Water wheels for energy recovery in the outlet of wastewater treatment plants

Using the example of the water wheel at the Warendorf central wastewater treatment plant

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1 Abstract

The annual wastewater flow that is treated by public wastewater treatment plants in Germany amounts to approx. $10 * 10^9 \frac{m^3}{a}$ and forms an "artificial" hydropower potential that can be used for energy generation or recovery. In the context of this paper, energy recovery in the outlet of wastewater treatment plants is examined using the specific example of the water wheel at the Warendorf central wastewater treatment plant. The "artificial" hydropower potential can be roughly estimated at up to 20 to 105 $\frac{GWh}{a}$, whereby this is largely dependent on the hydraulic gradient. The strong variance results, among other things, from the findings of the water wheel operation in Warendorf. The decisive aspect here is the differential factor, which describes the deviation between the theoretical and actual energy yield of the water wheel. The factor includes maintenance work, downtimes and insufficient inflows, which are associated with a loss of output. In the case study, the annual energy recovery amounts to approx. 2 % of the annual electricity consumption of the wastewater treatment plant and can be estimated to 23,500 kWh (2022). In the context of the economic analysis, it can be seen that despite the "low" yield, economic operation is possible if the system is viewed as a long-term investment - payback period of the example is approx. 14,5 years. The 27-year operation (1996 - 2023) of the water wheel at the Warendorf central wastewater treatment plant confirms this and important findings on successful practical operation can be shown in the context of this paper.

Keywords: energy recovery, wastewater treatment plant, water wheel, potential, real example

2 Introduction

Over 96 % of the total German population is connected to the public sewer system, which feeds the collected wastewater into around 10.000 public wastewater treatment plants. The wastewater flow amounts to a total of approx. $10 * 10^9 \frac{m^3}{a}$, which is purified by the public wastewater treatment plants and then fed back into the water cycle [1].

This wastewater flow forms an "artificial" hydropower potential that can be used to generate or recover energy. This can take place, for example, within the sewer network, in drop structures or in the outlet of wastewater treatment plants [2, 3]. In the context of this paper, energy recovery in the outlet of wastewater treatment plants is considered using the specific example of the water wheel of the Warendorf central wastewater treatment plant, although it should be mentioned that other hydropower machines are available for potential utilization, such as hydropower screws or various turbines.

3 Methods and approach

This paper is based on an on-site visit of the waterwheel of the Warendorf central wastewater treatment plant (population value: 80.000), which was built in 1996. Through the operation of this waterwheel until today (2023), important practical knowledge could be collected regarding energy recovery through water wheels. These are supplemented by the results of online research and the associated literature, which is primarily based on the keywords. On the one hand, it is thus possible to estimate the total hydropower potential of wastewater treatment plant outlets in Germany and, on the other hand, advantages and disadvantages as well as practical experience can be shown with regard to utilization by means of top-shaft water wheels.

4 Hydropower potential of the wastewater treatment plant outlets

The theoretical hydropower potential in the outlet of a wastewater treatment plant results from the design discharge and the hydraulic gradient between the

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receiving water and the outlet [3]. It can be calculated using the following formula [4]:

$$P_{el} = \rho * g * h * Q * \eta \quad (1)$$

- $P_{el} = electrical\ power\ in\ W$
- $\rho = density\ of\ the\ medium\ in\ \frac{kg}{m^3}$
- $g = gravitational\ acceleration\ in\ \frac{m}{s^2}$
- $h = drop\ height\ or\ wheel\ diameter\ in\ m$
- $Q = volume\ flow\ of\ the\ medium\ in\ \frac{m^3}{s}$
- $\eta = overall\ efficiency\ of\ the\ hydropower\ machine\ in\ \%$

Under the following assumptions, the theoretical total hydropower potential of Germany's wastewater treatment plant outlets can be estimated as shown in Figure 1 (potential according to drop height without differential factor [differential factor: Deviation between theoretical [Theoretical yield$_{8760\frac{h}{a}}$] and actual energy yield [Real yield (2022)], based on the water wheel at the Warendorf central wastewater treatment plant shown in Table 1]):

- $\rho = 1000\ \frac{kg}{m^3}$
- $g = 9,81\ \frac{m}{s^2}$
- $Q = 317,1\ \frac{m^3}{s}$
- $\eta = 0,7$ [3]

If the findings from the operation of the water wheel at the Warendorf central wastewater treatment plant are taken into account, it can be seen that the potential can vary significantly due to the differential factor of approx. 4.95 (potential according to drop height with differential factor).

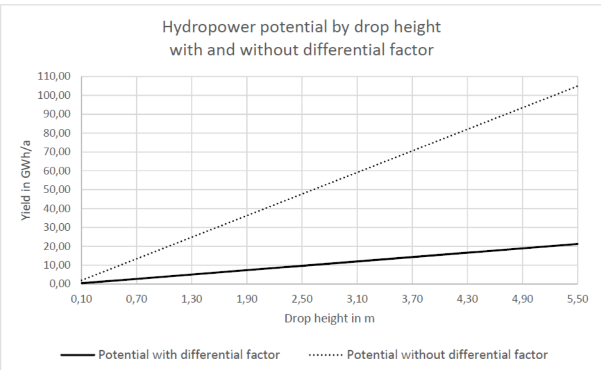

Fig. 1: Estimation of the total hydropower potential of wastewater treatment plant outlets in Germany

A more precise estimate of the total hydropower potential of wastewater treatment plant discharges in Germany is difficult, as this would require a closer examination of the individual plants with regard to their discharge volumes and hydraulic gradients.

5 Water wheel of the Warendorf central wastewater treatment plant

Due to the hydraulic gradient of > 5 m between the outlet and the receiving water, the waterwheel of the Warendorf central wastewater treatment plant was designed as a top-shaft cell construction - see Figure 2. The treated wastewater is fed (partly shown in Figure 2) via a foil-lined wooden channel and is equipped with an overflow so that the design flow rate of 400 l/s is not exceeded, for example in the event of heavy rainfall. A shut-off valve is also installed so that the flow to the water wheel can be shut off in the event of an emergency. The water wheel itself consists of a hot-dip galvanized steel shaft as well as spokes and reinforcing struts on which the stainless steel paddles/cells are mounted. The shaft rests on two bearings and ends in a coupling. In the event of a frictional connection, the speed is adjusted by a planetary gearbox, which enables the significantly higher nominal speed of the asynchronous generator. The design parameters and other key figures are shown in Table 1 [5]. The differential factor describes the deviation between the theoretical and actual energy yield of the water wheel. The factor includes insufficient inflows, maintenance work and downtimes, which are associated with a loss of output.

Fig. 2: Water wheel in the outlet of the Warendorf central wastewater treatment plant (2023)

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Tab. 1: Design parameters and key figures of the water wheel at the Warendorf wastewater treatment plant

Parameter	Unit	Value
Type of construction	-	top-shaft
Year of construction	yyyy	1996
Drop height	m	5,5
Water wheel diameter	m	4,83
Width of water wheel	m	1,5
Wheel speed	rpm	6,5
Max. absorption capacity	l/s	400
Theoretical output (manufacturer specification)	kW	13,6
Actual output	kW	12,6
Theoretical yield$_{8760\frac{h}{a}}$	$\frac{kWh}{a}$	116.219
Real yield (2022)	$\frac{kWh}{a}$	23.500
Differential factor yield	-	4,95
Electricity requirement (2022)	kWh	1.270.000
Real energy recovery	%	2
Total energy recovery	$kWh_{1996-2023}$	634.500

6 Advantages and disadvantages of a water wheel for energy recovery and findings from practical operation in Warendorf

Due to the 27 years of existence and operation of the waterwheel at the Warendorf wastewater treatment plant, important findings could be gained, which are listed below in combination with advantages and disadvantages.

(+) Due to the continuous operation of the sewage treatment plant and the hydraulic gradient between the outlet and the receiving water, there is always (waste-)water potentially usable for energy recovery ([5], findings from internal study from 1990).

(+) The system design is simple and tends to require little maintenance. Regular maintenance includes two gear oil changes per year as well as regreasing the shaft bearings [5].

(-) Due to the established technology, water wheels are generally robust and durable systems [2, 6]. When designing or constructing the system, the resulting torque or mechanical forces and loads should not be underestimated. In the case of the Warendorf waterwheel, it was necessary to replace the coupling and redesign the spokes several times [5]:
- Version 1: Classic construction with a set of wooden spokes leading to insufficient stability
- Version 2: Double spoke set made of hot-dip galvanized steel getting cracks at the weld seams after approx. 10 years of operation
- Version 3: Double set of spokes made of hot-dip galvanized steel and reinforcing struts and plates

(+) The effluent water from a wastewater treatment plant does not contain any impurities [3] or fish populations, so that neither a screen nor a fish ladder is required, which reduces the construction costs.

(-) The difference between theoretical and actual yield can be significant - see differential factor yield at Table 1.

(+) The Warendorf waterwheel was realized near the Ems-cycle-path and represents, among other things, visible public relations work [5] - "Fascination waterwheel".

7 Discussion and conclusion

It is already clear from the estimation of the hydropower potential of Germany's wastewater treatment plant outlets (Figure 1) that an individual consideration of the wastewater treatment plant with regard to discharge volume, hydraulic gradient and general location is always necessary. In general, however, the collection of this data is simple, so that a rough estimate of the potential is easy. Further planning is then possible, particularly in the context of the constant (waste-)water flow.

Table 1 shows that there can be a factor difference of up to 4,95 between the theoretical and actual yield. Furthermore, the energy recovery of 2 % of the annual electricity consumption can be assessed as low, but economically viable operation is possible, which is shown in Table 2 below. No statements were made by the Warendorf wastewater treatment plant with regard to investment, maintenance and operating costs. The values assumed in this regard in order to make an estimate are indicated by sources. The industrial

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electricity price for 2023 was assumed to be constant, although it is subject to annual fluctuations.

Tab. 2: Economic assessment (estimation) of energy recovery by the waterwheel at the Warendorf wastewater treatment plant

Parameter	Unit	Value
Operating time	a	27
Real yield (2022)	$\frac{kWh}{a}$	23.500
Industrial electricity price (2022) [7]	$\frac{Euro}{kWh}$	0,2251
Gross savings through energy recovery	$\frac{Euro}{a}$	5.290
Maintenance and operating costs [4]	$\frac{Euro}{a}$	1.500
Net savings through energy recovery	$\frac{Euro}{a}$	3.790
Investment costs (estimate [4])	$Euro$	55.000
Amortization time (excl. new construction spokes)	a	14,51
Net savings until 2023	$Euro$	102.330
Previous "profit" (2023)	$Euro$	47.325

Table 2 shows that the economically viable operation of a water wheel for energy recovery is possible, but that it is a long-term investment. With reference to the Federal Network Agency's electricity price analysis [7], however, the potential savings increase annually due to the constantly rising price trend. Apart from the repeated redesign and repair of the spokes, the 27 years of operation of the waterwheel at the Warendorf central wastewater treatment plant to date is a positive confirmation of the technology. Nevertheless, other technologies for energy recovery should also be considered in the course of planning, which include for example: Hydropower screws, Pelton turbines, through-flow turbines and submersible pump turbines [3].

8 Outlook

Due to the constantly growing global demand for energy [8] and the advancing energy transition, the topic of energy recovery will become even more relevant. Utilizing the "artificial" hydropower potential of wastewater treatment plant outlets is a possibility, regardless of the technology used. Building on this paper, a closer look at the differential factor and a detailed comparison of the available technologies would be useful.

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