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Advanced energy recovery strategies for wastewater treatment plants and sewer systems using small hydropower

V. Berger[1], A. Niemann[1], T. Frehmann[2] and H. Brockmann[2]
[1] *Institute of Hydraulic Engineering and Water Resources Management, University of Duisburg-Essen, Germany,*
e-mail: viktoria.berger@uni-due.de
[2] *Emschergenossenschaft, Kronprinzenstraße 24, 45128 Essen, Germany*
e-mail: frehmann.torsten@eglv.de

Abstract: Operation strategies of wastewater disposal and treatment are changing at the moment. Due to the huge energy demand needed for wastewater collection and treatment more and more efforts are carried out to gain an energy recovery not only at wastewater treatment plants (WWTPs) but also from the urban water cycle. Today WWTPs are usually the facilities with the highest energy demand in public ownership. Thus, renewable energy facilities are added in order to reduce the overall demand of energy supply taken from the power grid. Consequently also small hydropower plants are part of this strategy, using an again new identified site for small hydropower implementations. Hydropower can be applied for energy recovery as well as for energy storage. Promising new developments in pilot testing phase and under investigation are pointed out. This paper gives an overview of the approaches so far, suitable techniques as well as restrictions which have to be considered for an operation of small hydropower concepts for energy recovery and storage. Finally a case study of a communal WWTP and the corresponding sewer system is presented. Results show that some sewer structures may be suitable for an implementation of energy recovery or storage facilities, but application is still limited, due to economic reasons, whereas the implementation of an Archimedean screw in the outlet of the WWTP is technically and economically feasible.

Key Words: small hydropower, energy recovery, urban drainage, sewer systems, WWTP

1. INTRODUCTION

It is well known that wastewater treatment plants (WWTPs) are high energy consuming facilities. They account for up to 75 % of the overall energy demand of a municipality or like not unusual in Germany, within a non-profit water association (Berger et al. 2013). Within the last decades it was established that wastewater should no longer be addressed as waste but as a resource. For example the Water Environment Federation stated in 2011 that WWTPs are “resource recovery facilities that produce clean water, recover nutrients and have the potential to reduce the nation’s dependence upon fossil fuel through the production and use of renewable energy” (WEF 2011). In this context, the German water association “Emschergenossenschaft” focuses on the production of renewable energy, i.e. energy recovery on WWTPs. In this paper we will present as a case study the WWTP in Bottrop/Germany which treats 1.3 Mio. population equivalent (PE) and has already been technically and energetically optimised by improving the sludge treatment (Schmelz et al. 2007), benchmarking energy usage (Stemplewski et al. 2001) and replacing high energy consuming devices, respectively. The new integral strategy for plant operation and energy management (cf. Figure 1) also consists of the application of renewable energies. Solar cells are nowadays state of the art and can easily be applied as the WWTP provides large roof and fallow areas. The additional integration of a wind turbine is also analysed (Stemplewski 2012). Consequently, the applicability of hydropower is investigated as WWTPs provide a well-defined discharge and, depending on the location, a certain hydraulic head. Examples for the use of hydropower systems in wastewater treatment plants are well known. Technologies used range from water wheels and Archimedean screws to turbines (Hafner 2004, Pinnekamp 2007, Frehmann et al. 2012). In general, the outlet structure, i.e. the head to the river is used for energy generation. Problems due to the medium were not reported; in few cases the incorrect design of the device resulted in excessive mechanical wear. Chapter 3 will report about the installation of a hydropower device on the WWTP Bottrop.

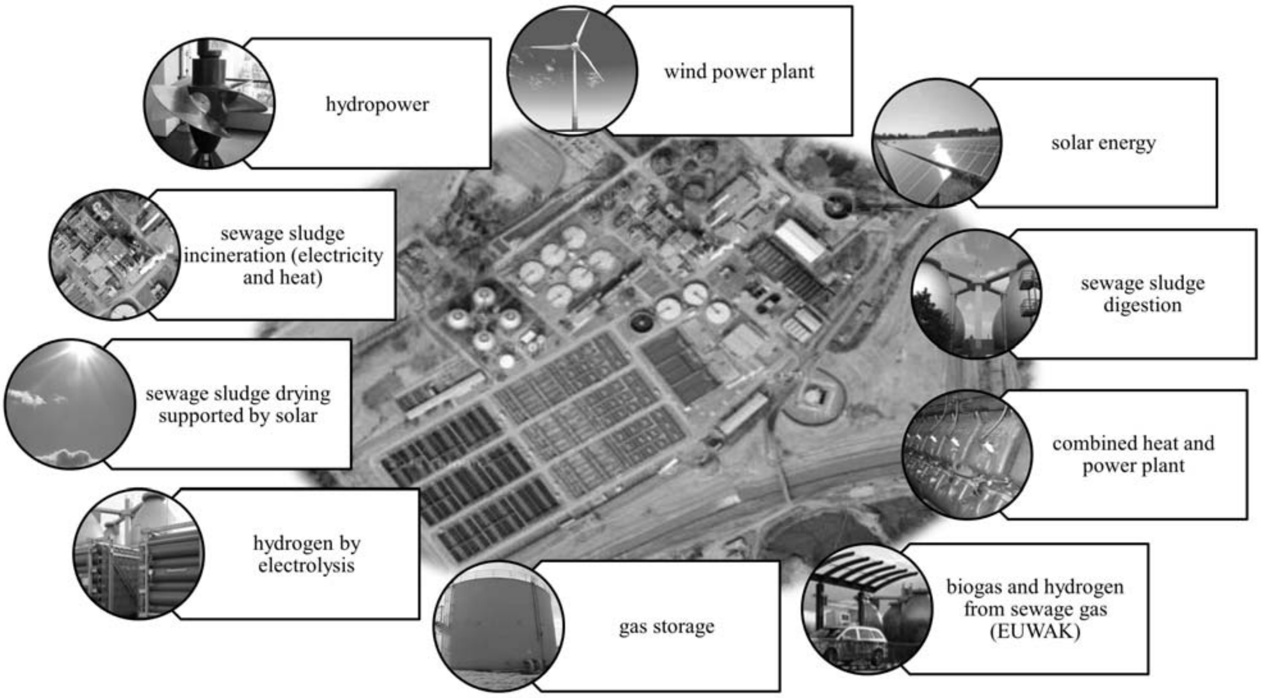

Figure 1. Elements of an integral energy management strategy on WWTPs, the "hybrid power plant Bottrop" (Stemplewski 2012)

In a second step, hydropower applications in sewer systems should eventually be analysed as sewers provide continuously running and quite often falling water. Moreover no conflicts due to intervention in nature have to be expected as sewers are technical structures. To use the existing heads and a certain space for additional devices, hydropower should be applied within the manholes. Surprisingly, there are only few reports about hydropower devices in sewer systems. One example is an overshot water wheel in Aachen/Germany. The available wastewater discharge ranges between 30 l/s and 120 l/s; the useable head is 6 m. This results in a theoretical output of 6.7 kW. In a research project, an overshot water wheel was installed crosswise the flow direction, which achieved an average daily output of 65 kWh (4.4 kW). Various technical and structural defects, particularly considering explosion prevention and protection, corrosion resistance and problems accessing the underground devise, resulted in long downtimes. During the operational phase it was found that there was no clogging or entanglements as the water wheel developed a type of "self-cleaning effect" as a result of the rotational movement. The low feed-in compensation made this project not economic. After some years the water wheel was finally removed (Bolle and Billmaier 2012).

Nevertheless, chapter 4 will describe the analysis of the sewer system feeding the WWTP Bottrop, as it provides a unique chance for the implementation of hydro power in sewer systems as it will be completely changed due to the Emscher conversion project and is under reconstruction right now. From 2017, the wastewater will be discharged in 400 km sewers. The core structure, the new main intercepting sewer Emscher (AKE) has a length of 55 km, a depth of up to 40 m and transports the wastewater of a catchment area of approx. 427 km² to four WWTPs that provide the required purification capacity of 4.8 million PE (Teichgräber et al. 2006). Approx. thirty manholes lead the wastewater from the single catchments to the AKE. If the implementation of hydropower is already planned before construction, it will reduce costs significantly and optimize the hydraulic design of the manholes.

2. HYDROPOWER POTENTIAL AND AVAILABLE TECHNOLOGIES

The hydropower potential in Europe has been considered as largely exploited. Thus, recent studies report on unused capacities in Germany totalling approx. 40 TWh (Anderer, Dumont et al. 2010). The total installed hydropower capacity in Europe is around 210 GW. Additionally 35 GW are provided by pumped storage plants. Nevertheless, there is a remaining technical feasible hydropower potential of 650 TWh a year in Europe (EURELECTRIC 2011). This potential is mainly found at locations previously considered uneconomical, such as weirs or mill races.

Therefore research and industry aim to further develop established technologies and develop new technologies to activate this potential, especially for heads of less than 10 m (Müller and Kauppert 2002). A certain lack represent flow rates between 1 and 7 m³/s, as major shares of the technologies are designed for either smaller or larger discharges. Figure 2 shows the application range of various small hydropower devices that have been reviewed. For a given combination of head and flow rate all technologies surrounding the intersection can be chosen. In a second step the theoretically feasible technologies have to be analysed based on the constructional boundary conditions.

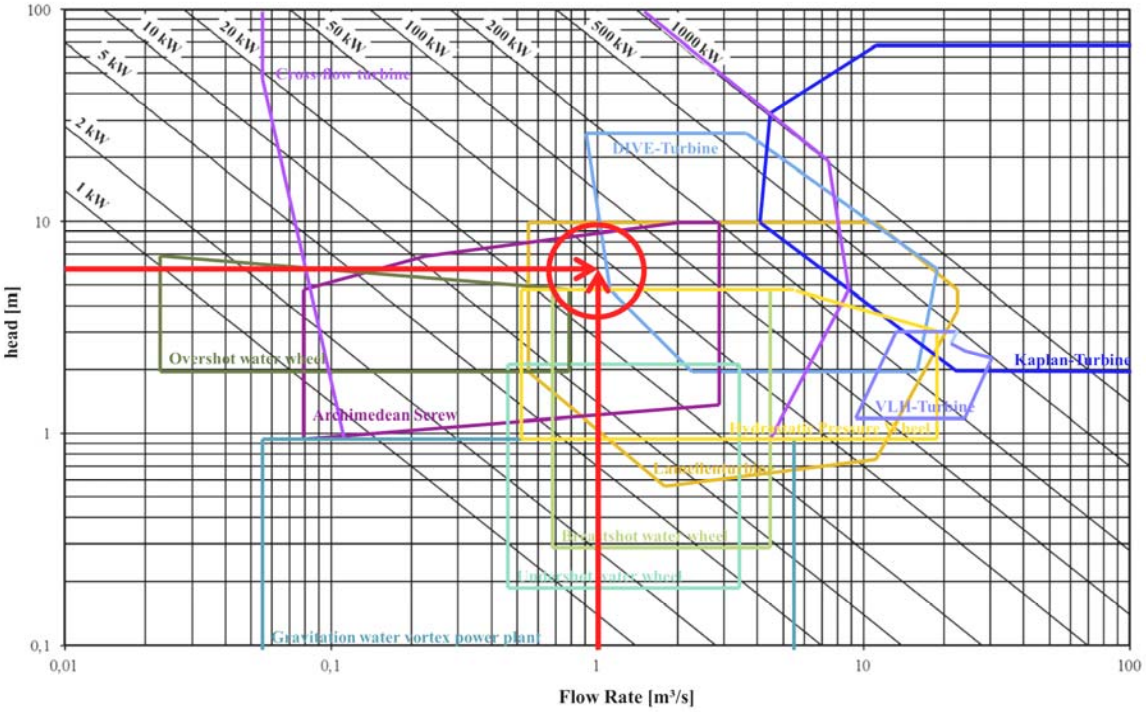

Figure 2. Application ranges of different small hydropower devices (Frehmann, Berger et al. 2013), red arrows mark the intersection for a given head of 6 m and a flow rate of 1 m³/s as an example

In general, hydropower systems can be divided into the following categories: water wheels, turbines and turbine based concepts, Archimedean screw, flow energy converters, mechanical conveyor belts. As flow converters are designed for the use of the kinetic energy of rivers they won't be presented in further detail.

Water wheels are generally designed for low discharges. They are the most classical hydropower technique, which can be divided by the point of water loading into overshot, breast shot and undershot, respectively. Overshot water wheels have a low capacity per blade, which leads to a larger width, but the highest efficiency. Undershot water wheels have a higher capacity per blade and are therefore capable of higher discharges (Denny 2004). Water wheels provide in general a high efficiency (around 80 %) for flow rates between 20 and 120 % of the ideal flow rate, which makes them very suitable for varying discharges. They are available in different materials and offered by several, mostly traditional, small companies. Moreover, some further developments of water wheels can be found, which are also commercially available.

Kaplan turbines are also feasible for low-pressure applications, although they are optimised for heads bigger than two meters. Moreover, further developments of the Kaplan turbine like the horizontal mounted Straflo-turbine as well as the tube turbine focus on very low heads. All pressure turbines still need a penstock for the intake and a draft tube as outlet. This causes a certain amount of constructional work which makes the implementation of a classical turbine at low heads not economic (Giesecke and Mosonyi 2009).Therefore, this technology has been integrated into various small-scale hydropower concepts which attempt to reduce the amount of constructional work using modular concepts. Examples such as the DIVE turbine, mobile power stations, VLH turbines or water vortex power plants are now being used for the first time in natural water bodies (Bozhinova et al. 2012). Nevertheless, all concepts are more suitable for sites of at least 50 kW.

Since ancient times the *Archimedean screw* is used to lift water or sludge to higher levels. Since several years they are also used vice versa to generate energy in very low-head situations (Hellmann 2003). The falling water moves the helical blades wrapped around the axis which drives via a gearbox the generator. Due to its construction the Archimedean screw has a wide range of high efficiency. The flow rate(maximum 10 m³/s) determines the diameter of the screw (up to 4 m), whereas the length is determined by the head depending on the angle (Lashofer et al. 2011), where a lower ankle increases the efficiency (Müller and Senior 2009). Disadvantageous can be the required huge dimensions due to the flat angle (< 30 °) as well as the high load due to a massive steel construction. They are nowadays state of the art and produced in different standardized versions.

Concepts based on the principle of *mechanical conveyor chains* consist of buckets or blades mounted on a conveyor belt, which is moved by the potential energy of the water. This construction makes them adjustable even to narrow sites. Currently, there is one technology commercially available, which is designed for smaller heads and flow rates in natural water bodies (Malcherek et al. 2011). Another prototype (Kastner 2006), which seemed to be well-suited especially to wastewater applications, disappeared.

2.1 Applicability of hydropower in sewer systems

There are serious restrictions on the application of hydropower in sewer systems. In contrast to drinking water distribution networks, in which turbines and further hydropower concepts are already in use for pressure reduction and the simultaneous recovery of energy (Löhner 2012), untreated wastewater is a far more complex medium. The chemical composition, in particular pH value, oxygen content and temperature result in increased corrosiveness. Therefore, all devices have to be made of resistant materials such as stainless steel or grey cast iron. Additionally, the composition of wastewater causes an explosive atmosphere; thus all components have to be designed accordingly.

The physical composition of the wastewater is the limiting restriction for hydropower in sewer systems. Contraries such as timber or stones can damage parts of the device. Fine contaminants such as sand may have a permanent abrasive effect and result in increased wear. Contaminants consisting of cohesive materials such as cat litter or Benton it can clock the device. Fibrous contents like tissues, ropes or hairs lead to entanglement. Entanglement represents a particularly high risk for propeller-based concepts such as turbines. Therefore, turbines can only be used after preliminary treatment, i.e. screening, which would need energy and the frequent removal of debris. Additionally, propeller based concepts are more sensible to varying discharges and atmospheric influences. To avoid cavitation, an upper reservoir would have to be implemented. This would lead to standing wastewater which causes an explosive and toxic atmosphere. In summary, turbines are not suitable for the application in combined sewer systems. Preference should be given to Archimedean screws, water wheels or trough conveyor concepts, respectively. These devices are not under risk of cavitation and, in particular overshot waterwheels and Archimedean Screws, may pass larger contraries due to their design. In any case, the suitability of the technology as well as the boundary conditions such as flow rate, available space, chemical and physical composition of the sewage have to be considered carefully.

2.2 Applicability of hydropower on WWTPs

In general, WWTPs are suitable for hydropower due to mechanically and, depending on the position, biological treated wastewater. In addition, the given discharge is well documented and the technically formed tanks and channels generally allow an implementation. Screens and trash racks are not needed, as the water is already treated. The integration into the energy grid of the WWTP is very simple and expert staff for operation and maintenance is located nearby and available day and night.

The installation of a hydropower unit within the treatment tanks is rather difficult as the treatment must not be disturbed as well as the outflow has to be guaranteed all the time. Gravity flow is usually used within a WWTP; large heads between the tanks can therefore not be expected. Available space is quite rare alongside the tanks. The most likely sight is the outlet structure. The outlet structure provides a certain head for energy recovery and, depending on the construction, some space for an additional device and carries the complete discharge. Depending on the given structure as well as flow rate and head, turbines, water wheels, Archimedean screws or technologies based on conveyor chains may be applied. Turbines should already be planned during the building/construction phase as they need certain concrete structures; if a continuous discharge can be guaranteed they are low in maintenance and contribute constant energy.

2.3 Economics

The economy of a hydro power plant is mainly determined by the yield. If the produced energy will be fed into the energy grid a compensation of 0.12 €/kWh will be obtained (BMU 2011). On the other hand the produced energy may also be used to enhance the self-energy production and thereby minimize energy costs. Energy costs range at the moment at 0.19 €/kWh, but are expected to reach 0.25 € within the next years. Additionally, hydropower improves not only the self-energy production but also the operator’s carbon footprint. Hence it is economically worthwhile to use the produced energy on-site.

Manholes are most often not found near high energy consuming facilities. Thus it is most likely that the produced energy will be fed into the grid. WWTPs on the other hand have a high energy demand. The thereabout produced energy can be used directly and will enhance the self-energy rate. Thus it is mostly likely that hydropower on WWTP is economically more suitable than in sewer systems.

2.4 Conclusions for applicability of small hydropower in wastewater disposal

Although there is a considerable number of concepts available for the use of small heads, only few of these can be applied in sewer systems or on WWTPs, respectively, as most technologies do not fit the narrow spatial conditions and combination of discharge and head. Thus, research and development are currently focusing on application in rivers, which provide quite different boundary conditions. Classical devices like Kaplan turbines, water wheels or Archimedean screws seem most suitable. Nevertheless, the applicability of hydropower in sewage disposal is still limited due to technical reasons and has to be further analysed and developed.

Summing up, hydropower is theoretically realisable in wastewater disposal; however, there are sophisticated requirements with respect to safety and corrosion protection, which have a negative impact on project costs. Construction costs maybe minimised if the hydropower device is planned in advance.

3. CASE STUDY WWTP BOTTROP

The water associations Emschergenossenschaft/Lippeverband operate 44 WWTPs. Altogether they provide a theoretical potential of 372 kW for energy recovery at their outlet structures. At eleven sites hydropower is already implemented or will be implemented soon, these sites provide an output of 328 kW, which equals annual savings of 169,000 €. The other sites are technically not suitable due to manifold reasons. Following, the analysis of the WWTP Bottrop is described.

The WWTP in Bottrop was systematically investigated. Concerning a first estimation, four possible sites have been investigated in further detail:

- Digesters
- Outlet of chamber filter presses
- Outlet of primary sedimentation
- Main outlet

It was investigated that sludge treatment is not suitable for hydropower application due to the characteristics of the sludge. Despite the big heads of the digesters of about 30 m the characteristics of the sludge would block any mechanical energy conveyer and thereby disrupt sludge treatment. The outflow of the chamber filter presses could not be used as in-pipe devices are rarely available and the discharge was too little to find an economic solution. Between primary sedimentation and activated sludge tanks a head of approx. 1 m was detected. The mechanically treated sewage is suitable for hydropower units but the design of the basins prevents the installation. Only the outlet structure can be used for hydropower. Depending on the water level in the river there is a net head of 1.40 up to 1.80 m. The average flow rate is 4 m³/s; within a margin of 40 %. Considering hydrological and constructional restrictions, an Archimedean screw was identified the best solution.

While designing an Archimedean screw within the outlet of a WWTP several restrictions have to be considered. To secure undisturbed treatment, the discharge has to be guaranteed all the time, even at heavy rain events and if the hydropower unit is damaged, respectively. To guarantee the outflow in these cases it is suggested to mount the Archimedean screw in the middle of the channel in combination with a weir of the given head. In operating conditions the weir will damp the water and lead it to the screw; if the screw is not able to use all the water available or is damaged, two bulkheads in the weir on the left and right can be opened to guarantee the rated discharge.

Figure 3 shows a possible implementation of an Archimedean screw of 3 m diameter. The costs will be dominated by construction costs. The hydropower unit accounts hereby only for 1/3 of the total costs. The constructional effort, i.e. the alteration of the outlet channel securing both the flood discharge as well as the stability, generates the lion's share. The expected average power is 40 kW, which leads, depending on hydrologic conditions, to an annual work of 340,000 kWh. Considering expected energy costs of 25 ct/kWh, the profit totals 85,000 €/a. As the WWTP in Bottrop has an annual energy demand of approx. 40,000 MWh, whereof 29,000 MWh are already produced on-site (which equals a self-energy production of 72.5 %) the additional self-produced energy by hydropower would enhance the self-energy rate by 0.9 %-points to 73.4 % (Berger et al. 2013).

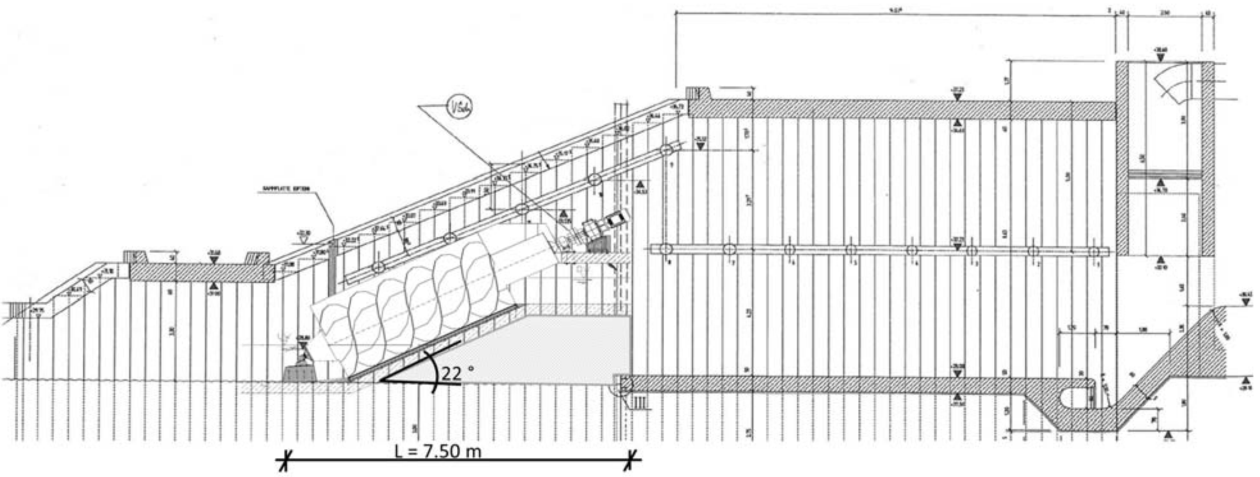

Figure 3. Possible position of the Archimedean Screw in the outlet of the WWTP Bottrop

4. CASE STUDY EMSCHER SEWER

The Emscher sewer (AKE) is becoming the main intercepting sewer in the river Emscher catchment. In order to collect the wastewater and lead it to the WWTPs by gravity flow over a length of 51 km, it is constructed up to 40 m below the ground. The wastewater is collected in the catchments and then passed to the AKE in more than 30 manholes. The wastewater falls thereby between 5 – 20 m. The dry weather discharges vary between approx. 5 L/s in the smallest catchment up to 1,000 L/s in the largest catchment. Altogether the manholes provide a theoretical potential of 160 kW, which equals a feed-in compensation of 150,000 € a year; following a first estimation, only half of them is worth further consideration. In this paper, the analysis of the manhole with the highest potential is described.

This manhole hosts a so-called vortex drop structure to transfer the sewage from the given catchment to the AKE. The vortex structure aims to reduce energy and minimise the formation of aerosols. The wastewater is passed through a swirl chamber and through an eddy to a down pipe which ends in a stilling chamber, where the water is calmed down before entering the main sewer. The manhole has an internal diameter of 23 m and an overall height of around 30 m. The inlet from the catchment area is located approx. halfway up. The down pipe has a diameter of 1.6 m and a height of 4.72 m. The gross head is 6 m. The stilling chamber has a base area of 7 x 3 m. As the floor slopes to the outlet, the height increases from 3.05 up to 4.18 m. The flow rate varies between 0.1 L/s at night's minimum up to 1.9 m^3/s at day's maximum. For a first estimation of the potential the mean daily discharge of 1 m^3/s will be considered. In case of rain, the flow rate is approx. three times the mean daily discharge. Thus, hydropower should be designed for the dry weather flow in order to guarantee continuous energy production. With a flow rate of 1 m^3/s and a head of 6 m, the theoretical energy output is 59 kW.

For the installation of a hydropower system there are no constructional restrictions at present, i.e. structural changes are possible as the manhole is not jet under construction. The simplest solution would be the integration of the device in the stilling chamber. Referring to chapter 2, an Archimedean screw and water wheels, respectively, are examined. Both systems cannot be installed in the stilling chamber due to their dimensions. Therefore an application outside the stilling chamber has to be investigated. A screw for a flow rate of 1 m^3/s and a head of 6 m would have a diameter of approx. 1.7 m and a length of approx. 11 m. Owing to the length of the screw an intermediate bearing should be installed. The generator can be mounted on the gallery of the swirl chamber. A water wheel on the other hand would have a diameter of approx. 5.7 m and a width of approx. 1.3 m.

The hydraulic boundary conditions make the integration of a hydropower device difficult. The inlet pipe is more or less rectangular to the AKE. Using the vortex the inflow is ideally directed into the new flow direction. An Archimedean screw or water wheel, respectively, can only be integrated behind the vortex drop structure after the water has been redirected (cf. Figure 4). Thus, the rain weather discharge has to be guaranteed all the time. The entire volume first has to pass through the vortex; the dry weather flow has to be directed to the hydropower device while the rest flows into the main sewer, which requires a bypass solution.

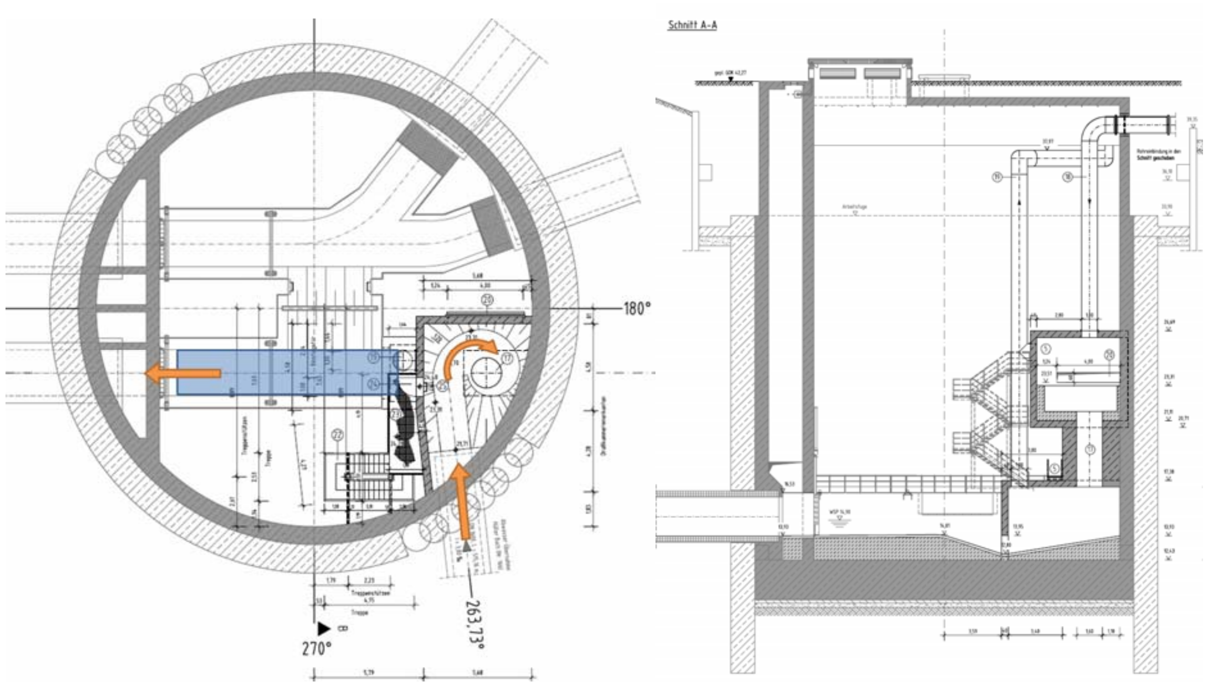

Figure 4. Typical manhole with vortex drop structure of the AKE in top view (left) and site view (right) with flow directions marked by arrows and a possible location for a hydro power device (rectangle)

In addition to the technical feasibility, the cost-effectiveness has to be considered. Considering the given example, the theoretical potential of 59 kW has to be corrected to a defined efficiency (water to wire) of 65 % - owing to the medium - which leads to a remaining potential of approx. 38 kW.

If this potential is correlated to 7,500 operating hours per year, the annual output is about 285,000 kWh. Taking into account the current German feed-in compensation according to (BMU 2011) of 12.57 ct/kWh, this leads to a possible annual yield of 35,825 €. Considering the following assumptions,

Operating hours:	7,500 h	Interest rate:	4 %
Output:	38 kW	General inflation:	2 %
Feed-in comp.:	12.57ct/kWh	Returning period:	20 years
Operating costs:	0.02 €/kWh		

a sum of approx. 300,000 € can be invested. Taking into account the costs of the needed devices and the additional costs due to the corrosive atmosphere and medium, respectively, a cost-effective implementation is not possible. Furthermore, bearing in mind the uncertainties due to the characteristics of untreated sewage and fluctuating discharges there are significant additional risks during operation which have to be considered within the project.

5. CONCLUSIONS AND OUTLOOK

Rising energy prices force operators of sewer systems and WWTPs to intensify the use of existing potentials to increase the self-energy production and energy recovery. Many measures have already been implemented; this paper analyses the applicability of hydropower and in particular systems for low heads in technical sites of the water associations Emschergenossenschaft/Lippeverband.

There are currently no suitable and cost-effective solutions for the use of small hydropower in sewer systems or rather manholes. Turbines are not suitable for use in wastewater and Archimedean screws and water wheels, respectively, can rarely be integrated into the structurally optimised manholes due to their large dimensions. Thus, a hydropower device has to be designed carefully. Usually, it should be designed according to the dry weather discharge to obtain continuous operation; the fluctuations between night's minimum and day's maximum hereby require a broad range of efficiency. In order to ensure optimum flow condition for the device, structural adjustments of the manhole building are indicated. Low efficiencies due to the medium as well as declining feed-in compensation have also to be taken into account.

Concerning WWTPs, different sites have been analysed. As gravity flow is usually used on the plants, it is expected that the most promising site is the outlet structure, as a certain head to the receiving river is usually given to guarantee discharge even at flood conditions. Constructional restrictions determine the applicable technology, it has been described that only few small hydropower techniques are suitable.

Out of the large number of small hydropower technologies available, only a few can be used under the difficult conditions in sewer systems and WWTPs, respectively. Thus, in most cases they are not economic. Continuous developments in the fields of hydropower technologies as well as material sciences have to be observed within the next years, as some innovative ideas and prototypes are currently under testing. Moreover, it is anticipated that the continuing increase in energy costs will have a positive impact on the economics of small hydropower systems.

If suitable discharges and heads are available, hydropower is a simple and effective way to enhance self-energy production and thereby saving energy costs as well as improving the operator's carbon footprint. Considering the long lifetime of hydropower plants the implementation of hydropower is a foresighted investment.

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