpendicular to the flow, the blades in the upper half are in a parallel position. The external gear allows a both-sided and a one-sided bearing. Thus, the StECon can be used for obtaining renewable energy from hydropower as well as a ship propulsion solution. With the freely movable sun wheel of the planetary gear an optimum position to the flow is always achieved. As a ship propulsion solution, this allows a high maneuverability. With the rotation of the sun wheel, the blades can also be brought in an indifferent position, wherein the StECon stops the rotational motion in the flow. Classical water wheels can only be stopped when the water supply is interrupted.

Figure 2. Principle model of the StECon (above) and functional model with 48 cm rotor diameter (bottom).

2. Application areas of the StECon

Figure 3 shows an overview of the application areas of the most usually known hydropower plants. The range for drop heights \( h < 1.0 \) m is previously only handled by undershot waterwheels. In Micro-power stations, there are also low-pressure turbines that have just very small power yields. The StECon here represents a significant improvement, since it can be used as an optimized ecologically compatible small hydropower plant that produces efficiently energy at sites with small heads. Thus, hydropower potentials with small drop heights can be used, which are so far not been used by any
other hydropower plant. The blue highlighted area in Figure 3 represents according to current knowledge the potential workspace of the StECon.

![Figure 3](image_url)

**Figure 3.** Application areas of hydropower plants with expected classification of the StECon, supplemented after [4].

Designs with horizontal and vertical axis, in one- or two-sided constructions are conceivable. This enables the use in various applications, e.g. as two-sided for horizontal use in shallow running water or one-sided for vertical use as an outboard propulsion.

3. State of the Art – cycloidal propellers

The StECon belongs to the group of the cycloidal propellers, i.e. all movements are repeated in cycles in circular orbits.

![Figure 4](image_url)

**Figure 4.** Blade movement of the KBP (left) and the VSP (right) [5].

The same movement as the StECon has the in 1926 mentioned Kirsten-Boeing Propeller (KBP), a drive concept for airships and ships (Figure 4, left) [3]. Previous developments have already been mentioned in 1852 as Oldham's paddle-wheel, which date back to the Hooke's feathering Wheel in 1681 [1]. Due to the complex kinematic propulsion with many moving parts, the KBP was never used on an industrial scale and never for energy production from hydropower. Also for recent developments of the KBP there is still no specific application (for example, Patent No. WO 2004/074680).

Another cycloidal propeller is the Voith Schneider Propeller (VSP), developed around 1920, which is used as a proven propulsion solution in marine technology [6]. The VSP needs a relatively elaborate...
gear, controlled by connecting rods, in order to always flow the blades from only one side (Figure 4, right). This gear kinematic allows no reversal of the force or torque direction, which is why the VSP is not suitable for energy production. In table 1 the differences between StECon and VSP are summarized and compared.

| Table 1. Differences between StECon and VSP. |
|---------------------------------------------|
| **StECon** | **VSP** |
| Gear | planetary gear with 3 times tooth meshing | controlled by rods |
| Flow toward the blades | at the first turn from the front and from behind in the second | only from one side (180° reversal of the blade according to one rotation) |
| Suitability as a propulsion solution | ✓ | ✓ |
| Suitability for energy production | ✓ | Not suitable |

The StECon is an invention of Mr. Hans-Ludwig Stiller. The theoretical promising concept of a new hydropower plant has been submitted at the German Patent and Trade Mark Office (DPMA) under the title "Compact waterwheel" (HLS KWR) on 03/15/2011. The patent with the number 10 2011 014 086 was granted on 12/16/2013 and confirms the state of the art. The HLS KWR was published first as “StEwaKorad” and will now operate under the name “StECCon”.

4. Research project for explaining the performance features of the StECon

With the 6th Energy Research Program "Research for an environmentally friendly, reliable and affordable energy supply", the Federal Government of Germany promotes the research and development of new technologies for the future energy supply. The Research Institute for Water and Environment (FWU) from the Department of Civil Engineering and the Chair of Engineering Design, CAD and Mechatronics (KCM) from the Department of Mechanical Engineering at the University of Siegen are supplied for the period from 10/01/2014 to 03/31/2016 by the Federal Ministry for economy and Energy (BMWi) for carrying out the research project StEwaKorad. Aim of this project is to understand the features and characteristics of the StECon as an energy converter producing renewable energy in the head range of deep and undershot waterwheels. The investigations as a propulsion solution are not part of this study. The complex movements of the blades and their interaction with the flow are analyzed with models and prototypes in a physical model experiment. The flow resistance forces of different blade shapes were also tested in another labor experiment and verified by a 3D numerical model. The project includes the development of a prototype at the appropriate scale. At the end of the project are characteristic performance data available.

4.1. Laboratory measurements on the test model

After the theoretical consideration of the StECon, a vertical-sided test model with five blades was constructed (StECon 4.0; 1:3 scale) (table 2). To carry out the experiments on the test model in the hydraulic laboratory of the University of Siegen, an appropriate measuring technique (torque, speed, braking apparatus, water level, and phase adjustment) was developed and installed [2]. Table 2 shows the developed test model StECon 4.0, the blade modifications at the SECon 4.1, 4.2 and 4.3 and the measured maximum efficiency and the maximum mechanical power.

Since the StECon with d = 26 cm is about half as wide as the flume in the laboratory, experiments for an unlimited flow with a possibility of flowing around the StECon of 1:2 (figure 5) as well as for a limited flow with a possibility of flowing around the StECon of 1:1 were possible. The aim of the investigations was primarily to analyze the behavior of StECCon regarding to its effective power and its
actually existing efficiency during different experimental conditions and to collect relevant characteristics for the dimensioning of the prototype. In addition, the StECon was examined in terms of its gaps, blade shape and its "relative drop height".

**Table 2.** Test models of the StECon, maximum efficiencies and maximum mechanical performance in the limited flow [2].

| Designation and layout | Explanation | maximum efficiency | maximum mechanical power |
|------------------------|-------------|--------------------|--------------------------|
| StECon 4.0             | First test model. ballraced gear, rectangular blades; Slenderness ratio blades 1: 6.5 | 31.5 % at 30 l/s | 6.35 W at 50 l/s |
| StECon 4.1             | First test model. Edges of the blades were pointed at a 30° angle | 41 % at 30 l/s | 6.35 W at 50 l/s, at the same water level as 4.0 → higher power |
| StECon 4.2             | First test model. narrower blades → Modified Gap sizes; Slenderness ratio blades 1: 6.2 | 20 % at 30 l/s | The smaller the gap, the higher efficiency and mech. power. |
| StECon 4.3             | First test model. Stainless steel sheet with lenticular profil | 18 % at 50 l/s | 6.30 W at 60 l/s, 12 Watt at 100 l/s, Increased absorbing power negatively effects efficiency and power |

Figure 6 shows the measured power and efficiency of the StECon 4.1 as a function of \( h_2/h_1 \), were \( h_1 \) is the uninfluenced measured water level above the StECon and \( h_2 \) is the measured water level behind the StECon. Table 2 and figure 6 show, that the blade shape has a high impact on the efficiency of the StECon. Thus, in order to increase the efficiency of the StECon, experiments were performed to determine the most optimal blade shape for the StECon.
4.2. Optimization of the blade shape

In order to find an optimal blade shape, possible blade shapes were constructed with CAD (figure 7) and experimental forms of these shapes (450 mm x 98 mm x 15 mm, 1:2.5 scale) were created in PVC-U by means of a 3D printer.

Each blade shape was investigated on its flow properties in 10° increments of the blade position in relation to the flow direction. These experiments were carried out in a smaller, separate flow channel. To determine the relative flow properties of each blade shape the water levels before and behind the blades were measured by ultrasonic sensors. The experimental setup is shown in figure 8.
The determination of the absolute forces acting in x- and z-direction is realized by two load cells with a maximum load limit of 1 kg. The accuracy of the system is above 0.2%. From the measured forces, the overall moments were determined. The highest overall moments arise for the blade shapes "flat board", "rectangle", "S-shape" and "diamond", because these shapes have all a significant streaming tear off edge in a perpendicular orientation to the flow in common and the resulting detachment vortexes have no negative impact on the blades. The form, which yielded the highest efficiency on the test model, however, was the sharp rectangular profile. It is to be clarified whether there is the maximum efficiency and the maximum power with different optimum blade shapes. In addition it still needs to be examined on the prototype, what effects the mutual influence of the flow on all blades have on the absolute power.

4.3. Design and optimization of the planetary gear

For the development of the planetary gear with 3 times tooth meshing with a new cogwheel combination and very uniform meshing the forces and torques were determined on the basis of measurements on the test models. By means of an equivalent model could be demonstrated for the measured values that all blades contribute in any position to a positive overall moment (figure 9). This overall moment is constant at any angular positions of the blades. Even the blades, which move opposite the flow, increase the overall moment and do not brake the StECon. Only when a blade reaches the parallel position to the flow direction, it becomes the indifferent moment of zero [2]. The overall moment was calculated from the lift and drag force on each blade (figure 10). The lift forces $F_l$ were calculated by

$$F_l = \frac{1}{2} \cdot v^2 \cdot c_l \cdot A \cdot \rho$$

(1)

$$c_l = \sin(2 \cdot \alpha)$$

(2)
were \( \rho \) is the density of water, \( A \) is the blade surface, \( v \) is the flow velocity, \( c_l \) is the coefficient of lift and \( \alpha \) is the blade angle. The drag forces \( F_d \) were calculated in accordance with the drag coefficient \( c_d \).

\[
F_d = \frac{1}{2} \cdot v^2 \cdot c_d \cdot A \cdot \rho \tag{3}
\]

\[
c_d = 1.8 \cdot (\sin \alpha)^2 \tag{4}
\]

**Figure 9.** Calculated overall moment of an equivalent model of the StECon.

**Figure 10.** Lift, drag and resulting forces on the StECon.

Figure 10 shows some blade positions of the StECon during rotation. The forces on the individual blades have been illustrated in the global coordinate system. The lift forces of the blades are always pointing in the positive or negative x-direction. The drag forces are always pointing in the positive y-direction. The resulting forces were calculated as follows.
The optimum gear for the StECon consists of cogwheels with 15, 18 and 30 teeth (figure 11). This special design is necessary because of the three times tooth meshing and the fact that first cogwheel has to mesh with the last cogwheel. The optimized distances between the cogwheels and the profile shifting, lead to a very good tooth meshing and thus to a very low idle power. Tooth head and tooth backlash are within the allowable framework for gearing. The gear calculation was made using the software KISSsoft accordance with ISO 6336: 2006 method B.

\[ F_{rev} = \sqrt{F_i^2 + F_d^2} \]  

(5)

4.4. Construction and production of the prototype

Based on the test model measurements in the hydraulic laboratory and the theoretical calculations of the forces and moments on the StECon with the design of an optimized planetary gear the prototype of the StECon was designed using the 3D CAD program ProEngineer with a diameter of 48 cm. The construction of the prototype contained planetary gear, bearing, retainer and floor bearing and blades with a length of 58.5 cm and a width of 17 cm. Figure 12 shows the 3D CAD drawing of the prototype as a sectional view. The production of the prototype was assigned to a specialist company. With an incident flow area of \( A = 0.20 \text{ m}^2 \) and a flow velocity of \( v = 0.90 \text{ m/s} \) a produced mechanical power of about 50 Watts could be expected. To reach the maximum power of the wheel, a rotational speed is estimated with about 30 l/min.

Figure 11. Optimized cogwheel assembly of the planetary gear (left), Principle plastic model (middle), Prototyp (right).

Figure 12. 3D CAD drawing of the StECon Prototyp, sectional view (left), StECon Prototyp (right).
5. Summary and outlook
In the field of small fall heights and flow velocities the StECon could be a significant technical improvement, to generate resource-saving renewable energy with no damaging emissions. With its compact design and its specific features, such as forward and backward running, the single and double-sided gear design and the optimized alignment to the flow direction, completely new application possibilities arise. These include mobile as stationary tide and current generators as well as hybrid solutions, either as a generator or as a propulsion system. The high expectations of the economy have to be confirmed in a research project at the University of Siegen. Aim of this research project is to investigate the performance and characteristics of the StECon as an energy converter for producing renewable energy from hydropower with low fall heights including sea currents. The mentioned complex movements of the blades and their interaction with the flow were analyzed with test models in a hydraulic laboratory. The first results with different boundary conditions (e.g. different blade shapes) showed promising maximum efficiencies of 26.8 % in the unlimited flow and 41 % in the limited flow. The high expectations have been partially confirmed on test models and are to be investigated on the prototype. After the completion of this research project it is intended to apply for a following research project, where the optimized prototype of the StECon is installed under real operating conditions in the outlet channel of a wastewater treatment plant. There measured values will be recorded in continuous operation. The aim of this following project is to get the StECon ready for market.

References
[1] Bourne J 1852 A treatise on the screw propeller. London
[2] Jensen J, Wieland J, Schmidt J, Metzger J, Stiller H-L, Lohe R, Lohr W, Jung T and Cramer J 2015 Bericht BMWi-Projekt StEwaKorad. Unveröffentlichter Projektzwischenbericht
[3] Sachse H 1926 Kirsten-Boeing Propeller. Technical Memorandums – National Advisory Committee For Aeronautics. In: Zeitschrift für Flugtechnik und Motorluftschifffahrt. p.1-4, Washington
[4] Saenger N 2014 Wasserbau und Wasserwirtschaft. Contribution in: Schneider, K. J. (Hrsg.): Bautabellen für Ingenieure. 21. Auflage. Werner Verlag. In German.
[5] Soltnai M 2013 Auslegung einer vertikale Windkraftanlage. Bachelorarbeit. Hochschule für Angewandte Wissenschaften Hamburg. Online available at: http://edoc.sub.uni-hamburg.de/haw/volltexte/2013/2154/pdf/Thesis.pdf. In German.
[6] Voith Turbo Schneider 2010 Der Voith Schneider Antrieb. Firmenprospekt der Voith Propulsion GmbH & Co. KG Heidenheim, In German

Acknowledgments
Special thanks to the Federal Ministry for Economic Affairs and Energy of Germany (BMWi) for sponsoring the research project StEWaKorad from 10/01/2014 to 03/31/2016 within the 6th Energy Research Program "Research for an environmentally friendly, reliable and affordable energy supply".

At the end of the editorial deadline of this paper, the results of measuring the prototype had not yet been available.